APPLICATION NOTE
ANE202611001

Characteristics and Selection of Common Peripheral Passive Components

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Nov. 3, 2026

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ABSTRACT

Resistors, capacitors, and inductors are the most fundamental yet often overlooked passive components in analog circuits and switching power supplies, particularly regarding their non-ideal characteristics: the resistance is correct but the gain deviates, the capacitance is sufficient but the filtering performance degrades, or the inductance is selected but the inductor overheats severely. The root causes of these issues often lie not in the nominal parameter values themselves, but in the neglect of temperature characteristics, DC bias effects, self-heating effects, saturation characteristics, parasitic parameters, and derating guidelines. This paper reviews the parameter boundaries, environmental constraints, failure risks, and layout considerations that must be concurrently addressed during the engineering component selection of these three types of devices, providing an actionable and comparative selection framework for analog circuit design, switching power supply design, and system reliability assessment.

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1 Resistors

A resistor is the most fundamental passive component in a circuit, primarily performing functions such as current limiting, voltage division, current sensing, impedance matching, and load setting. Common types include chip resistors, color-band resistors, and NTC thermistors. Color-band resistors use color-coded markings and axial-lead packaging, and their SMT production flow is more cumbersome than that of conventional chip resistors; the resistance of an NTC thermistor varies significantly with temperature and is not a fixed-value resistor. Therefore, this article mainly uses chip resistors as an example for discussion.

1.1 Main Parameters of Resistors

The first step in resistor selection is to clarify the basic requirements of the application scenario for resistance value, tolerance, power rating, temperature coefficient of resistance (TCR), and withstand voltage. Table 1 uses a typical chip resistor as an example to show its main parameters as follows:

Table 1 Main Parameters of a Resistor[1]

Main Parameter	
Resistance Value	10 kΩ
Resistance Tolerance (Accuracy)	1%
Power Rating	0.063 W (70℃)
TCR	±150 ppm/℃
Temperature Range	-55℃ to 155℃
DC Voltage	50V (maximum continuous voltage at full rated power), 100 V maximum overload voltage, 100 V dielectric withstand voltage

Tip: The resistance value determines the function; tolerance and TCR determine accuracy over the full temperature range; power and voltage determine safety. None of these can be omitted.

1.2 Nominal Resistance and Tolerance of Chip Resistors[1][2]

The resistance of chip resistors is identified by silkscreen codes, with different tolerance levels corresponding to different coding systems.

1.2.1 5% Tolerance, E-24 Series

E-24 series resistors are represented by 3 digits or codes, as shown in Figure 1.

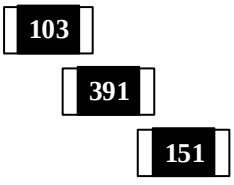


Figure 1 E-24 Series Resistors

The numbers in the E-24 series correspond to $10^{n/24}$, where n ranges from 0 to 23. Therefore, the coefficients for the E-24 series resistors are shown in Table 2.

[1] The parameter example is cited from the general specification datasheet of the Yageo AA0402 series thick-film chip resistor.

Table 2 E-24 Series Coefficients

E-24 Decode Value					
10	11	12	13	15	16
18	20	22	24	27	30
33	36	39	43	47	51
56	62	68	75	82	91

Representation of E-24 chip resistor resistance values:

a) **Resistors greater than 10 ohms:** XYZ, where XY is the E-24 series coefficient and Z represents the corresponding exponent. The resistance value is expressed as $XY * 10^Z$. For example, the resistor shown in Figure 1 is marked with 103, where XY is 10 and Z is 3, so the resistance is $10 * 10^3 = 10k\Omega$.

b) **Resistors less than 10 ohms:** XRY, where R represents the decimal point, e.g., 5R1 represents 5.1Ω.

1.2.2 1% Tolerance, E-96 Series

E-96 series resistors are represented by 4 digits or codes, offering higher accuracy and denser resistance values, as shown in Figure 2.

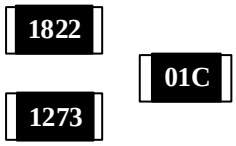


Figure 2 E-96 Series Resistors

The numbers in the E-96 series correspond to $10^{n/96}$, where n ranges from 0 to 95. The coefficient table for the E-96 series resistors is detailed in Appendix 5.1; in engineering practice, directly consulting the manufacturer's silkscreen manual is more efficient.

Representation of E-96 chip resistor resistance values:

a) **Resistors greater than 10 ohms:** WXYZ, where WXY is the E-96 series coefficient and Z represents the corresponding exponent. The resistance value is expressed as $WXY * 10^Z$. For example, the resistor shown in Figure 2 is marked with 1822, where WXY is 182 and Z is 2, so the resistance is $182 * 10^2 = 18.2k\Omega$.

b) **Resistors less than 10 ohms:** XRY, where R represents the decimal point, e.g., 5R10 represents 5.1 Ω.

c) **E-96 also has a Multiplier Code marking method**; the correspondence between its Code and the E-96 series coefficients is detailed in Appendix 5.2. For example, the resistor shown in Figure 2 is marked with 01C, where 01 corresponds to an E-96 series coefficient of 100 and C corresponds to 10^2, so the resistance is $100 * 10^2 = 10k\Omega$.

Tip: For applications with low accuracy requirements (such as pull-up/pull-down and current limiting), E-24 ±5% is sufficient and cost-effective; for critical paths such as voltage reference dividers, gain setting, and current sensing, E-96 ±1% or higher accuracy must be selected.

1.3 Rated Power, Rated Voltage, and Power Derating

1.3.1 Static Ratings: Power and Voltage

In addition to the resistance value, rated power and rated voltage are particularly important key indicators in resistor selection and are important criteria for determining the resistor package. The correspondence between the rated power, rated voltage, and package of common chip resistors is shown in Table 3.

Table 3 Rated Power and Rated Voltage of Common Chip Resistors[2]

Package		Rated Power P_r ($\leq T_S$=70℃)	Rated Voltage U_r
Imperial	Metric		
0201	0603	1/20 W	25 V
0402	1005	1/16 W	50 V
0603	1608	1/10 W	50 V
0805	2012	1/8 W	150 V
1206	3216	1/4 W	200 V
1210	3225	1/3 W	200 V
1812	4832	1/2 W	200 V
2010	5025	3/4 W	200 V
2512	6432	1 W	200 V

Tip: When selecting a package, first calculate the steady-state power dissipation, then compare it with Table 3. The power dissipation must not exceed 60% of the rated power P_r at T_S = 70°C (Zone II derating), and the operating voltage must not exceed 70% of the rated voltage U_r. Both power and voltage must be satisfied simultaneously, taking the smaller of the two limits.

1.3.2 Temperature Derating Curve

The rated power specified in the datasheet applies only to ambient temperatures at or below 70°C; between 70°C and T_{max}, it derates linearly to zero. In engineering practice, the Zone II derating standard is applied, with a steady-state power derating factor of 0.6, i.e., actual power dissipation ≤ 0.6 × P_r (when $T < T_s$), and further linear attenuation when above T_s. The derating standard for Zone II application of resistors is shown in Table 4.

Table 4 Derating Standard for Resistors in Zone II Applications[3]

Derating Parameter		
Steady-state Power	$T < T_s$	$\leq 0.6 \times P_r$
	$T \geq T_s$	$\leq [0.6 - (T - T_s)/(T_{max} - T_s)] \times P_r$
Transient Single-pulse Power		$\leq 0.7 \times P_m(t_1)$
Multi-pulse Power	$t_2 > 100\mu s, t_2/t_1 > 200$	$\leq 0.7 \times P_m(t_1)$
	$t_2 > 100\mu s, t_2/t_1 \leq 200$	$\leq 0.01 \times P_m(t_1) \times (t_2/t_1)^{0.85}$
	$t_2 \leq 100\mu s$	$\leq 0.01 \times P_m(100us \times (t_1/t_2)) \times (t_2/t_1)^{0.85}$
Steady-state Voltage		$\leq 0.7 \times U_r$
Transient Voltage		$\leq 0.7 \times U_m$

[2] The rated power and rated voltage of resistors from different manufacturers and series vary slightly.

Where U_r is the rated maximum operating voltage, U_m is the peak pulse voltage, P_r is the rated power given by the manufacturer at temperatures below T_s, T_s is the rated operating temperature given by the manufacturer, T_{max} is the nominal maximum operating temperature, t_1 is the pulse width, P_m is the maximum single-pulse power supported at pulse width t_1, and $(t_1 + t_2)$ is the pulse period. The final resistor power curve after Zone II derating is shown in Figure 3.

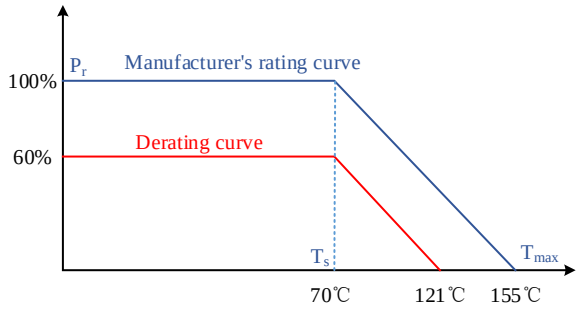


Figure 3 Resistor Power under the Zone II Derating Standard

Tip: For environments above 70°C (such as sealed enclosures or near heat sources), the power limit must be recalculated according to the derating curve; the 25°C nominal value must not be used directly.

1.3.3 Pulse Power Scenarios

In addition to DC operating conditions, resistor applications such as RC snubber circuits and startup protection circuits involve instantaneous high-power operation. For such scenarios, resistor manufacturers generally provide single-pulse peak power curves (with some variation between manufacturers; the curves provided by each manufacturer shall prevail), as shown in Figure 4.

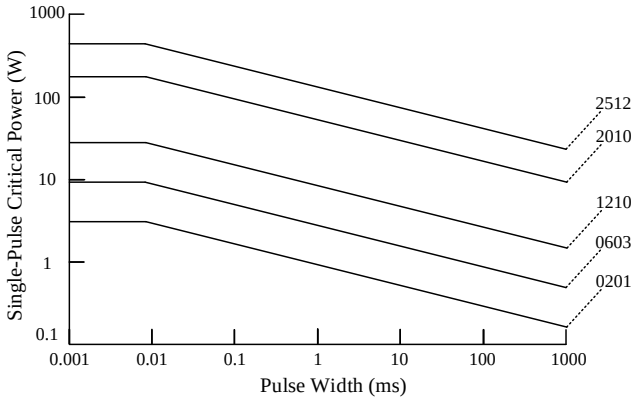


Figure 4 Single-Pulse Peak Power Curve of Resistors[4]

This curve represents the maximum single-pulse power P_m that the resistor can support at different pulse widths (time length t_1), where the pulse width is based on a rectangular wave, as shown in Figure 5.

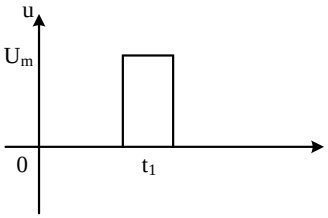


Figure 5 Single-Pulse Power

In actual applications, the relationship between power and time for resistors varies widely, so equivalent pulse width fitting is required for different application scenarios. For example, the equivalent rectangular pulse width for an RC discharge waveform is T = τ/2, where τ = RC is the time constant of the circuit; the equivalent rectangular pulse width for a triangular wave is T = t/3, where t is the duration of the triangular wave; the equivalent rectangular pulse width for a half-sine wave is T = t/2, where t is the duration of the half-sine wave; the equivalent rectangular pulse width for a damped oscillation waveform is T = τ/4, where τ is the time constant.

For multi-pulse power scenarios, the derated power needs to be evaluated based on the maximum single-pulse power P_m, the power pulse width (time length t_1), and the on/off ratio t_2/t_1. The definitions of t_1 and t_2 are shown in Figure 6.

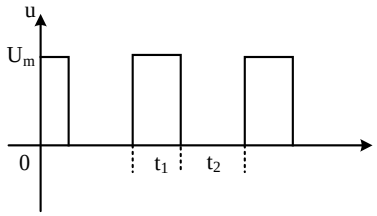


Figure 6 Multi-Pulse Power

Pulse power falls into two categories: single-pulse and multi-pulse. For single-pulse, you just look up the manufacturer's $P_m(t_1)$ curve. For multi-pulse, thermal accumulation effects come into play, so derating must be evaluated under the following three scenarios:

1) $t_2 > 100\mu s$ and $t_2/t_1 > 200$: The pulse interval is long enough that heat fully dissipates, making it equivalent to a single pulse. Apply $\leq 0.7 \times P_m(t_1)$.
2) $t_2 > 100\mu s$ and $t_2/t_1 \leq 200$: Thermal accumulation cannot be ignored. Derate according to $\leq 0.01 \times P_m(t_1) \times (t_2/t_1)^{0.85}$.
3) $t_2 \leq 100\mu s$: The pulse width is extremely short. P_m must be re-read from the curve using the equivalent pulse width $t_1 = 100\mu s \times (t_1/t_2)$, then derated according to $\leq 0.01 \times P_m(t_1) \times (t_2/t_1)^{0.85}$.

Tip: Multi-pulse is the most commonly overlooked cause of resistor failure during selection. Meeting the single-pulse requirement does not mean you've met the multi-pulse requirement. You must measure the actual t_1 and t_2 from the waveform and calculate them using the scenario-specific formulas. Estimating from experience is not acceptable.

1.4 Thermal Evaluation of Chip Resistors

Since the rated power of a resistor is strongly temperature-dependent, correctly evaluating the resistor temperature is an important means of determining whether the selected resistor meets application requirements. The heat of a chip resistor is mainly transferred through the solder pads to the PCB by thermal conduction (accounting for more than 90%); therefore, the heat dissipation capability of the PCB is the key factor determining the actual temperature rise of the resistor. In engineering practice, the temperature at the resistor terminal area is used as the monitoring point, and it must be ensured that the temperature at this point is within the range allowed by the derating curve.

PCB trace width directly affects heat dissipation. The wider the trace, the lower the temperature rise and the higher the allowable power dissipation, as shown in Figure 7. Therefore, in high-power scenarios, in addition to selecting a larger package, the area and width of the copper pad connection should also be increased.

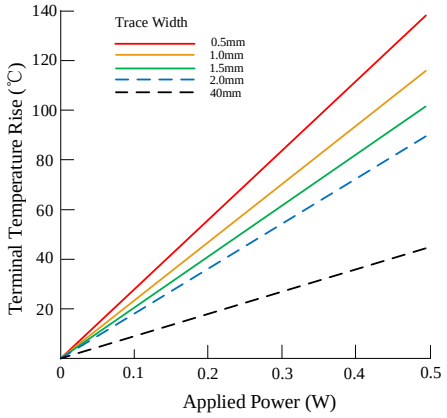


Figure 7 Trace Width and Temperature Rise[5]

Tip: Under different application conditions, the maximum allowable power of the same resistor is completely different. Therefore, the evaluation of resistor application conditions must be based on voltage, power rating, and the actual operating environment to determine the final resistor selection.

1.5 Temperature Coefficient of Resistance (TCR)

The temperature coefficient of resistance (TCR) is the relative change in resistance per 1°C change in temperature (unit: ppm/°C), calculated as shown in Equation (1).

$$TCR = \frac{R_2 - R_1}{R_1(T_2 - T_1)} \times 10^6 \ \ ppm/℃ \quad (1)$$

Where R_1 is the resistance at the reference temperature; T_1 is the reference temperature; R_2 is the resistance at any temperature; T_2 is any temperature.

For ordinary chip resistors, TCR determines the maximum deviation of resistance accuracy over the operating temperature range. The TCR of conventional thick-film resistors is typically between ±100 and ±200 ppm/°C, thin-film resistors can achieve ±10 to ±50 ppm/°C, and precision metal foil resistors can even be as low as below ±1 ppm/°C.

In engineering design, special attention must be paid to: TCR and initial tolerance combine to form the total resistance deviation over the full temperature range. For example, a ±1%, ±150 ppm/°C resistor at an 85°C temperature rise (25°C → 110°C) has an additional drift of $150 \times 10^{-6} \times 85 = 1.275\%$, and the total deviation exceeds 2.2%, far exceeding the initial tolerance itself. Therefore, for scenarios with stringent low-drift requirements (such as precision reference dividers, high-gain amplifiers, and high-precision current sources), TCR often has higher selection priority than initial tolerance. It is preferable to choose a 0.5% + 25 ppm/°C thin-film resistor than a 0.1% + 200 ppm/°C thick-film resistor.

In addition to conventional resistors, there is another type of thermistor whose core purpose is to utilize TCR. Its resistance varies significantly with temperature, with sensitivity far higher than ordinary resistors, and it is widely used in temperature detection and temperature compensation scenarios.

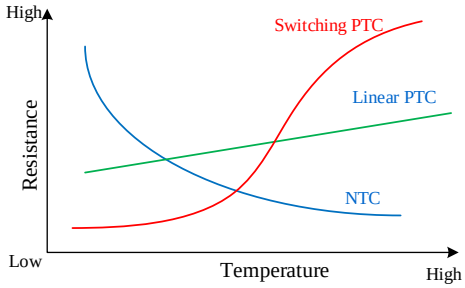


Figure 8 Thermistor Temperature Characteristic Curve

According to the sign of the temperature coefficient, thermistors are divided into two categories:

1) NTC (negative temperature coefficient thermistor): resistance decreases as temperature rises, with extremely high sensitivity; a small temperature change can cause a significant resistance change. Mainly used in scenarios such as input surge suppression and over-temperature protection.
2) PTC (positive temperature coefficient thermistor): resistance increases as temperature rises, and can be further divided into two types based on characteristic differences: (a) switching-type PTC, whose resistance rises sharply and nonlinearly with temperature, mostly used in over-current /over-temperature protection circuits; (b) linear PTC, whose resistance changes approximately linearly with temperature, can be used for high-precision temperature detection and temperature drift compensation.

Tip: For conventional resistor selection, the lower the TCR, the better, prioritizing resistance stability over the full temperature range; for thermistor selection, the goal is predictable resistance variation with temperature, requiring selection of NTC or PTC based on the specific application scenario and matching with the appropriate signal conditioning circuit.

1.6 Current Sensing Resistor Routing[6]

The selection of current sensing resistors (low resistance, high accuracy, low drift) must be combined with correct PCB layout to achieve performance. The core method is Kelvin four-wire connection, as shown in Figure 9, which separates the voltage detection points from the current path to avoid errors introduced by trace resistance.

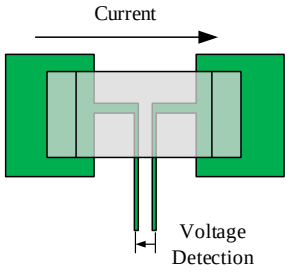


Figure 9 Kelvin Connection Method

Even with Kelvin connection, the current inflow direction and detection point position still affect detection accuracy. Typically, current direction can be divided into three categories: (1) current passes straight through the sensing resistor; (2) current flows into the resistor at a right angle and flows out in the same direction; (3) current flows into the resistor at a right angle and flows out in the opposite direction. In direction (1), the closer the detection point is to the center of the resistor pad, the smaller the error; in

directions (2) and (3), the influence of copper foil on the detection result increases significantly, and the optimal detection point may deviate from the center position, requiring simulation to determine the specific position. Therefore, in PCB layout, priority should be given to ensuring that the current path passes through the sensing resistor in a straight line, avoiding right-angle turns; if straight routing cannot be achieved due to layout constraints, the optimal detection point position must be determined through simulation.

Tip: The accuracy of the sensing resistor ultimately depends on the combined error of "the resistor itself + PCB routing + detection position." Selecting the right resistor but with improper layout will still double the error. In principle, let the current pass straight through the resistor, lead the voltage detection lines directly from the inner side of the pad, and make the two detection lines as equal in length and symmetrical as possible.

1.7 Resistor Selection Process Summary

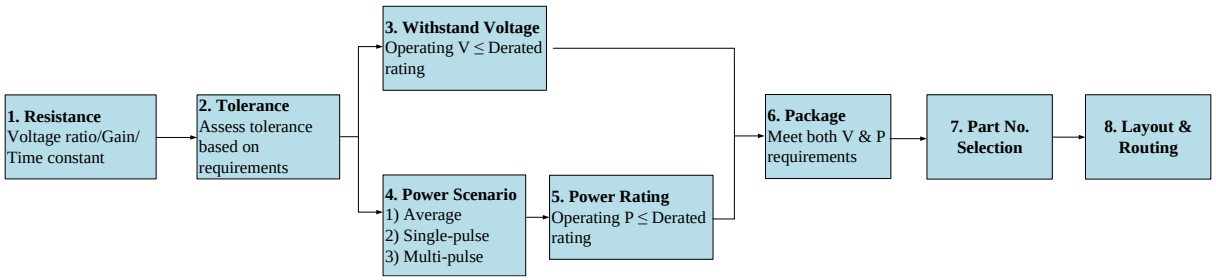


Figure 10 Resistor Selection Flowchart

2 Capacitors

A capacitor is one of the main fundamental passive components constituting a circuit, primarily helping the circuit achieve functions such as energy storage, filtering, coupling, bypassing, and voltage regulation. Commonly used capacitor types in engineering include: multilayer ceramic capacitors (MLCC), aluminum electrolytic capacitors, tantalum electrolytic capacitors, etc.

2.1 Main Parameters of Capacitors

The first step in capacitor selection is to clarify the basic requirements of the application scenario for capacitance value, tolerance, equivalent series resistance (ESR), withstand voltage, temperature range, and service life. Table 5 uses typical MLCC parameters as an example to show the main parameters:

Table 5 Basic MLCC Parameters[3]

MLCC Basic Parameter	
Capacitance Value	22 μF
Tolerance	±20%
Rated Voltage	10 Vdc
Temperature Characteristic	X5R
Operating Temperature	-55℃ to 85℃
Package/Case	0603 (1608M)
Thickness Dimension (max)	0.8 mm

[3] The parameter example is cited from the general specification datasheet of the Murata GRM187R61A226ME15 series MLCC.

2.2 MLCC

MLCC is formed by stacking ceramic dielectric films printed with internal electrodes in a staggered manner, sintering at high temperature to form a ceramic chip, and then applying metal external electrodes at both ends of the chip, forming a monolithic-like structure, hence also called a monolithic capacitor. Its advantages include small size, non-polarity, good high-frequency characteristics, and low ESR.

2.2.1 Classification of MLCC

MLCC falls into three classes based on different dielectric materials, with their characteristics compared as follows:

Table 6 MLCC Characteristic Comparison

Class	Dielectric Type	Temp. Characteristic	DC Bias	Aging	Typical Application
Class I	Non-ferroelectric	Linear, minimal variation	Almost no effect	None	Oscillators, resonant circuits, high-frequency coupling
Class II	Ferroelectric	Nonlinear	Significant decrease	Present	Bypass, decoupling, general filtering
Class III	Ferroelectric	Nonlinear, extremely large variation (-82% to +22%)	Extremely severe	Obvious	Low capacitance stability required

The temperature characteristic of capacitance (TCC) of Class I ceramic capacitors is expressed in the form of "letter + digit + letter" codes according to the Electronic Industries Alliance (EIA) standard, with specific meanings shown in Table 7. For example, C0G indicates a temperature capacitance characteristic of 0 ± 30 ppm/°C; U2J indicates a temperature capacitance characteristic of -750 ± 120 ppm/°C.

Table 7 EIA Class I Ceramic Capacitor TCC Codes

Significant Digits of Temperature Coefficient		Multiplier of Temperature Coefficient		Tolerance in ppm/°C	
C	0.0	0	-1	G	±30
M	1.0	1	-10	H	±60
P	1.5	2	-100	J	±120
R	2.2	3	-1000	K	±250
S	3.3	5	+1	L	±500
T	4.7	6	+10	M	±1000
U	7.5	7	+100	N	±2500
		8	+1000		

The temperature capacitance characteristics of Class II & III ceramic capacitors are expressed according to the EIA standard, with specific letter and digit meanings shown in Table 8. For example, X7R indicates an operating temperature range of -55°C to +125°C with a capacitance change not exceeding ±15%; Y5V indicates an operating temperature range of -30°C to +85°C with a capacitance change of -82% to +22%. Compared with Class II ceramic capacitors, Class III ceramic capacitors have extremely poor temperature characteristics and capacitance values severely affected by DC bias voltage. According to the EIA standard, ceramic capacitors ending with the letters T, U, or V are all Class III ceramic capacitors.

Table 8 EIA Class II & Class III Ceramic Capacitor TCC Codes

Minimum Temperature		Maximum Temperature		Capacitance Change Permitted	
X	-55℃	4	+65℃	A	±1.0%
Y	-30℃	5	+85℃	B	±1.5%
Z	+10℃	6	+105℃	C	±2.2%
		7	+125℃	D	±3.3%
		8	+150℃	E	±4.7%
		9	+200℃	F	±7.5%
				P	±10%
				R	±15%
				S	±22%
				T	+22%/-33%
				U	+22%/-56%
				V	+22%/-82%

Tip: Class I has the highest accuracy and stability, but capacitance is usually ≤ 10 nF; Class II is the most commonly used trade-off choice in engineering, with capacitance up to the μF level and acceptable accuracy; Class III, although having large capacitance, has poor stability and is only recommended for low-cost occasions insensitive to capacitance variation.

2.2.2 Key Electrical Characteristics of MLCC

Capacitors are not ideal in actual circuits; their equivalent model is "C + ESL + ESR," as shown in Figure 11. Therefore, attention must be paid to their impedance characteristics and ESR characteristics at different frequencies, as shown in Figure 12.

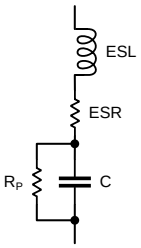


Figure 11 Capacitor Equivalent Model

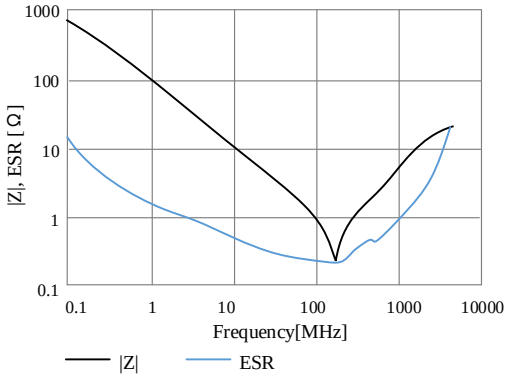


Figure 12 |Z| and ESR vs. Frequency of MLCC[7]

Based on this model, two key parameters can be derived:

1) **Dissipation factor (DF):** mainly reflects the heating characteristics and frequency characteristics of the capacitor; the smaller the DF, the lower the heating loss and the better the high-frequency characteristics.

$$\tan\delta = \frac{\text{Active power loss}}{\text{Reactive energy storage power}} \approx 2\pi f * C * ESR \quad (2)$$

2) **Self-resonant frequency (SRF):** the capacitor is capacitive below SRF and inductive above SRF; in filter circuits, it must be ensured that the target frequency is below SRF.

$$f_{SRF} = \frac{1}{2\pi\sqrt{C*ESL}} \quad (3)$$

For Class II & III ceramic capacitors, the influence of DC bias voltage on ceramic capacitors must be considered when selecting the capacitance value in practical applications. As the bias voltage increases, the effective capacitance of the ceramic capacitor decreases, as shown in Figure 13. Therefore, for Class II & III ceramic capacitors, it is generally recommended that the rated withstand voltage be at least twice the DC bias voltage.

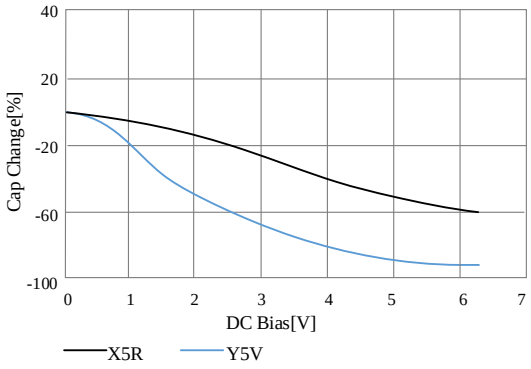


Figure 13 MLCC Effective Capacitance vs. DC Bias Voltage[8]

In addition, as described above, different types of MLCC have different temperature capacitance characteristics, so the temperature characteristics of capacitors are also parameters that require key attention in applications. Circuit design needs to incorporate the capacitance variation of MLCC over the full temperature range into tolerance analysis.

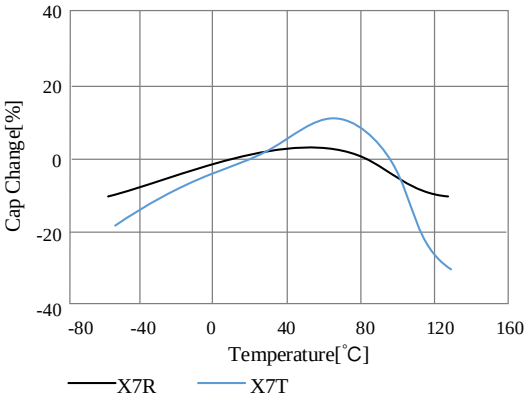


Figure 14 MLCC Effective Capacitance vs. Temperature[9]

Tip: In filtering/decoupling applications, not only the nominal capacitance but also confirmation that the capacitor is capacitive at the target frequency (< SRF) and that ESR is sufficiently low is required; the DC bias effect of Class II/III capacitors is the most hidden: the same 22 μF/10 V capacitor may have only 10 μF remaining at 5 V bias; always check the effective capacitance-voltage curve in the datasheet.

2.2.3 Noise Issues in MLCC

All dielectrics undergo mechanical deformation under an electric field, known as the inverse piezoelectric effect or electrostriction effect. When MLCC is used as the output filter capacitor of a switching power supply, the periodic AC voltage causes periodic deformation, which pulls the PCB through the solder pads to produce "noise," particularly noticeable in large-package capacitors (such as 1206, 1210, etc.). When the noise frequency is within 20 Hz to 20 kHz, it can be received by the human ear, producing audible noise.

The switching frequency of general switching power supplies is mostly above 100 kHz, and no noise is generated during steady-state operation. However, when the load has significant dynamic changes in the 20 Hz to 20 kHz range, noise problems may be triggered, and noise reduction measures need to be considered in the overall design.

Tip: In audio equipment and silent scenarios, if MLCC squealing occurs, it can be mitigated by selecting small-package capacitors, using flexible-termination MLCCs, switching to polymer capacitors, or adding external mechanical damping (such as adhesive fixing).

2.3 Aluminum Electrolytic Capacitors

Aluminum electrolytic capacitors use aluminum metal as the positive electrode and a surface aluminum oxide layer as the dielectric, and are classified by electrolyte type into liquid, solid, and hybrid aluminum electrolytic capacitors. Their characteristic is large capacitance, achieved by etching the aluminum foil surface to increase surface area and using an angstrom-level extremely thin oxide film as the dielectric.

The characteristics of the three types of aluminum electrolytic capacitors are compared as follows:

Table 9 Aluminum Electrolytic Capacitor Characteristic Comparison

Type	Electrolyte Form	ESR	Life	Low-Temp. Characteristic	Typical Application
Non-solid (Liquid)	Liquid electrolyte	High	Limited	Poor (significant capacitance drop at -40°C)	General power smoothing, industrial equipment
Solid	Conductive polymer	Low	Improved	Relatively good	High-frequency low-ripple power supplies, DC-DC modules
Hybrid	Liquid + polymer	Low	Long	Relatively good	Automotive electronics, high-reliability power supplies

2.3.1 Main Parameters of Aluminum Electrolytic Capacitors

The main parameters of aluminum electrolytic capacitors are shown in the following table:

Table 10 Basic Parameters of Aluminum Electrolytic Capacitors[4]

Aluminum Electrolytic Capacitor Basic Parameter	
Operating Temperature Range	-55℃ to +105℃
Rated Voltage Range	6.3 V_{DC} to 50 V_{DC}
Electrostatic Capacitance Range	10 μF to 1800 μF
Capacitance Tolerance	±20% (120 Hz/20℃)
Leakage Current	1≤0.01CV or 3 (μA) (whichever is larger, measured 2 minutes after applying rated voltage)
Durability	After applying rated voltage and rated ripple current at +105°C ± 2°C for 2000 hours, tested at +20°C: – Capacitance change rate: ≤ ±30%; – Dissipation factor (tan δ): not exceeding 200% of the initial limit; – Leakage current: not exceeding the initial limit.
High-temperature Storage Life	After storage without voltage at +105°C ± 2°C for 1000 hours, meeting the above durability limits.
Resistance to Soldering Seat	After reflow soldering and stabilization at +20°C: – Capacitance change rate: ≤ ±10%; – Dissipation factor (tan δ): not exceeding the initial limit; – Leakage current: not exceeding the initial limit.

1) **Voltage derating:** The capacitance of aluminum electrolytic capacitors is almost unaffected by DC bias voltage. During use, ensuring that the maximum steady-state voltage does not exceed 90% of the rated value and the instantaneous surge voltage does not exceed the nominal rated voltage meets the general derating standard.
2) **Temperature characteristics:** The capacitance of aluminum electrolytic capacitors varies significantly with temperature. The capacitance of non-solid aluminum electrolytic capacitors decreases at low temperatures and recovers as temperature rises (as shown in Figure 15); meanwhile, their ESR increases significantly as temperature decreases (as shown in Figure 16).

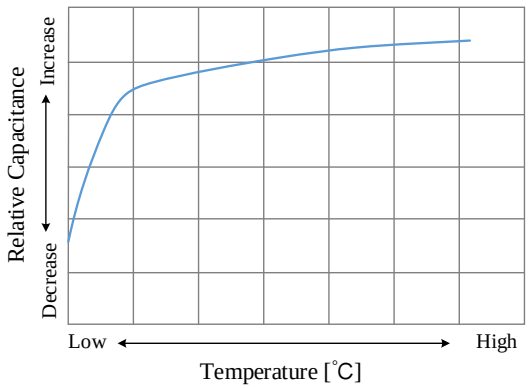


Figure 15 Capacitance vs. Temperature for Non-Solid Aluminum Electrolytic Capacitors

[4] The parameter example is cited from the general specification datasheet of the Panasonic EEEFP1V101A aluminum electrolytic capacitor.

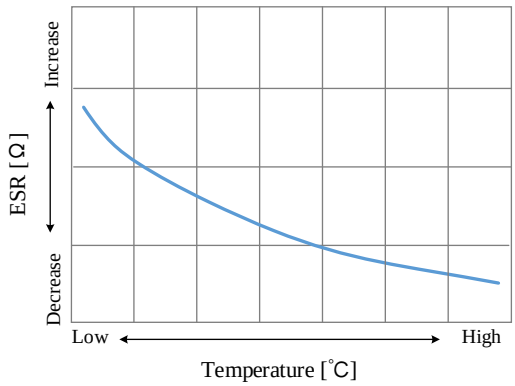


Figure 16 ESR vs. Temperature for Non-Solid Aluminum Electrolytic Capacitors

Tip: In low-temperature scenarios (outdoor equipment, automotive cold start), the actual capacitance and ESR of aluminum electrolytic capacitors differ greatly from those at room temperature; during design, ripple voltage and loop stability must be calculated based on the actual parameters at the lowest operating temperature. The low-temperature characteristics of solid/polymer aluminum electrolytic capacitors are significantly better than those of non-solid capacitors; the specific datasheet shall prevail.

2.3.2 Life Evaluation of Aluminum Electrolytic Capacitor

The life of aluminum electrolytic capacitors is a dimension that must be quantitatively evaluated in selection. Its failure mechanism is the vaporization of the electrolyte under temperature influence, gradually permeating through the sealing rubber, leading to capacitance decrease, ESR increase, and ultimately open-circuit failure (electrolyte dry-out). Temperature is the primary factor determining life.

Aluminum electrolytic capacitors must be strictly evaluated for service life in combination with actual application scenarios during use. For non-solid aluminum electrolytic capacitors, the "10°C 2x rule" generally applies (for every 10°C decrease in operating temperature, life doubles), and a simple evaluation can be made according to this principle. The detailed life evaluation formula is as follows:

$$L_X = L_O \times 2^{\frac{T_O - T_X}{10}} \times 2^{\frac{\Delta T_O - \Delta T_X}{5}} \quad (4)$$

$$\Delta T_X = \Delta T_O \times \left(\frac{I_X}{I_O}\right)^2 \quad (5)$$

Where L_X is the expected life (h) at actual operating temperature T_X; L_O is the guaranteed life (h) specified at the maximum operating temperature and rated ripple current; T_O is the maximum operating temperature (°C); T_X is the actual operating temperature (capacitor surface temperature) (°C); ΔT_O is the internal temperature rise of the capacitor at rated ripple current (°C); ΔT_X is the internal temperature rise of the capacitor at equivalent actual ripple current (°C); I_O is the rated ripple current (A); I_X is the equivalent actual ripple current (A).

Table 11 Ripple Current Frequency Correction Coefficients[5]

Frequency (Hz) / Capacitance (μF)	120	1k	10k	100k
10 to 470	0.65	0.85	0.95	1.00
560 to 1800	0.75	0.9	0.95	1.00

The equivalent actual ripple current usually contains multiple frequency components and must be synthesized using the frequency correction coefficients (as shown in Table 11) by linear interpolation or logarithmic interpolation according to Equation (6):

$$I_X = \sqrt{\left(\frac{I_{f1}}{F_{f1}}\right)^2 + \left(\frac{I_{f2}}{F_{f2}}\right)^2 + \cdots + \left(\frac{I_{fn}}{F_{fn}}\right)^2} \quad (6)$$

Where F_{fn} is the correction coefficient corresponding to the ripple current frequency; I_{fn} is the ripple current component at the specific frequency.

Taking the following capacitor specification as an example:

Guaranteed life at maximum operating temperature and rated ripple current	3000 h
Maximum operating temperature	105℃
Actual operating temperature	85℃
Rated ripple current	1.9 A (100kHz)
Actual ripple current	0.95 A (10kHz)
Internal temperature rise of capacitor at rated ripple current	5℃

Equivalent actual ripple current:

$$I_X = \frac{0.95A}{0.95} = 1A \quad (7)$$

Capacitor internal temperature rise:

$$\Delta T_X = 5℃ \times \left(\frac{1A}{1.9A}\right)^2 = 1.385℃ \quad (8)$$

The final aluminum electrolytic capacitor life under this application condition is:

$$L_X = 3000h \times 2^{\frac{105℃-85℃}{10}} \times 2^{\frac{5℃-1.385℃}{5}} \approx 19807h \quad (9)$$

The life of solid/polymer aluminum electrolytic capacitors is significantly better than that of non-solid capacitors; in general, only the ambient temperature factor needs to be considered, without complex ripple current calculations. The life calculation methods of polymer capacitors vary slightly among manufacturers; the manufacturer's datasheet shall prevail.

[5] The parameter example is cited from the general specification datasheet of the Panasonic EEEFP1V101A aluminum electrolytic capacitor.

Tip: Temperature is key to aluminum electrolytic capacitor life evaluation; ripple must be converted to an equivalent value. If the calculated life is lower than the expected service life of the equipment, capacitors with higher temperature ratings, larger packages, or solid/hybrid capacitors must be selected.

2.3.3 End-of-Life Design Margin

At the end of life, the ESR of aluminum electrolytic capacitors increases significantly and capacitance decreases significantly. Many powered devices experience abnormalities at the end of life, largely related to this. In the design of circuits sensitive to impedance, such as switching power supplies, the parameter shift at end of life must be incorporated into the design margin.

Tip: In high-reliability scenarios such as power supply output filtering, even if the life formula calculation meets the requirements, an additional 20% to 30% ESR margin should be reserved to ensure normal operation at end of life.

2.4 Capacitor Selection Process Summary

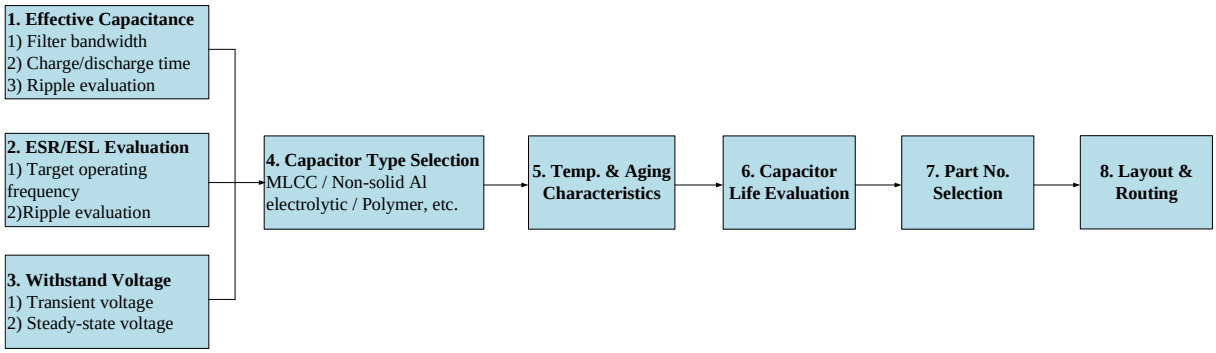


Figure 17 Capacitor Selection Flowchart

3 Power Inductors

An inductor is one of the three fundamental passive components in electronic circuits, capable of converting electrical energy into magnetic energy and storing it. Power inductors are core components in power supply systems, utilizing inductor characteristics to achieve voltage conversion and filtering; their performance directly determines the conversion efficiency, output ripple, and load capacity of the power supply. How to select an appropriate inductor is a key step in power supply design.

3.1 Main Parameters of Power Inductors

The first step in inductor selection is to clarify the basic requirements of the application scenario for inductance value, tolerance, direct current resistance (DCR), saturation current, temperature rise current, SRF, and withstand voltage. Table 12 uses a typical power inductor as an example to show its main parameters:

Table 12 Basic Parameters of a Power Inductor[6]

Power Inductor Basic Parameter			
Parameter	Test Condition	Value	Tolerance/Remark
Inductance L	100 kHz/10 mA	6.8 μH	±20%
Rated Current $I_{RP,40K}$	ΔT=40K	6.5 A	Max.
Saturation Current @10% $I_{SAT,10\%}$	IΔL/L<10%	3.2 A	Typ.
Saturation Current @30% $I_{SAT,30\%}$	IΔL/L<30%	6.8 A	Typ.
DC resistance R_{DC}	@20℃	28.3 mΩ	Typ.
DC resistance R_{DC}	@20℃	31.7 mΩ	Max.
Self-resonant Frequency f_{SRF}	/	18 MHz	Typ.
Operating voltage V_{OP}	DC	80 V	Max.

Tip: Inductance value determines ripple magnitude, DCR determines DC loss, saturation current determines the peak current limit point, and temperature rise current determines thermal safety; all four are indispensable. The SRF must be much higher than the switching frequency.

3.2 Saturation Characteristics of Inductors

The core risk of inductors lies in magnetic saturation. As the inductor current rises, the magnetic field strength increases accordingly, the core permeability decreases, and the inductance decreases. As shown in Figure 18, the inductance decreases as current increases. In extreme cases, the inductor approaches a "pure conductor," commonly known as inductor saturation. At the moment of saturation, the inductive reactance disappears, and the current rises sharply, potentially damaging power devices and loads. This situation must be avoided in power supply system design.

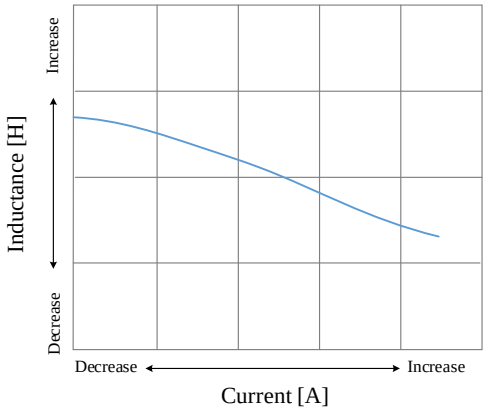


Figure 18 Inductance vs. Current

Tip: In power supply design, the inductor peak current must not exceed the nominal value of the saturation current (I_{SAT}), and a margin of more than 20% should be reserved. If the system has load transients, the transient overshoot current must also be included in the peak current calculation.

3.3 Temperature Rise Characteristics of Inductors

The rated current (temperature rise current) of an inductor is an important indicator for evaluating the heat dissipation characteristics of the inductor, usually defined as: the current value at which the overall

[6] The parameter example is cited from the general specification datasheet of the Würth 7443845030068 power inductor.

temperature rise of the inductor reaches a specified limit (typically ΔT = 40°C) after applying DC current without external heat dissipation. However, since its test condition is DC current, this parameter is only a reference for heat dissipation capability; in actual power supply systems, both AC and DC components exist in the power inductor, and the heat loss generated by the AC portion cannot be correctly evaluated through this parameter.

As shown in the inductor temperature rise curve in Figure 19, the actual temperature rise is the combined result of copper loss and core loss.

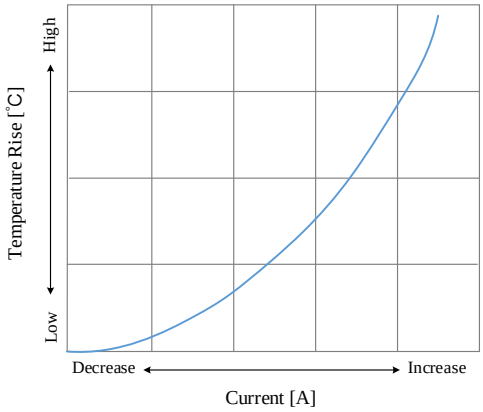


Figure 19 Inductor Temperature Rise Curve

Tip: Temperature rise current is the "bottom-line parameter" for thermal safety; in practical applications, it is recommended that the load average current not exceed 80% of the temperature rise current at ΔT = 40°C. For high-frequency or large-ripple current applications, additional evaluation of the additional temperature rise caused by AC loss is required.

3.4 Equivalent Model and SRF of Inductors

An actual inductor is not an ideal device. In addition to the series resistance DCR, due to parasitic capacitance between turns/layers, its equivalent model is "L + DCR + C," as shown in Figure 20.

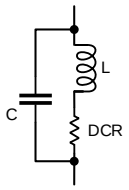


Figure 20 Inductor Equivalent Model

From the above equivalent model, the SRF can be derived:

$$f_{SRF} = \frac{1}{2\pi\sqrt{LC}} \quad (10)$$

The impedance characteristics are shown in Figure 21. When the operating frequency is less than SRF, the inductor is inductive (impedance increases with frequency) and can be used for power conversion; when the operating frequency is approximately equal to SRF, the inductor is purely resistive (impedance maximum), and the filtering effect is optimal; when the operating frequency is greater than SRF, the inductor is capacitive (impedance decreases with frequency), losing the inductor function.

Tip: When used as a power inductor, make sure it stays in the inductive region across the entire operating frequency band. As a rule of thumb, keep the power supply's switching frequency below 50% of the SRF.

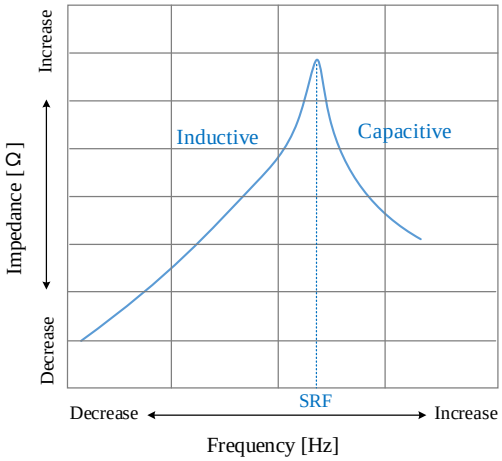


Figure 21 Inductor Impedance Characteristics

3.5 Withstand Voltage Characteristics of Inductors

The withstand voltage of an inductor mainly depends on the insulation layer of the enameled wire, the interlayer insulation material, and the dielectric strength of the magnetic core. The withstand voltage capability varies significantly among different types of inductors: general wire-wound inductors naturally have extremely high withstand voltage (hundreds of volts or more), and most scenarios do not require much consideration of withstand voltage; for molded inductors (coils embedded in magnetic powder and pressed), their insulation characteristics are affected by the production process, and some products have a withstand voltage of only tens of volts. When using such inductors, the datasheet must be consulted to confirm the maximum operating voltage V_{OP}, and it must be ensured that the steady-state voltage does not exceed 80% of the rated value.

3.6 Loss Analysis of Power Inductors

The losses of power inductors can be divided into two major categories: **copper loss** (winding loss) and **core loss** (magnetic core loss). An accurate understanding of the composition of the two losses is the basis for optimizing power supply efficiency and conducting thermal evaluation.

3.6.1 Copper Loss

Copper loss consists of two parts: DC loss and AC loss.

1) **DC loss:** generated by the DC resistance DCR, following Joule's law. The smaller the DCR (thicker wire, shorter winding), the smaller this part of the loss.
2) **AC loss:** when high-frequency current flows through the winding, due to the skin effect and proximity effect, the winding AC resistance (ACR) is much greater than DCR, generating additional AC copper loss.
   - **Skin effect:** when alternating current passes through a conductor, the current distribution on the conductor cross-section is uneven. The current density on the conductor surface is greater than that at the center, and this trend becomes more pronounced at higher frequencies. The effective conductive cross-sectional area decreases, and ACR >> DCR.
   - **Proximity effect:** when multiple wires are arranged side by side or wound in layers, the

alternating magnetic fields generated by adjacent wires induce eddy currents in each other, causing the current to be squeezed to the side of the wire close to the adjacent wire, significantly reducing the effective conductive area and further increasing ACR.

Tip: DC copper loss can be accurately evaluated based on the copper wire cross-sectional area, length, and number of turns of the winding; AC copper loss needs to be estimated in combination with the ACR/DCR ratio at the operating frequency, which is usually provided by the inductor manufacturer or measured with an impedance analyzer.

3.6.2 Core Loss

Core loss consists of three parts: hysteresis loss, eddy current loss, and residual loss.

1) **Hysteresis loss:** during the magnetization process of the magnetic core material, part of the energy is converted into potential energy, and the other part is converted into heat energy due to overcoming internal friction of the material. The area of the hysteresis loop intuitively reflects the magnitude of hysteresis loss (the larger the area, the higher the loss). The main influencing factors include maximum operating magnetic flux density (B), maximum magnetic field strength (H), residual magnetism (Br), and coercive force (Hc). Hysteresis loss can be effectively improved by increasing the core cross-sectional area, optimizing the magnetic circuit design, and reasonably opening air gaps to reduce the magnetic flux density swing.
2) **Eddy current loss:** the magnetic core generates induced electromotive force in an alternating magnetic field. Due to the limited resistivity of the magnetic core material, the induced electromotive force drives eddy currents to flow, and energy is dissipated as heat. Using high-resistivity materials (such as ferrite) or making the magnetic core into thin sheets (such as silicon steel laminations) can significantly reduce eddy current loss.
3) **Residual loss:** mainly caused by magnetization relaxation effects or magnetic lag effects, usually relatively low and negligible in engineering.

Since inductor manufacturers generally cannot provide detailed key parameters of magnetic core materials, it is difficult to obtain accurate core loss values through theoretical calculation in practical applications. Some first-tier manufacturers provide inductor loss calculation tools or loss curve charts, which can provide the core loss of the corresponding inductor based on actual operating conditions to assist users in relevant design evaluation.

Tip: In high-frequency applications (> 1 MHz), the proportion of core loss rises sharply, and low-loss core materials should be prioritized; in low-frequency high-current applications, copper loss dominates, and DCR should be prioritized for reduction. The most reliable method in actual engineering is to use online simulation tools provided by manufacturers for evaluation, rather than deriving by oneself.

3.7 Inductor Selection Process Summary

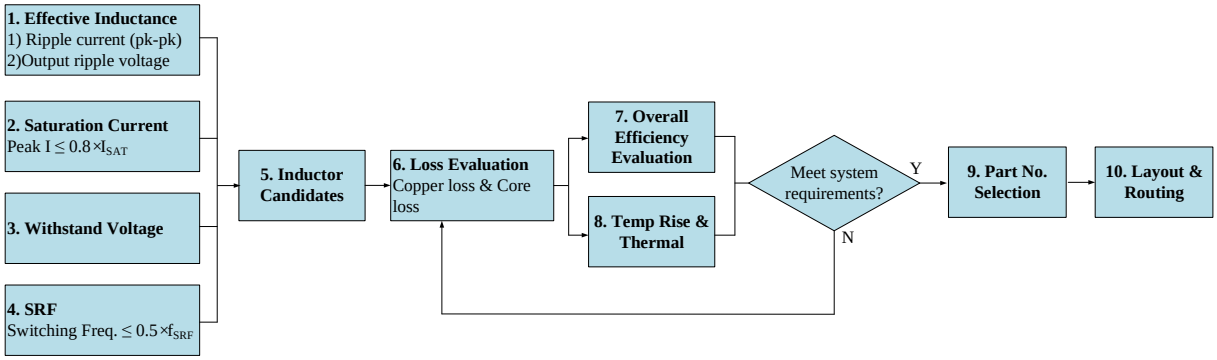


Figure 22 Inductor Selection Flowchart

4 References

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[9] Murata Manufacturing Co., Ltd. What is the temperature characteristics of ceramic capacitors[EB]. 2012-10-15.

5 Appendix

5.1 E-96 Series Coefficients

E-96 Decode Value					
100	102	105	107	110	113
115	118	121	124	127	130
133	137	140	143	147	150
154	158	162	165	169	174
178	182	187	191	196	200
205	210	215	221	226	232
237	243	249	255	261	267
274	280	287	294	301	309
316	324	332	340	348	357
365	374	383	392	402	412
422	432	442	453	464	475
487	499	511	523	536	549
562	576	590	604	619	634
649	665	681	698	715	732
750	768	787	806	825	845
866	887	909	931	953	976

5.2 E-96 Series Code Correspondence

E-96 Multiplier Code						
Code	1	2	3	4	5	6
R-Value	100	102	105	107	110	113
Code	7	8	9	10	11	12
R-Value	115	118	121	124	127	130
Code	13	14	15	16	17	18
R-Value	133	137	140	143	147	150
Code	19	20	21	22	23	24
R-Value	154	158	162	165	169	174
Code	25	26	27	28	29	30
R-Value	178	182	187	191	196	200
Code	31	32	33	34	35	36
R-Value	205	210	215	221	226	232
Code	37	38	39	40	41	42
R-Value	237	243	249	255	261	267
Code	43	44	45	46	47	48
R-Value	274	280	287	294	301	309
Code	49	50	51	52	53	54
R-Value	316	324	332	340	348	357
Code	55	56	57	58	59	60
R-Value	365	374	383	392	402	412

Code	61	62	63	64	65	66
R-Value	422	432	442	453	464	475
Code	67	68	69	70	71	72
R-Value	487	499	511	523	536	549
Code	73	74	75	76	77	78
R-Value	562	576	590	604	619	634
Code	79	80	81	82	83	84
R-Value	649	665	681	698	715	732
Code	85	86	87	88	89	90
R-Value	750	768	787	806	825	845
Code	91	92	93	94	95	96
R-Value	866	887	909	931	953	976

Code	A	B	C	D	E	F	G	H	X	Y	Z
Multiplier	10^0	10^1	10^2	10^3	10^4	10^5	10^6	10^7	10^-1	10^-2	10^-3

REVISION HISTORY

NOTE: Page numbers for previous revisions may differ from those in the current version.

Date	Rev	Description
2026-11-03	REV.A	Initial Release

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