Panasonic
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Your Committed Enabler

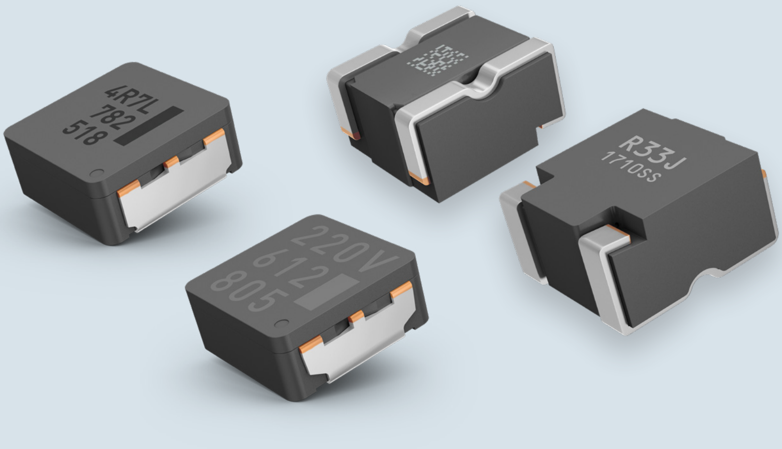
A comprehensive guide to Power Inductors

Cost-effective performance and reliability for automotive and industrial applications

White Paper

Panasonic Industry Europe GmbH
Device Solution Business Division
Product Management - Power Inductors

IN Your Future



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1. Introduction

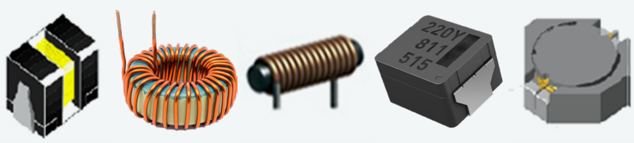
This technical guide summarises the different types of inductors, their correct usage, different applications, and Panasonic's inductor portfolio.

1.1 What is an inductor?

An inductor is a passive electronic component that stores energy in a magnetic field when current flows through it. An inductor resists the rate of change of the current passing through it by developing a voltage in opposite polarity proportional to the rate of change. Ideally an inductor allows the DC current to pass while generating high impedance for AC current. It is commonly used in electronic circuits for filtering, oscillation, and power conversion.

Figure 1. Typical inductor

Figure 2. Different shapes and types of inductors



1.2 Power inductor

Power inductors may also feature shielding or encapsulation to prevent interference with other components in the circuit. They are commonly used in power supplies, voltage regulators, DC-DC converters, and other electronic circuits where energy storage and filtering are required.
A power inductor is often A power inductor is often used to convert electrical energy into magnetic energy by storing, then supplying energy to the circuit to regulate current flow. It can also smooth out voltage spikes or to filter out high-frequency noise in power supply circuits to ensure smooth current flow.
In addition, a power inductor is used to filter EMI noise, conducted or radiated, helping to fulfil EMI / EMC regulations.
Power inductors can range in size from small, surface-mount components to large, high-power devices with a through hole structure used in industrial applications.
They are typically made of a coil of wire wound around a magnetic core material, such as ferrite or metal magnetic material core. The inductance value of a power inductor determines its ability to store energy, while its DC resistance and saturation current rating determine its efficiency and ability to handle high currents without losing inductance.

1.3 Automotive grade inductors

All Panasonic inductors (ETQPxM series) are automotive grade and fulfil the strict quality and reliability tests of automotive AEC-Q200 and IATF16949 certification.
AEC-Q200 is a set of automotive industry standards that define the requirements and test procedures for passive electronic components, including inductors, to ensure their reliability in harsh automotive environments.
Some of the AEC-Q200 tests that inductors must pass are shown in table 1 below :

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Table 1. AEC-Q200 test for inductors
Reliability Test Items (Automotive grade standard)

Items	Condition	Evaluation time
Temperature cycling	-40℃ (10min) ~ +150℃(10min)	2000 cycles
Vibration	10G (5Hz ~ 2kHz)	XYZ directions
	30 G (5Hz ~ 2kHz)	(4h each)
High temperature exposure	150℃	2000h
High Temperature operating Life	150℃,DC rated current	
Biased humidity	85℃, 85%RH	2000h
Operating life in humidity	85℃,85%RH,DC rated current	
Low temperature exposure	-40℃	2000h

1. **Temperature cycling test:**
   The inductor is subjected to repeated temperature changes between high and low temperatures to evaluate its ability to withstand thermal stress.
2. **High-temperature storage test:**
   The inductor is stored at a high temperature for an extended period to test its ability to maintain its electrical properties.
3. **Thermal shock test:**
   The inductor is subjected to rapid temperature changes to test its ability to withstand sudden thermal stress.
4. **Mechanical shock test:**
   The inductor is subjected to mechanical shock to test its ability to withstand physical stress.
5. **Vibration test:**
   The inductor is subjected to vibration to test its ability to withstand mechanical stress.
6. **Resistance to soldering heat test:**
   The inductor is exposed to high temperatures during the soldering process to test its ability to withstand very rapid thermal stress.
7. **Moisture resistance test:**
   The inductor is subjected to high humidity and temperature to test its ability to withstand moisture.
8. **Electrical testing:** The inductor is tested for its electrical properties, such as inductance, resistance, and capacitance, to ensure they are within the specified limits.

1.4 Types of inductors

There are several types of inductors, each with its own specific uses and characteristics. This section discusses some common types and they are summarised in table 2 below.

1.4.1 Air core inductor

This type of inductor has no magnetic core, hence air core. It is often used in high-frequency applications because it has a low level of magnetic interference. It has low inductance and is suitable for high-frequency applications, i.e. RF, GHz range.

1.4.2 Iron steel core inductor

This type of power inductor has a magnetic core made of iron steel or a magnetic alloy and it can handle high currents. Moreover, it can guarantee high inductance values in the low frequency range and a high level of magnetic interference. Because of these features, it is often used in power conversion applications such as reactors and power factor correction (PFC) circuits.

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1.4.3 Metal - composite inductor

A metal - composite inductor uses a metal powder mold core and is made up of a coil of wire wound around a magnetic core made of a metal alloy with high magnetic permeability. It is used in electronic circuits to store and release energy in the form of a magnetic field, typically in applications where high current handling capacity and smaller physical size are required.

1.4.4 Ferrite core inductor

This type of inductor has a core shaped like a doughnut and is often used in filters for audio applications and common mode choke coils (CMC) because it has low magnetic interference and low radiation. It can handle high currents and has high inductance.

1.4.5 Toroidal inductor

This type of inductor has a core shaped like a doughnut and is often used in filter for audio applications and common mode choke coil (CMC) because it has low magnetic interference and low radiation. It can handle high currents and has high inductance.

1.4.6 Coupled inductor

This type of inductor has two or more windings on the same core and is often used in power electronics as a transformer and SEPIC convertor. It can step up or step down voltage and isolate one circuit from another.

Due to their higher efficiency and common usage, Panasonic is focused on and specialised in metal core inductors. As the core, a metal - composite material is used.

Table 2. Common inductor types and usage

	Type of Inductor	Usage	Inductance (H)	Current Capacity (A)	Frequency Range (Hz)	Magnetic Interference	Physical Size
	**Air core inductor**	High-frequency applications	10nH below	Up to 1A	Up to GHz range	High	Small
	**Metal - composite inductor**	Power applications, higher peak current applications	100nH –100uH	Up to 100A	100kHz - 5MHz	Low	Small
	**Ferrite core inductor**	Power applications	1μH to 1H	Up to 10A	Up to MHz range	Low to high	Medium
	**Toroidal inductor**	Audio or CMC applications	1μH to 1mH	Up to several hundred A	Up to kHz range	Low	Large
	**Coupled inductor**	Power electronics	1uH to 100uH	Up to 10A	Up to MHz	Low to high	Large

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2. Characterisation

This section discusses the characterisation data of the metal - composite core and the ferrite core.

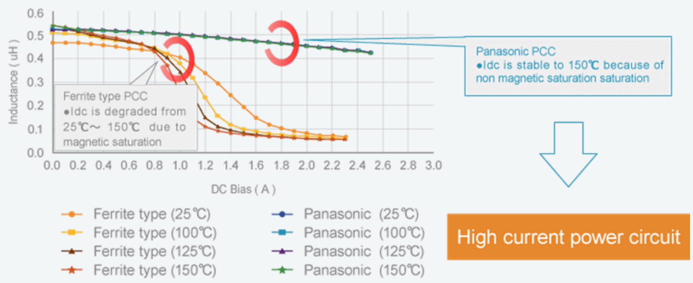
2.1 Ferrite core vs. metal - composite core

For power supply, the market trend is towards smaller inductors which are suitable for higher power.
Compared to ferrite core inductors, metal-core inductors fulfil those needs. Therefore, the following section will compare the two technologies.
The name metal - composite is derived from the characteristic that the metal powder in the core is surrounded by an isolation material.

2.2 Stable inductance even for high DC current

Metal - composite core inductors have a higher saturation current capability compared to ferrite core inductors.
This is due to the core made of a metal alloy with higher maximum magnetic flux density. This material has a higher electrical conductivity than ferrite, which allows it to generate a larger magnetic field before reaching saturation.
The higher saturation current with the very stable inductance capability of metal - composite core inductors makes them ideal for high-current applications, such as power supplies and motor drives.
Figure 3 below shows the inductance versus the DC bias current comparison between metal - composite core inductors and ferrite core inductors. The metal - composite core inductors ensure high stability of the inductance value even with high currents and at high temperatures.

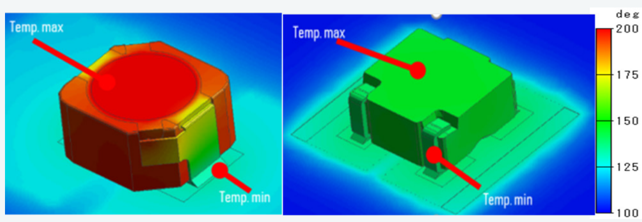
Figure 3. Inductance versus DC bias current



2.3 High heat dissipation

Inductors with a metal - composite core (compared to the ferrite type) have a higher thermal dissipation from the inner coil to the outside core. The metal - composite core design shows higher thermal dissipation with uniform temperature distribution resulting in maximum operating temperature compared to the ferrite type. This is due to the homogeneous structure, where the whole coil is surrounded by molded core.
Ferrite inductors, on the other hand, have an air gap that thermally isolates the coil. In this case, the heat can only be dissipated through the copper wire as shown in figure 4 below. This limits the maximum operating temperature and current for ferrite core inductors due to the temperature characteristics and adhesive glue used.

Figure 4. Heat dissipation, MC core versus ferrite core



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2.4 Low AC loss

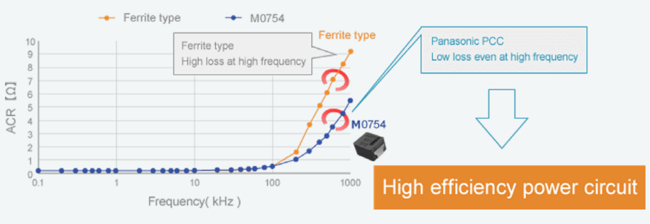
DC loss in the wire is caused by the DC resistance and AC loss is caused by the AC resistance as expressed by equations 1 & 2 below.

$$DC\ loss = Irms^2 \times DCR \qquad \text{Equation (1)}$$

$$AC\ loss = IAC\ RMS^2 \times ACR \qquad \text{Equation (2)}$$

As shown in figure 5 below, for metal - composite inductors, the AC resistance and therefore the AC loss is smaller compared to the ferrite type inductors due to the molded structure without any air gap resulting in the shorter magnetic path. The metal core with its unique design structure resulting in the higher permeability results in less leakage of the magnetic flux compared to the ferrite inductor core. Ferrite-inductors, on the other hand, have an air gap which results in a leakage of flux.

Figure 5. AC impedance, MC versus ferrite types



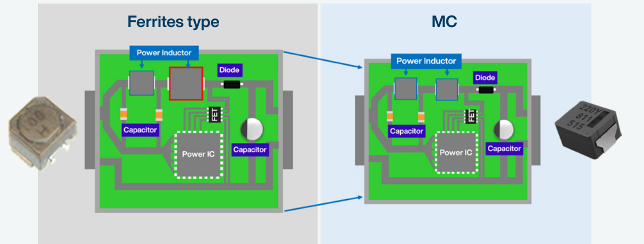
2.5 Downsizing (miniaturisation)

Metal - composite type inductors can achieve the same performance in a smaller size resulting in up to 50% space saving on the PCB, due to:

1. **Higher magnetic density:**
   Metal powder has a higher magnetic density (Tesla value).
2. **Higher saturation current**
   Higher saturation current allowing them to handle more current without losing inductance, therefore the inductors can be designed with fewer turns. The saturation current can be defined as the DC current at which the inductance value has dropped by 30%. The unique characteristic is that there is no hard saturation and inductance (L) has a linear trend over current (A). This is helpful for higher peak current applications.

This makes metal - composite inductors ideal for applications where size and weight are critical factors, such as mobile devices and automotive electronics. The small size with the same performance on the one hand results in the smaller PCB size and allows more components, helping to reduce the total cost. The small size inductor (metal core in this case) will result in fewer parasites as well.

Figure 6. Miniaturization, MC versus Ferrites type



2.6 Long life stability

Metal - composite inductors have a better stability over their lifetime.

1. **Adhesion material:**
   Ferrite inductors use epoxy or acrylic for the adhesion of the ferrite core and the windings.
   Epoxy or acrylic material will chemically degrade over a lifetime due to heat stress. Potential risks are audible noise and malfunction of the inductor. Metal - composite inductors on the other hand, do not use any adhesion. The metal powder is simply molded with high temperature resist-resin.

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2. **Wire coating:**
   Ferrite inductors use polyurethane as a coating for the windings inside the inductor. It is easier to solder. However it is weak and has a higher risk of layer short. Metal - composite inductors use polyamide-imide enamelled copper wire which shows higher stability.

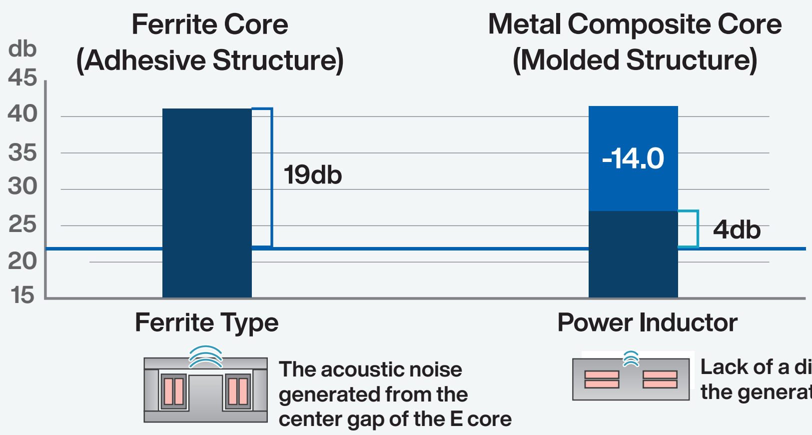
2.7 Higher power efficiency

Metal - composite inductors have a higher power efficiency than ferrite inductors because of their low loss material and design.
The higher saturation current capability allows for greater current handling capacity without loss of inductance. Therefore, the inductor can be designed with fewer turns, which leads to a lower DC resistance. This results in lower power loss and higher efficiency.

2.8 Acoustic noise reduction

Ferrite inductors have an air gap to reduce the saturation of the inductor. Due to the interaction of the magnetic field with that of the air gap, ferrite inductors cause noise at audible frequencies.
Metal - composite inductors on the other hand, do not have an air gap. This results in a large reduction of acoustic noise compared to ferrite types as shown in figure 7 below.

Figure 7. Acoustic noise, MC core versus ferrite core



Test Conditions	Burst Conditions
· Input 5V · Output 2V · Current Value 0-10A · Frequency 200KHz · Load Interval 4KHz	· Burst Frequency 150H · Duty 50%

Background Noise 22db

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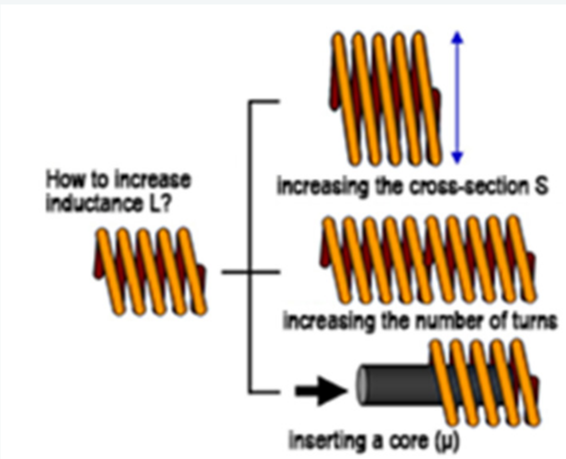
3. Nomenclature (basic theory)

The basic principle of an inductor is based on Faraday's law of electromagnetic induction, which states that a changing magnetic field can induce an electrical current in a nearby conductor. When a voltage is applied to an inductor, it creates a magnetic field around the coil. The magnetic field then stores energy, which is proportional to the amount of current flowing through the inductor.
The inductor resists changes in the current due to the magnetic fields tendency to oppose any changes in the current flow. This property is known as inductance, which is measured in Henries (H). The higher the inductance, the greater the magnetic field for a given current, and the greater the energy stored in the inductor.
Inductors are widely used for filtering and power conversion in industrial and automotive applications.

3.1 Physical units

Inductance is commonly represented by the symbol "L", chosen in honour of the physicist Henrich Lenz, the inventor of Lenz's Law related to electromagnetic induction theories.

Figure 8. Inductance - physical parameters



$$L = \frac{(k\mu SN^2)}{l}$$

Where:

- L = Inductance (H)
- K = Nagaoka coefficient
- μ = Core permeability (H/m)
- N = Number of coil turns
- S = Coil and core sectional area (m^2)
- l = Coil length (m)

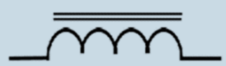
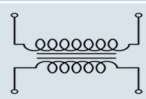
Based on this equation, the inductance can be increased by:

- Increasing the sectional area S (L ∝ S)
- Increasing the number of turns N (L ∝ N)
- Increasing the permeability μ by inserting a core. (L ∝ μ)

3.2 Circuit symbols

Figure 9 below shows the common symbols used for inductors.

Figure 9. Symbol of inductor and transformer

Inductor type	Symbol
Inductor with air core	
Inductor with magnetic core	
Transformer	

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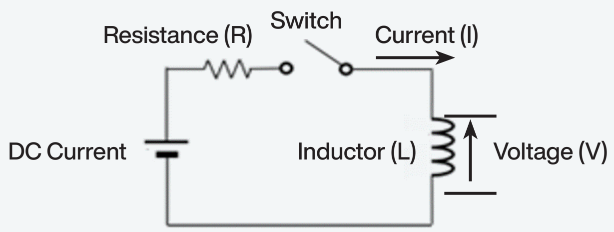
3.3 Behaviour

As explained in connection with inductors' structure, inductors are essentially wire coils and therefore the current basically flows through when a voltage is applied. However, because the inductors are components designed for electromagnetic induction, current does not simply flow. The behaviour of the inductors when DC or AC voltage is applied is described hereafter.

3.3.1 Voltage and current behaviour for DC

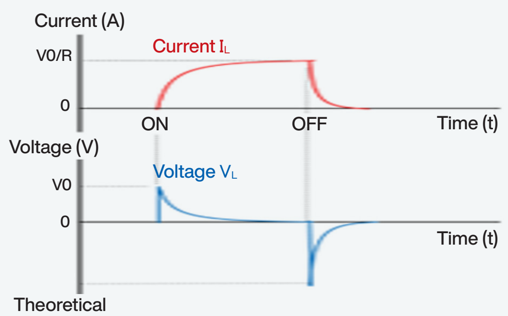
As shown in the circuit diagram, when the switch is turned ON to enable DC supply for the circuit, current flows through the inductor, resulting in the changing magnetic flux that is generated by changes in the current flowing through the inductor (wire coil), thereby generating an electromotive force (induction electromotive force) on the inductor. Since the inductor is basically a single wire coil, this is referred to as self-induction. This electromotive force is generated in a direction opposite to that of the current and restricts any increase in the current. Conversely, the electromotive force restricts any decrease in current when the switch is turned OFF.

Figure 10. Inductor biased with DC Current



Although the current (IL) starts flowing when the switch is turned ON, its increase is restricted by the electromotive force. Therefore, the current rises for a certain time constant, and after the rise, a constant current flow depending on the resistance component. When the switch is turned OFF, the current falls and becomes zero with a given time constant. The voltage (VL) indicates the electromotive force of the inductor when the switch is generated on the inductor is

Figure 11. Current and voltage waveform across inductor



Although the current (IL) starts flowing when the switch is turned ON, its increase is restricted by the electromotive force. Therefore, the current rises for a certain time constant, and after the rise, a constant

$$V=L=\frac{\Delta I}{(\Delta L)} \quad \text{Equation (3)}$$

Where:

- V: Electromotive force (V)
- L: Inductance (H)
- ΔI/Δt: Change rate of current (A/s)

Although the current (IL) starts flowing when the switch is turned ON, its increase is restricted by the electromotive force. Therefore, the current rises for a certain time constant, and after the rise, a constant current flow depending on the resistance component. When the switch is turned OFF, the current falls and becomes zero with a given time constant. The voltage (VL) indicates the electromotive force of the inductor when the switch is generated on the inductor is proportional to the change rate of the current (ΔI /Δt) expressed by equation 3 below.

As shown by the current waveform diagram, because the current increases relatively slowly when the switch is turned on, the electromotive force rises only up to the power supply voltage. When the switch is opened, the current is cut off instantly. In that case, the decrease of current is sudden compared with the high rate of change (ΔI / Δt) when the switch is turned on. As a result, the change rate as a function of time is higher, generating a higher electromotive force.

The current does not become zero instantaneously when the switch is turned off, due to the discharge current flowing between the switch terminals as a result of the high voltage generated at the inductor. Inductors can generate such a high electromotive force because an inductor can convert electric energy to magnetic energy and store it inside the inductor. The storable energy can be expressed by equation 4 below and is proportional to the magnitude of the inductance.

$$W=\frac{1}{2}LI^2 \qquad \text{Equation (4)}$$

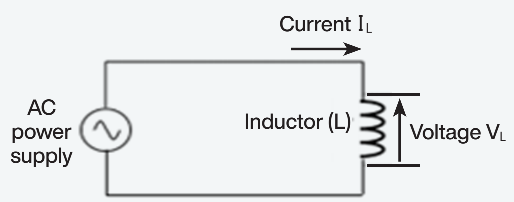
Where:

- W: Energy (J)
- L: Inductance (L)
- I: Current (A)

3.3.2 Voltage and current behaviour for AC

As described earlier, the magnitude of the electromotive force generated on an inductor is proportional to the rate of change of the current flowing through the inductor. This behaviour is the same when DC supply is replaced with AC power supply as shown in Figure 12 below.

Figure 12. Inductor circuit with AC power supply



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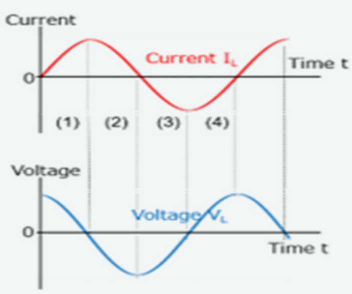
Area (1) Current from zero to positive peak (I):
At the beginning, the rate of change of the current is very high and results in a higher voltage drop. As the current rises, the rate of change of the current decreases, resulting in the lower voltage drop until it reaches the peak value where the rate of change of current is zero and the resulting voltage drop is zero.

Area (2) Current from positive peak to zero:
Negative voltage appears when the current starts falling from its maximum value. As a result, the voltage reaches its minimum value when the current becomes zero due to the maximum change rate of the current as shown in figure 13 below.

The areas (3) and (4) as shown in figure 13 below follow the same principles as explained above.

Figure 13. AC voltage & current across inductor



Looking at these current and voltage waveforms, one can notice that when the current waveform is sinusoidal, the voltage waveform is also sinusoidal, and the current waveform is behind the voltage waveform by a ¼ cycle (the phase of the current is behind by 90°).

In addition, a larger voltage is generated when the rate of change of the current is high, which means that a larger voltage is generated at higher frequencies at which current changes are higher.

However, because the voltage of actual inductors is the same as the voltage of AC power supplies, increasing the frequency at a constant voltage will decrease the flowing current when considering the voltage as the reference.

In other words, in the case of AC, inductors have higher resistance, so-called inductive reactance, depending on the frequency of the AC waveform, i.e. the higher the frequency of the AC waveform, the higher the inductive reactance resulting in lower current flowing through the inductor.

$$X_L = 2\pi f L \quad \text{Equation (5)}$$

$$I = \frac{V}{X_L} = \frac{V}{2\pi f L} \quad \text{Equation (6)}$$

Where:

- XL: Inductive reactance (Ω)
- f: Frequency (Hz)
- L: Inductance (H)
- V: AC voltage (V)
- I: AC current (A)

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3.3.3 Inductor basic functions

Inductors have three basic characteristics as described below:

1. Inductors generate a magnetic field across them when current flows through them. Conversely, current flows when their magnetic field changes.
2. Inductors convert the electric energy into magnetic energy as well as store the energy.
3. Inductors pass direct current (DC) and block alternating current (AC), the higher the frequency of AC, the more inductive reactance to block.
   The above-mentioned characteristics 1 and 2 are caused by the magnetic action of current and its reverse, i.e. electromagnetic induction, whereas characteristic 3 refers to the DC and AC characteristics of inductors caused by impedance.

The specific examples below explain the use case of the above-mentioned characteristics.

3.3.4 Principle of transformer:

Inductors generate a magnetic field across them when current flows through them; conversely the current flows when their magnetic field changes. The current flowing in the primary wire wound will generate a magnetic field cutting the secondary wire wound; this causes the generation of current in the secondary wire wound. This is due to electromagnetic induction, which is referred to as mutual induction in the case of transformers. The electromagnetic induction between the primary and secondary coils of the transformer will induce a voltage across the secondary coil; the amount of voltage induced in the secondary coil is directly proportional to the number of turns in the secondary coil.

3.3.5 Principle of power inductors:

Principle of choke coils: Convert electric energy into magnetic energy and store it.
As an example of an inductor in a DC/DC converter: When the switch is ON, the current flowing through the inductor generates a magnetic field across it, which results in the storage of energy in the form of magnetic energy. When the switch is OFF, the current stops flowing through the inductor, resulting in the discharge of the stored magnetic energy. The magnetic field changes, causing current to flow. This effect is electromagnetic induction, which is referred to as self-induction in the case of inductors that consist of a single wound wire.

Figure 14. Transformer basic structure

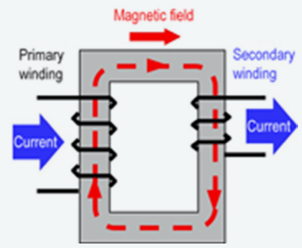
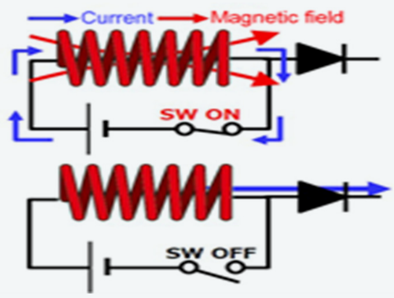


Figure 15. Working principle of choke Inductance



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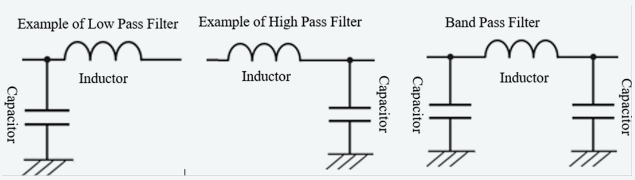
3.3.6 Filter high frequencies

The inductors pass the DC current and block the AC current; the higher the frequency of the AC current, the more reactance of the inductor to block the AC current. Inductors can be combined with capacitors to form a low-pass or high-pass filter shown in figure 16 below. The impedance of the inductor as well of the capacitor is a vital characteristic when designing the filters. The impedance characteristics will be described in detail below.

Figure 16. Inductor in high pass low pass & band pass filter



3.3.7 Impedance characteristics

In theory, ideal inductors have zero power losses across them. However, the simplified equivalent circuit of inductors is composed of series resistance (DCR), stray capacitance (Cp) in addition to inductance (L), as shown in figure 17 below. The resistance (R) represents the resistance of the wound wire and a core whereas the capacitance (Cp) mainly consists of the capacitance offered by the wire coils.

Figure 17. Inductance equivalent circuit

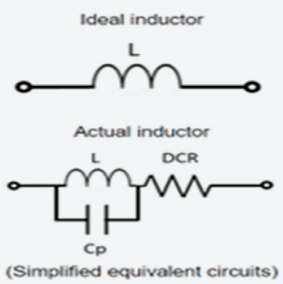
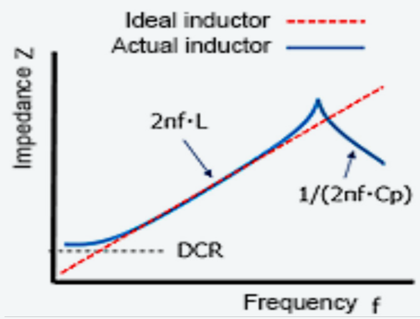


Figure 18 below shows a conceptual image of the impedance behaviour of an ideal and actual inductor with respect to frequency. As shown in Figure 18, the impedance of ideal inductors increases linearly as frequency increases. However, in actual inductors, a self-resonance phenomenon occurs due to stray capacitance, and the impedance decreases as the frequency increases, resulting in the inductors losing their original function. The total losses of the inductor are the sum of DC losses and AC losses.

Figure 18. Inductance impedance versus frequency



The impedance (Z) of the inductor and absolute value of impedance (Z) are expressed with equations 7 and 8 below respectively.

$$Z = R + j\omega L + \frac{1}{j\omega C} \qquad \text{Equation (7)}$$

$$|Z| = \sqrt{R^2 + (X_L + X_C)^2} \qquad \text{Equation (8)}$$

Where:

- Z: Impedance (Ω)
- R: DC resistance component DCR (Ω)
- C: Stray capacitance Cp (F)
- J: Imaginary number
- ω: 2πf; f = frequency (Hz)
- L: Inductance (H)

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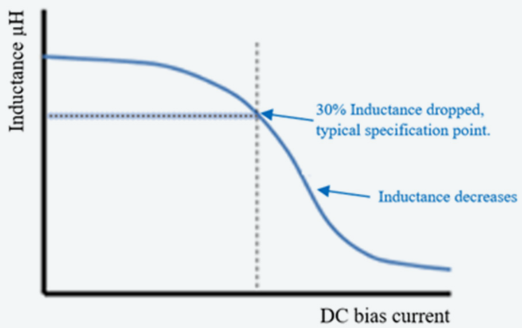
3.3.8 Magnetic saturation

Inductors become magnetically saturated when the current flowing through them exceeds the saturation current value specified in the product datasheet. Magnetic saturation results in a decrease of the inductance of the inductor. As shown in figure 19 below, when an inductor is saturated, the impedance is very small and the current flowing through the inductor is abnormally high. As an example, the DC-DC converters may suffer lower efficiency and malfunction. Magnetic saturation allowable current is an important characteristic of inductors.

3.3.9 AC-resistance (ACR)

Although only the DC resistance (DCR) was discussed in the earlier section in detail, the inductors also include a resistance component that generates eddy current losses at the core and a resistance component of conductive wires that increases due to skin and proximity effects. These components are referred to as AC resistance (ACR). The AC resistance (ACR) is directly proportional to the operating frequency of the AC source and has a significant impact on the power losses of inductors. The increase in ACR results in the increase of the temperature across the inductor and therefore needs to be taken into consideration in practical use. (Eddy current losses, skin effects, and proximity effects will be described later.)

Figure 19. Inductance saturation at DC current



3.3.10 Q factor

The Q factor of the inductor is defined as the ratio of the inductive reactance to its resistance at the operating frequency of alternating current (AC).

$$Q = \frac{X_L}{R} = \frac{2\pi f L}{R} \qquad \textit{Equation (9)}$$

The Q factor also defines the losses in the inductor, i.e. the higher the Q factor, the less energy is lost and the better the stability at higher frequencies.

$$Q = \frac{\textit{Energy stored per cycle}}{\textit{Energy dissipated per cycle}} \qquad \textit{Equation (10)}$$

The higher its Q factor, the closer an inductor is to an ideal inductor and the lower the ACR losses.

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4. Major Specifications of Inductors in Datasheets

The major specifications of inductors are shown below in table 3. Although various characteristics of inductors were explained in the previous section, not all the characteristics are designated as specifications.
Table 3 below summarises the typical inductor parameters specified in the datasheets of inductors. the specific parameters in the datasheets may differ by manufacturer, therefore carefully check as per requirements.

Table 3. Typical inductor parameters

Specification items	Meaning / condition, etc.
Inductance (L value) [µH]	Nominal inductance at a specific frequency
DC resistance (DCR) [Ω]	Resistance component of a conductor (cooper wire) that consistutes an inductor
Rated current temperature rise(ΔT) [A]	Rated currrent value at which the temperature rise when AC current is applied reaches 40k
Rated current DC bias (ΔT) [A]	Rated currrent value at which the L value decreases from initial value to the specified rate when DC current is applied DC bias
Mounting	External force must be less than 4.9N (dependent on case-size)

4.1 Inductance (L)

Indicates the inductance value in Henries (H) at a specified frequency (e.g. 100kHz); the tolerance of inductance is given as a percentage i.e. ±20%, ±30% or higher.

4.2 DC resistance (DCR)

The DC resistance of the inductor is measured at the direct current (DC) supplied to the inductor. The DCR depends on the length of the wire, the diameter of the wire and its terminal. The DC resistance of the inductor is specified in Ohm (π) and its tolerance as a percentage of the nominal value in the datasheet, i.e. ±5%, ±10% or higher.

4.3 Rated current

The rated current - ie the maximum allowed current of the inductor is specified by:

1. The current at which the temperature of the inductor increases by 40K with the following two conditions.
   Condition 1: Mounted on the multi-layer PCB with high heat dissipation (heat dissipation constant 5.5x5.0x3.0mm: Approx. 52 K/W, 5.5x5.0x4.0 mm: Approx. 48 K/W)
   Condition 2: Mounted on the 4-layer PCB of FR4 material with a thickness of 1.6mm, supplied with DC current.
2. The current at which the inductance drops by a certain value, for example -30%. This current is also called DC bias current.

4.4 Vibration resistance (G)

The vibration resistance ensures the stability of the inductor against high vibration, specified in G. With an amplitude of 5 mm or less, sweep speed of 1 oct / min, frequency of 5-2000 Hz, 3 directions /2 hours each, total 6 hours as an example are shown in Table 4 below:

Table 4: Vibration resistance of PCC

ETQP5M470YFM	TQP4M150KVC	ETQP4M470KFM
Amp. 5mm max. /10G Sweep rate: 1 octave/min Frequency: 5 – 2000Hz 3 axes / each 2h, total 6h	Amp. 5mm max. / 5.0G Sweep rate: 1 octave/min. Frequency: 5-2000Hz 3 axes /each 4h, total 12h	Amp. 5mm max. / 4.4G Sweep rate: 1 octave/min. Frequency: 5-000Hz 3 axes /each 2h, total 6h

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4.4.1 Correct usage

Table 4 below contains the precautions for use and the associated risks:

Table 5. Inductor important parameters and correct uses

Parameters	Precautions for use	Risk
Temperature	Ensure that temperature rise of inductor is within specified limits	Layer short: Reduction of lifetime
Voltage	Avoid applying voltages above the specified limits	Change in characteristics Damage the isolation of core and wire
Surge current	Avoid surge current	Layer short results in core crack
Vibration / mechanical shock	Avoid vibrations above specified limits	Results in cracks, wire breaks, chipping; breaking of solder connection, deterioration of electric characteristics
Heatsink	Usage needs to be aligned (to ensure electric isolation)	Layer short, lower inductance value, mechanical damage, heat up
Soldering	Resoldering with soldering iron should be done within 3 seconds at max. 350°C	Damaged wire coating, short between windings
Contamination	Avoid usage under the following conditions: • In liquid such as water, oil, chemicals, or organic solvents • In direct sunlight, outdoors and in dust • In salty air or air with a high concentration of corrosive gases such as Cl2, H2S, NH3,SO2, or NOx • In an environment where these products cause dew condensation	Core-crack, damage of wire coating, inductance drop, damaged isolation
Storage	Normal temperature (−5 to 35°C), normal humidity (85 %RH max.) Avoid storage at places with gases such as Cl2, H2S, NH3, SO2, and NOx; Avoid usage in direct sunlight	Damage of terminal surface oxidation, solderability.
Land-pattern	Land-pattern as described in the datasheet of each part number	Improperly soldered/mounted, unsafe electrical connection, less vibration resistance, heat up
EMI	Consider polarity marking	Electrio-magnetic interference with the circuit
ESD-protection	Assembly and in circuit	Damaged core isolation, layer short, inductance drop
Product specs	Product usage only within product specifications	Layer short, reduction of lifetime
Mounting	External force must be less than 4.9N (dependent on case-size)	Mechanical damage of inductor

5. Lifetime-Calculation

The lifetime of a power inductor depends on different factors, such as:

i. Operating condition
ii. Application
iii. Materials of the inductor
iv. Quality of the manufacturing process

Due to these different factors, there is not a single formula for calculating the lifetime.
One approach is to use accelerated life testing, which involves subjecting the inductor to conditions that simulate years of use in a short period of time. The inductor is then monitored for signs of degradation, such as changes in its electrical properties or physical appearance.
The temperature accelerating factor can be calculated with the equation below (Arrhenius equation).
The Arrhenius equation (Equation 11 below) states that for every 10 degree increase in temperature, the lifetime is reduced by half:

Acceleration formula:

$$K_T = L_1/(L_2 = exp\{E_a \mid k(1/(T_1 - 1/T_2))\} \qquad \text{Equation (11)}$$

Where:

- L1: Lifetime
- L2: Acceleration time
- Ea: Activation energy
- K: Boltzmann constant (8.62E-05eV/K)
- T1: Set temperature (in Fahrenheit)
- T2: Accelerating test temperature (in Fahrenheit)

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5.1 Losses

As with any electrical component, a power inductor experiences various types of losses; these can affect its efficiency and performance. The section below discusses the different kinds of losses a power inductor can experience.

5.2 DC losses

Copper losses occur due to the resistance of the inductor wire. When current flows through the wire, the resistance of the inductor wire itself causes the losses by converting the electrical energy into heat.

5.3 AC losses

Core losses occur due to the hysteresis and eddy current losses in the magnetic core of the inductor. Hysteresis losses occur when the magnetic domains in the core material are magnetised and demagnetised repeatedly, causing energy to be dissipated as heat.
Eddy current losses occur when there is a change in magnetic flux in the core, inducing a current that circulates within the core and causes heat to be produced.

5.4 Total loss

The total loss is the sum of the core-loss, DC loss (= the copper loss) and the AC losses expressed with the equation below:

5.5 Calculation of DC and AC loss

Table 5, below contains the details on the losses (AC, DC, core) of inductors:

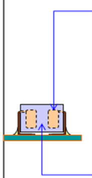
$$P_{total} = P_{core} + P_{DC} + P_{AC} \qquad \text{Equation (12)}$$

- Ptotal = total Power Loss
- Pcore = power loss due to the inductor's core
- Pdc = power loss due to copper in the coil
- Pac = power lossdue to eddy currents in the coil

5.6 Calculation of core loss

The core loss can be calculated as followed:

Table 6. AC & DC losses of inductors

Structure	Loss classification		Loss Calculation	Temperature Dependency	Frequency Dependency
	Coil loss	Copper loss	Pdc =Irms^2*Rdc Irms=SQR((Idc^2+IdcxIpeak+Ipeak^2)/3) (Rdc :Depends on temperature)	Yes	None
		Eddy current loss	Pac =Rac*Iacrms^2 Iacrms=IAC/2/SQR(3) Rac : Polynominal (using swf as valuable) Polynominal that is calcuculated from Acr and Pcore	Extremely Little Depend on material	Yes Raised a power
	Core loss	Hysteresis loss	Pcore : Polynominal (using swf, Iacrms and Duty as valuable) Polynominal that is calcuculated from core loss data of material, coil specification and dimension of the structure by simulation analysis.	Extremely Little Depend on material	Yes
		Eddy current loss		Extremely Little Depend on material	Yes Raised a power

$$\text{Core loss} = \frac{\text{Volume of magnetic material}}{\frac{\text{Magnetic density}}{\text{Switching frequency}}} \qquad \text{Equation (13)}$$

with

$$\text{Magnetic density} = \frac{\text{Inductance} \times \text{ACcurrent}}{\text{Winding turns} \times \text{cross sectional area MC core}} \qquad \text{Equation (14)}$$

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5.7 Loss simulation

Using Panasonic's power loss simulation tool, the different kinds of losses and the temperature rise can be calculated for most Panasonic inductors as shown in figure 20 below.

Figure 20. Panasonic inductor simulation tool

The details on the Panasonic supporting tool for power choke coils can be found here.

5.8 Application

Figure 21 below shows the most common use cases for the Panasonic metal - composite power inductor types. The Panasonic metal - composite power inductor types are specially designed to meet the waste range of automotive as well industrial applications as shown in figure 21.

5.9 Key applications

Automotive systems:

- Electric and hybrid vehicles
- Engine ECUs
- ADAS, autonomous driving
- Powertrains
- Motors, pumps and fans
- Body control

Industrial systems:

- Automation
- Servers
- LED drivers
- Power-supply modules

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Figure 21. Application example for Panasonic power inductors

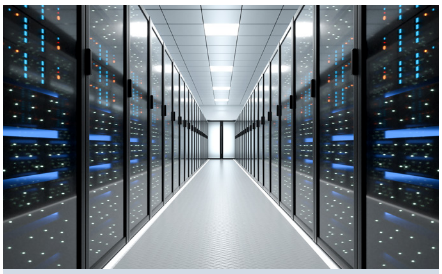
Applications

Circuit Function

- Noise Filter For Drive Circuits
- DC/DC Converter
- Voltage Regulator
- Buck/Boost Converters

Automotive

- HEV/EV
- Engine ECU
- ADAS
- Powertrain
- Lighting
- Autonomous Driving

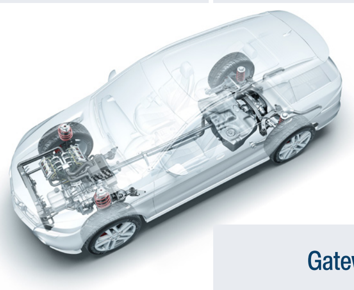


Industrial

- Automation
- Server
- LED Driver
- Power Supply Module

Automotive Application Examples

Engine ECU	Autonomous Driving	E-Power Steering	Transmission ECU	Battery Management System
E-Compressors	Navigation System			Battery ECU
Panel/HUD	On-board Charger			Camera
Radar	ADAS			Lidar
Fan Motor Driver	Domain Controller		Gateway	Monitor
LED Headlamp	Electrical Pump	48V/EV Inverter	Zone Controller	Door Motor Controller



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6. Panasonic Power Inductors (Metal - composite Type)

For metal - composite power inductors, Panasonic has large shares in the global automotive market as leading supplier with sustainable business growth and increased production capacity since 2006.
Since then, Panasonic has supplied billions of units of inductors with zero defects or failures reported from the field. This underlines their high reliability, even in harsh environments. This is why Panasonic is an approved inductor supplier for most of the major Tier-1 suppliers and OEMs.

6.1 Panasonic Product lines

Low profile high-current power metal - composite inductors offer robust performance in demanding automotive applications and unique features to meet the application requirements:

- AECQ200 compliant for automotive applications
- Low height design for mechanical robustness up to 30G vibration.
- Low DCR -20% help to reduce power loss.
- -45% less space with monolithic and magnetic shielded structure.
- Temperature stability -55degC to +155 deg C, +180degC in short time.
- Package variant from 5x5x3mm to 15x15x10mm core size, 0.33uH to 100uH design.
- High magnetic permeability & low magnetic leakage enhance EMC performance.
- Pin compatible with marketable footprint

6.2 Design features

This section briefly discusses the important design features of Panasonic metal - composite power inductors.

6.2.1 Robust wire coating

High temperature resistant coating (over 200°C) and high mechanical endurance (against scratches). Layer short is avoided.

6.2.2 Heat resistant magnetic core

The inductor core consists of metal powder and a binder, that serves as a connecting-material. The heat resistance of the binder is above 200 °C. It is highly resistant against heat cycles. There are no adhesives used for the binder.

6.2.3 Gap between terminal and core

Allows movement of the inductor core and therefore increases resistance against thermal and mechanical shock.

6.2.4 Monolithic molded structure

No air gap and less magnetic leakage result in better electromagnetic compatibility and help to avoid acoustical noise.

6.2.5 High magnetic density

High magnetic density of the metal magnetic material (more than 1.0 Tesla). Therefore, the inductors can achieve the same inductivity with a smaller core size. Ferrite has a magnetic density of only 0.4 Tesla.

6.2.6 Wire to terminal welding outside of core

The welding connection of terminal and lead wire is located outside of the core. So during the pressure process in production, the welding spot cannot be damaged. This results in a higher reliability.

6.2.7 Homogenous core and symmetric windings

Panasonic controls the molding-pressure at several locations of the metal core during the production process. Therefore, the positions of the lead wire inside the core stay the same. Stable electrical characteristics and save function of the inductor are ensured.

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6.2.8 Visible terminal
The two terminals are visible, even if the inductor is soldered onto the PCB. This ensures correct placement and the solder-quality can be checked visually.

6.2.9 Winding direction and polarity-marking
The winding direction is clearly displayed by polarity-markings on the inductor. Therefore the direction of the leakage flux is known and the inductors can be placed optimally on the PCB for good EMC-performance.

6.2.10 Dip-soldering of terminal
Using soft solder on the terminal, which is the same as with the reflow-soldering-process later. Due to the same material the quality and endurance of the solder-connection are increased. (Competitors use tinplating of a few micrometers, which is very hard. Cream solder is used during soldering. Because the two solders get mixed, there is a risk of layers/cracks.)

6.2.11 Robust terminal:
The inductor-series MC uses phosphor-bronze-material for the terminal. This material is both strong and elastic, which results in robust behaviour.

6.2.12 Chemically stable binding system:
Strong lifetime-stability against humidity, temperature cycles, substances.

6.2.13 Low loss:
The magnetic powder material particle size is controlled therefore the magnetic flux flows efficiently. This results in a reduced AC-resistance at high frequencies and low power loss.

6.2.14 High isolation voltage
Due to the strong wire coating and the controlled particle size, the inductors have a high isolation voltage.

6.2.15 Wire directly connected to PCB
The wire is attached along the terminal. After the inductor is placed on the PCB, both the terminal and the lead wire are connected to the PCB. The effect is a stable electrical and mechanical connection.

6.3 General line-up

As a pioneer of metal - composite power inductors, Panasonic offers a broad line-up of power inductors that offer the highest efficiency and reliability. This section discusses the main series line-up and comparison as well future products under development.
The Panasonic metal - composite family is commonly referred to as the ETQP family. Table 6 shows the main series line-up and comparison. For almost two decades, the ETQP power inductors series has proved itself as the most reliable solution when it comes to power inductors for the automotive industry with very robust performance for harsh automotive applications. The monolithic core and innovative terminal structure guarantee high performance and long-life stability against harsh vibrations and thermal stresses, which are typical of automotive operating conditions. The AEC-Q200 automotive qualified ETQP series is specified for wider operating temperatures, -55°C to 155°C with 2000 cycles, and guarantees a long operating life of approx. 15 years.

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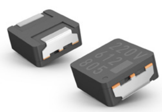
The product line shown in Table 6 below has features with different strengths targeted at the critical requirements of customers in the automotive industry.

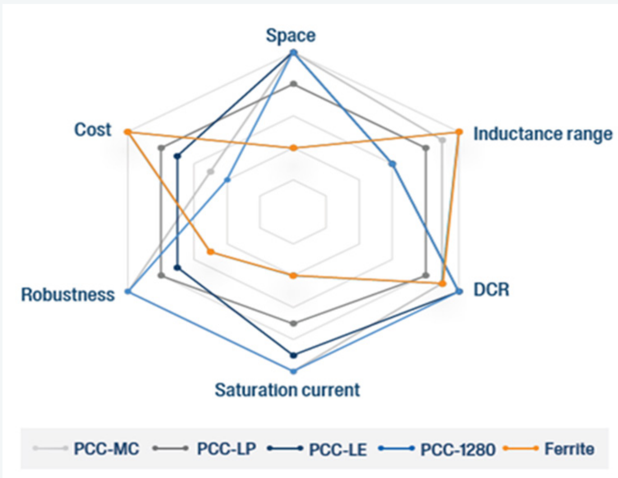
Table 7. Panasonic power inductors main series

Series	PCC-MC High Performance	PCC-LP Low Profile	PCC-LE LE type	PCC-1280/-1510 Large Current
Link	PCC-MC Productfinder | Panasonic Industry Europe GmbH	PCC-LP Productfinder | Panasonic Industry Europe GmbH	PCC-LE Productfinder | Panasonic Industry Europe GmbH	PCC-1280/-1510 Productfinder | Panasonic Industry Europe GmbH
Temperature range	-40 ~ +150°C	-55 ~ +155°C	-40 ~ +150°C	-40 ~ +160°C
Inductance range	0.33~100μH	0.33~47μH	3.3~47μH	0.33~4.7μH
Rated current	1.9~39.7A	2.1~23.9A	2.9~9.2A	20.2 – 83A
Package size (mm)	□5.5x5.0x3.0~ □10.9x10.0x6.0	□5.5x5.0x3.0~ □10.7x10.0x4.0	□6.4x6.0x4.8 □7.4x7.0x4.8	□13.2x12.6x8.0 □15.6×17.2×10.5
Benefit	▪ High performance ▪ Robust & high stability ▪ High saturation ▪ Low AC-power loss	▪ Low profile design ▪ Max 3.0 & 4.0mm height. ▪ Low DCR ▪ Pin layout compatible with IHLP series.	▪ Lower DCR ▪ Pin to pin compatible with Ferrite type	▪ High current ▪ Lower DCR ▪ 30G Vibration ▪ ½ package size

Figure 22 shows a comparison between the Panasonic metal - composite power choke coils ETQP series and ferrite type inductors. The Panasonic metal - composite power choke coils offer a higher degree of performance

Figure 22.
Performance of Panasonic inductors versus ferrite types



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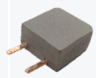
6.4 Application recommendation and future development

Table 8 provides the guideline for the selection of ETQP series for major applications in the automotive industry

Panasonic ETQP* Series

Table 8. Panasonic recommended series and future developments

	Series	High performance	LP Low Profile	LE Less Space	HiP-CV Concept	Anti-Vibration	4x4mm	12x12mm	15x15mm	≧20mm
Recommended series	ETQP*M***	ETQP*M*** YF*/YG*	ETQP3/4M** KV*	ETQP4M*** KFN/KFM	ETQP*M** TH*	ETQP5M*** YSK/YSC	ETQP2M*** PGR	ETQP8M*** JFA	ETQPAM*** JFW	TBD
	Appearance									
	Status	MP	MP	MP	TBD	MP	2027 -	MP	MP	TBD
	Size	0530-1054	0530-1040	0648-0748	0530-1054	0850-1060	420	1280	1510	20**-50**
	L [μH]	0.33-100	0.19-100	2.2-47	1.0-100	0.68-47	0.1-10	0.33-4.7	0.33-4.7	1.0-10
	I [A]	1.4-33.2	1.6-19.6	1.8-8.6	1.6-24.9	2.9-26.3	1.6-11.5	16.8-44.4	27-73	34-230
	DCR [mΩ]	3.8-348	2.18-242	9.6-201.6	1.94-165	1.75-125	4.2-212	0.7-4.9	0.4-3.0	0.07-3.5※
	Vibration [G]	30	30	4.4	50	30-50	10G※	30G	30G※	※

Automotive Applications

		High performance	LP Low Profile	LE Less Space	HiP-CV Concept	Anti-Vibration	4x4mm	12x12mm	15x15mm	≧20mm
Power- train	Engine	◎	○		◎	○				
	Transmission	◎	○		◎	◎	◎	◎	◎	
	Pump	◎	○		◎	◎		◎	◎	○
	Cooling Fan	○			○	◎		◎	◎	○
EV, HEV, PHV	BMS	○	◎	○	◎		○			
	Inverter	○	◎	○	◎					
	OBC	○	◎	○	◎			○	○	○
	48V DC-DC	○	○	○	○			◎	◎	◎
Body, Chassis & Safety	Brake, ABS	◎	○		○	◎		○	○	
	Steering, EPS	◎	◎		◎			◎	◎	◎
	BCM	○	◎		◎		○			
	Power Window	○	◎	◎	◎		○			
	Lighting	○	◎	◎	◎					
ADAS	DCU	○	◎	◎	◎		◎	○	○	
	Camera	○	◎	◎	◎		◎	○	○	
	Rader	○	◎	◎	◎		◎			
	Lidar	◎	◎	◎	◎		◎			
	T-Box	○	◎	◎	◎		◎			

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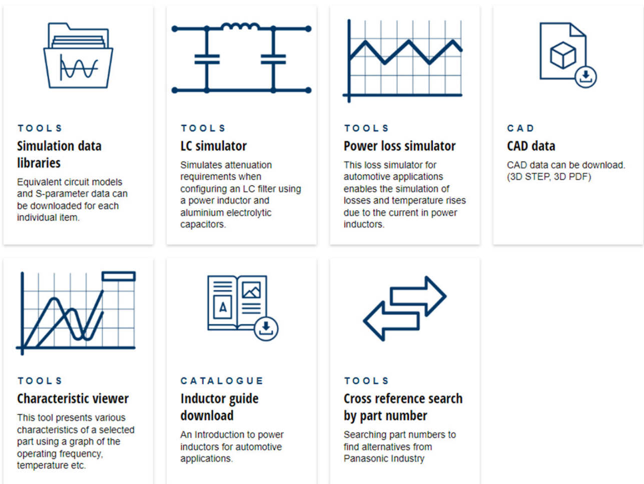
7. Web Tools and Support

Panasonic provides several web-based tools and supporting documents to help customers select the right part for the application, simulation tools for design support as well easy contact with the experts.

7.1 Web tools

The Panasonic web-based tools for inductors as shown below in figure 23 provide practical help during the design-in phase such as power loss simulation, characteristic of inductors, cross reference, CAD data.

Figure 23. Panasonic supporting tools for power inductors



Link Panasonic Webtools

Inductor product finder and parametric search

Productfinder | Panasonic Industry Europe GmbH

Models - Power Inductors for Automotive application - Inductors (Coils) - Panasonic

Panasonic
INDUSTRY

We are dedicated to the highest standards of global sustainability as **Your Committed Enabler**. Find out more on our website.

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