

Five questions about resistors

UNDERSTANDING THIS UBIQUITOUS PART CAN HELP YOU AVOID COMMON CIRCUIT PROBLEMS.

The resistor is one of the simpler electronic components. Engineers seldom examine resistor characteristics until there's a resistor-related problem with a circuit design. You can probably resolve 90% of these problems after answering these five key questions:

- How much voltage can I put on the resistor?
- What will be the temperature of the resistor in my circuit?
- How much surge will the resistor withstand?
- What makes a resistor fail?
- How much change in resistance can I expect?

HOW MUCH VOLTAGE?

On the surface, this question appears to be the simplest. If, for example, you have a 0.25W resistor, you look on the appropriate product sheet for the part and find that it lists 250V as the maximum voltage. However, your engineering instincts tell you that, because the part has 10Ω, you better not put 250V onto a 10Ω part that measures 0.250 in. long by 0.090 in. in diameter unless you first get behind a concrete wall.

You can find the correct value of the maximum continuous voltage to put onto the 10Ω part by remembering the following: For capacitors, voltage rules; for inductors, current rules; and, for resistors, power rules. The primary parameter that you do not want to exceed for a resistor is the continuous-power rating, P_{RATED} . Because the rated power is the voltage squared divided by the resistance, the maximum continuous-voltage rating, V_{RATED} , is the square root of the rated power times the resistance: $V_{\text{RATED}} = \sqrt{P \times R}$. For the 10Ω, 0.25W example, the rated voltage is 1.58V, far less than the 250V that the spec sheet lists as the maximum voltage. You must make this calculation for each resistor value you use.

You determine when to use the specified maximum voltage or the calculated rated voltage using the critical resistance, R_{CRITICAL} . Resistor manufacturers define the critical resistance as the resistance at which the part dissipates rated power at the maximum continuous-voltage rating: $R_{\text{CRITICAL}} = (V_{\text{RATED}})^2 / P_{\text{RATED}}$. For the 0.25W part with a maximum voltage of 250V, the critical resistance is 250 kΩ. At resistances higher than the critical resistance, the maximum continuous rated voltage is 250V. At resistances lower than the critical resistance, you must calculate the square root of the power times the resistance to determine the maximum continuous-voltage rating.

If you do not apply the voltage continuously, you can put a higher voltage on a resistor for a short duration. Resistor man-

ufacturers define an STOL (short-time-overload) condition, the degree of which varies depending on the type of resistor. For power wirewound resistors, STOL can be two to 10 times the rated power for 5 or 10 sec. For most film resistors, STOL is 2.5 times the rated voltage, or 6.25 times the rated power, for 5 sec. For high-voltage resistors, STOL is commonly 1.5 times the rated voltage, or 2.25 times the rated power, for 10 sec. Refer to your resistor's product sheet to see how the manufacturer defines STOL and to find the maximum percentage of change in resistance that can occur when you apply the STOL voltage.

You should heed three notes of caution. First, STOL is a non-repetitive surge or overload condition. Second, putting two to 10 times the rated power on a resistor for more than 5 or 10 sec can cause permanent damage and can melt the solder joints that hold the part in place. Third, there is a maximum allowable STOL voltage: typically, two times the maximum continuous rated voltage. You should refer to the data sheet or call an application engineer if the data sheet lacks this information. In your calculation of the STOL voltage, do not let it exceed the maximum STOL voltage that the data sheet specifies. For example, for a 0.25W, 10-MΩ film resistor, the STOL-voltage calculation is 2.5 times the square root of the power times the resistance, or 1581V. However, the maximum allowable STOL voltage is two times the maximum continuous rated voltage of 250 or 500V.

Before you can establish the maximum voltage that you can apply to a resistor by considering the maximum continuous- and maximum STOL-voltage ratings, you must consider another set of conditions. When a resistor "sees" a STOL condition, the amount of power you apply may be as much as 10 times rated power for 5 sec. If you apply power for only 1 msec or 1 μsec, you should be able to apply even more than 10 times the rated power. Under a surge condition for a given type of resistor, you may be able to apply 100 or even 1000 or more times the rated power. A manufacturer may allow the voltage you apply to exceed the maximum STOL voltage of resistors that can handle high power surges. However, do not make this assumption. See the product data sheet or speak with the application engineer for information on the maximum power and voltage that you can apply for a given resistance value and pulse duration.

TEMPERATURE OF THE RESISTOR?

In the past, most resistors had solder-coated copper leads, so determining the "hot-spot" temperature was relatively straightforward. A standard test procedure allowed a specified lead length between the resistor and the pc board, and a fine-wire thermo-

couple determined the hot-spot temperature at various power loadings of the resistor. The design permitted no air movement across the part. From this data, you could make a temperature-versus-power-applied plot. For many resistors of 1W or less, the plot was a straight line from ambient temperature with no power to the hot-spot temperature at rated power. You expressed the slope of the line as the temperature rise in degrees Celsius per watt. For power resistors with a hot spot that exceeded 175°C, radiation caused a heat transfer, making the plot deviate somewhat from a straight line at temperatures higher than 175°C. Even so, engineers normally used a typical temperature-rise figure. For example, if a 2W resistor had a temperature rise of 80°C/W, then you could calculate the hot spot at 1.5W at an ambient temperature of 50°C as $1.5W(80°C/W) + 50°C$, or 170°C.

Surface-mount components have complicated the temperature question. Without leads, the surface-mount resistor transfers more of its heat directly onto the pc board. Because the parts are smaller, the density of heat-producing parts is higher. The type of pc board, the number of layers, and the weight of the copper plate for the traces all become important factors. A thermal-imaging camera rather than the fine-wire thermocouple often makes temperature measurements at all points on the board. The temperature of the solder joints may become more important than the hot-spot temperature.

The best information that the resistor manufacturer can provide is from powering a single component onto a given size and type of pc board. No universal test standards exist. They may

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provide this data as temperature rise or thermal resistance and express both in degrees Celsius per watt. Manufacturers sometimes provide two values—one for determining the hot-spot temperature and the other for determining the solder or terminal temperature. In recent years, heat-transfer software has become available to assist in predicting temperature of components at various points on a pc board. To use these programs, you must know the size of the component, the thermal resistance, and perhaps the weight of the component in grams. Just remember that thermal resistance is the largest variable due to the way manufacturers of resistor components make their measurements.

You will not get an answer about resistor temperature from the resistor manufacturer. The application engineer can provide data that can assist in the thermal analysis of your circuit. You can use this data to determine the size or family of products from a manufacturer to limit the maximum temperature to a desired value. If you compare similar components from different manufacturers, be aware that the conditions they use to obtain the thermal data may differ. When you prototype the pc board, the application engineer can assist in getting samples of one or more resistor products to evaluate. The question of operating temperature has always been difficult to answer. Unfortunately, the

answer has become more important as the size and weight of the finished product has decreased.

HOW MUCH SURGE?

A surge condition for a resistor is the application of a power level that exceeds the continuous-power rating of the part for a defined length of time or pulse width. The pulse width is normally 25% or less of the thermal time constant of the resistor. For example, if a resistor has a thermal time constant of 20 sec—time to reach 63% of the final temperature—then the application of a power pulse, exceeding the continuous-power rating, of 5 sec or less would meet your definition. If you apply the same pulse for 60 sec, the resulting temperature would exceed the continuous-rated-power temperature. Applications that have surges that last for seconds are rare. Most surges last for milliseconds or microseconds.

You need to consider both repetitive and nonrepetitive surge conditions. A repetitive surge applies power for a given pulse width and then repeats at a regular interval or time period. You can usually easily measure the period from the beginning of the power pulse to the beginning of the next power pulse because the leading edge of the pulse is often the most defined. For repetitive surges, the average power dissipation over the period of the pulses must not exceed the continuous-power rating of the resistor. To determine average power, first determine the rms power within each power pulse. For a rectangular pulse, this figure is the voltage squared divided by the resistance. For a half-sine-wave pulse, the power is $0.707V^2/R$. For common exponential-capacitor-discharge pulses, a conservative estimate of the rms power over one time constant of the pulse is $0.5V^2/R$. For other pulse shapes, power is normally 0.5 to 1 times the voltage squared divided by the resistance. To choose the proper resistor, be conservative; if anything, overestimate the power. The second step is to find the average power over the period. This figure is the pulse's power, P_{PULSE} , times the ratio of the pulse width to the period: $P_{AVG} = P_{PULSE}(PW/T)$, where P_{AVG} is the average power, PW is the pulse width, and T is the time.

For example, a rectangular pulse applies 100V to a 50Ω resistor for 5 msec. The pulse repeats every 0.75 sec. The average power is $V^2/R(PW/T)$ or $(100)^2/50(0.005/0.75) = 1.33W$. A 2W resistor is probably the smallest resistor that meets this surge condition. However, you need to quickly check two things. First, if the resistor will be operating in an unusually hot environment, then make sure that the average power is less than the power rating of the resistor after derating it to the temperature of your environment. For example, if the resistor has a power rating of 2W at 70°C and ambient temperature is 100°C, then go to the derating curve and make sure that its rating is still higher than 1.33W. Second, refer to the data sheet for information on repetitive pulses, or contact the application engineer to make sure the resistor can withstand the high power applied for a given pulse width. In this example, the resistor must handle $(100)^2/50$, or 200W for 5 msec.

A nonrepetitive surge is the application of a single high-power pulse to a resistor. The resistor then has sufficient time to cool to the ambient or initial temperature that preceded the pulse. The statement “power rules for resistors” becomes a little shaky under these conditions, when the energy rather than the power

you deliver to the resistor during the surge becomes paramount. With a short pulse, the temperature of the resistor material may reach hundreds of degrees Celsius by the end of the pulse. The substrate or case of the resistor remains cool because insufficient time remains for the resistor material to transfer heat during the short pulse. Hence, the resistor material cools down within a few seconds or less as heat flows to the cooler and larger parts of the resistor and, ultimately, to the pc board and the air.

If you apply too much energy, the resulting high temperature destroys the resistor material. Whether the resistor is metal-film, wire, glass or glass-ceramic, its material melts. Resistor manufacturers must accumulate much data to determine the amount of energy that you can apply during a nonrepetitive surge for a given pulse width. They may tell you how many millijoules or joules of energy that you can apply to a resistor. In this case, convert

DETERMINE THE VOLTAGE AND CURRENT FOR THE RESISTOR YOU EMPLOY AND THEN MAKE SURE THAT BOTH FALL WITHIN THE SPECIFIED MAXIMUMS.

your pulse to energy by multiplying the rms power of the pulse time by the pulse width in seconds and look for a part that has an energy rating that exceeds your calculated value. You should call an application engineer if the duration of your pulse does not match the time or range of times that correspond to the published energy rating.

Another way of presenting data for a nonrepetitive surge is a plot of maximum pulse power versus the pulse width. A plot of maximum power versus pulse shows that the power level is higher for a nonrepetitive surge than for a repetitive. However, make sure that you read all the fine print! For example, expect also to see a maximum permissible voltage and perhaps even a maximum permissible current. So, in addition to calculating the power you apply to the resistor, you must determine the voltage and current for the resis-

tor you employ and then make sure that both fall within the specified maximums.

If a surge condition falls between repetitive and nonrepetitive, you may have to ask an application engineer about how the manufacturer defines nonrepetitive surges for your selected resistor. For example, three equally spaced pulses that occur over a three-minute period upon initialization of a circuit may not recur until you turn the circuit off and back on again. You may have to check with an application engineer to see how the manufacturer defines a nonrepetitive surge for the resistor product you are considering. As a rule of thumb, treat any surge condition that is between repetitive and nonrepetitive as a repetitive surge.

WHAT CAUSES FAILURE?

Assume that a resistor has no defects, perfectly terminates, and attaches to the pc board with an ideal solder joint. You can bet that such a resistor can fail, and many conditions can cause it to do so. "Power rules" for resistors because the power you apply relates to operating temperature, which relates to oxidation. Resistor materials show little oxidation effects at temperatures lower than a threshold temperature. At temperatures higher than this temperature, oxidation effects typically translate into a positive change in resistance over time. The resistor manufacturer tests its resistors at a number of temperatures with power applications that vary from full load to no load. These test results translate into a maximum percentage of change in resistance when you operate the part at rated power at a given temperature. For example, a resistor may have a rating of 1W at 70°C.

The data sheet also provides a maximum-storage-temperature figure with no applied power. For a 1W part, 150°C is a common temperature where the power applied must be derated to zero. The degradation of the encapsulation material or the solder temperature of the terminal or leads may also influence the zero-power storage temperature of 150°C. Film and wirewound resistors at 0.5W and operating at 70°C may have internal resistance temperatures of 150 to 200 and 200 to 300°C, respectively.

Oxidation leading to a change in resistance can result when you exceed these temperatures by applying more than 1W.

Because oxidation is a temperature-time phenomenon, putting 1.5W on the 1W resistor may result in little change in 24 hours, but the part will then fail when time at the elevated temperature reaches hundreds of hours. A failure occurs when a part exceeds the maximum specified percentage of change in resistance. For example, 1W might be a failure when the percentage of change in resistance exceeds 0.5% when you operate the resistor at 70°C for 2000 hours. On the product sheet, look for the maximum load-life change.

A circuit fault may sometimes cause a resistor to run for an extended time at greater than rated wattage. Underestimating the ambient temperature is a more common problem than overestimating it. A 1W resistor may operate at a maximum of 0.9W, but, if it sees a 110°C ambient temperature, a failure may occur. You may also have to derate a resistor that sits next to another power resistor or a power transistor to prevent a failure.

Excess energy can result in a resistor failure. When this energy level produces a high enough temperature to destroy the resistor material, a catastrophic change in resistance may occur. Instead of a resistance that increases slowly with time for a moderate power overload, the resistance may increase many times or go to an open- or high-resistance state. When evaluating a resistor in a surge application, contact the application engineer and find out what percentage of change signifies a danger signal. Most resistors do not significantly change until the temperature spike from the surge approaches a problem area. You cannot measure that temperature for a 1- μ sec surge, but you can measure the change in resistance before and after the surge. For some resistors, even a few tenths of a percentage point of change may be a tip-off that the surge may be excessive.

Sometimes, you base your resistor selection on the surge that a computer-assisted analysis predicts. You prototype the circuit in the lab, and all is well. However, testing the initial production circuit shows failures of the resistor. Often, you can trace the cause to an unexpected surge condition, which may occur when you turn on a circuit or when someone rapidly turns it on and off. A resistor in a motor-control circuit may have a high turn-on surge

due to a rare mechanical load condition. You may need a storage oscilloscope to document the maximum possible surge voltage that appears across the resistor.

Voltage stress can also make a resistor fail. Normally, this stress comes into play only on resistors with resistance of more than 100 k Ω and voltage of more than 500V. Lower resistance values can also undergo high-voltage stress conditions during surge conditions. Manufacturers use lasers to trim film resistors to remove a 0.001- to 0.005-in. path. A voltage difference arises across this narrow path. Even if the difference is only 50V, the corresponding voltage stress is 50V divided by 0.005 in., or 0.001 in., which translates to 10,000 to 50,000V/in. stress. These levels would be a problem in the air. However, if the encapsulating material is a good dielectric, the part will not fail.

For a cylindrical-film resistor, the trim cut is a helix cut over perhaps 75% of the resistor's length. Two additional voltage stresses are present. First is the turn-to-turn

UNDERESTIMATING THE AMBIENT TEMPERATURE IS A MORE COMMON PROBLEM THAN OVERESTIMATING IT.

stress, or the voltage you apply divided by the number of resistor turns, divided by the distance between turns. Second is the overall stress. Here we must find the length of the resistor path; "uncoiling" the helix, this figure translates to resistor turns times diameter times π . The voltage stress is the applied voltage divided by the length of the resistor path. For a wirewound resistor, the volts-per-inch stress between wire turns can be excessive. Both film and wirewound resistors targeting high-voltage applications have enough turns to keep the voltage stress at a safe level.

You will realize that voltage stress has become a problem if a modest voltage-stress overload results in a negative change in resistance that exceeds the value for the maximum-STOL-percent change. Also, for a thick-film or composite resistor consisting of metal particles in a glass or ceramic matrix, particles sep-

arated by a thin layer of angstroms-thick dielectric may become microwelded together due to a voltage stress that exceeds the breakdown voltage of the dielectric. For a metal-film or wirewound resistor, a small arc may transport metal across a laser cut or between wires, again lowering the resistance. A negative change in resistance can also occur on any resistor type that has an organic encapsulation as the heat an arc generates can carbonize the encapsulation, providing a shunt path for current flow. High-voltage stresses that produce a high-energy arc can vaporize enough material to cause the resistive value to become significantly positive. A visual examination of the affected resistor often shows evidence of an arc. If you feel that your design is failing due to voltage stress, call the application engineer. Modifying the product or using a product designed for high-voltage stress should solve the problem.

Although rare, current density, the current flowing through a resistor divided by the cross-sectional area of the resistance material, can cause a resistor to fail. There is a limit to how much current can flow through a given area without causing damage. To visualize this scenario, imagine substituting a 22-gauge wire for a 12-gauge wire in a circuit carrying 20A. Like the finer gauge wire, a resistor fails due to a positive change in resistance if the current density is too high. Generally, the failure mechanism occurs only in resistors of 1 Ω or less. Again, if you expect current density on a failure mechanism, you can change to a resistor with greater cross-sectional area or use a material with a higher current-density rating.

CHANGE IN RESISTANCE?

Assume that a critical part of your circuit requires a 1-k Ω resistor. Computer-aided analysis indicates that, if the resistor remains within 4%—960 to 1040 Ω —over the life of the product, then you will meet the equipment specifications. You choose a resistor with a tolerance of 1% and a TCR (temperature coefficient of resistance) of 100 ppm/ $^{\circ}$ C; that is, a 0.01%/ $^{\circ}$ C change in resistance for each degree the temperature deviates from 25 $^{\circ}$ C, or room temperature.

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This figure means that the resistors will all have 990 to 1010 Ω of resistance at room temperature. Next, you solder the resistor onto the pc board, so you must allow for the additional resistance of the solder connection. The solder product sheet might specify a maximum of 0.1%. Now, you have used 1.1% of the 4%.

Now, check the circuit at the lower and upper limits of temperature operating range for the product: -50 to +75 $^{\circ}$ C, for example. At this point, the TCR comes into play. A TCR of 100 ppm/ $^{\circ}$ C is equivalent to 0.01%/ $^{\circ}$ C, so a 50 $^{\circ}$ C change in temperature means that the part can change in resistance by 0.5%. You have now used 1.6% of the 4%. Next, you begin long-term testing or field trials of the equipment.

Over an extended period of time, what other changes in resistance come into play? The major sources for change are load life, moisture, high-temperature storage, STOL, thermal shock or cycling, and mechanical shock and vibration. From knowledge of how and where your circuit will find use, you can select the sources of change that best fit your situation. For example, assume that the resistor will operate at approximately 80% of rated wattage and that some of the equipment will work

THE MAJOR SOURCES FOR CHANGE ARE LOAD LIFE, MOISTURE, HIGH-TEMPERATURE STORAGE, STOL, THERMAL SHOCK OR CYCLING, AND MECHANICAL SHOCK AND VIBRATION.

on oil rigs in the Gulf of Mexico. For this application, you might select STOL because power surges are common in almost all applications. You might also select load life and moisture as two criteria. If the application were automotive, you might consider thermal shock and vibration instead. If the maximum change for STOL, load life, and moisture were 0.2, 0.5, and 0.5%, respectively, then you add 1.2% to our previous total of 1.6% to obtain a

possible change in resistance of 2.8%.

Engineers often overlook one additional change: resistive change due to self-heating. This change usually comes into play when a resistor dissipates more than 50% of the rated wattage. For a resistor operating at 80% of the rated wattage, look at the data sheet. You'll find that the part has a temperature rise of 100°C at 80% of its rated wattage. The resistive material with a maximum TCR of 100 ppm/°C or 0.01%/°C will go from a 25°C room temperature at no load to 100°C+75°C, or 175°C, when you operate it at the maximum ambient temperature of 75°C at 80% of rated wattage. This operation could produce a maximum change of (175°C-25°C)(0.01%/°C), or 1.5%. You have allowed for the 25 to 75°C ambient change, causing a 0.5% shift, so you must include an additional 1.0% due to internal resistor-temperature change.

This calculation brings your total possible change to 3.8%, or a bit less than the maximum permissible change of 4%. If you had started with a 2%-tolerance resistor, which might have seemed an illogical choice at the beginning of the design, you would have faced some trouble. When change due to TCR is a large portion of overall change, then you might want to consider a resistor with a lower TCR. For example, in the above example, you could have used an initial tolerance of 2% if the TCR had been 50 ppm/°C, or 0.005%/°C.

An expert in statistics would have found a flaw in your arriving at a total of 3.8% change. If you have a number of events that can result in both plus and minus change, and there is an equal opportunity for each event to affect the outcome, and the standard deviations associated with each event are equal, you should calculate the total change as: $\sqrt{a^2+b^2+c^2+\dots+n^2}$, where a, b, c, and n are the individual percentage-point changes from tolerance, solder effects, TCR, STOL, load life, moisture, and self-heating. Applying this formula to your example yields a total percentage change of 1.67%. A problem can arise from these assumptions, however.

For example, for a given resistor type, our major causes of change may typically cause all positive changes. Also, depending on the environment, one or

YOU MUST ACCOUNT FOR MORE THAN JUST INITIAL TOLERANCE AND TCR IN ALLOWING FOR RESISTANCE CHANGE IN A CRITICAL CIRCUIT APPLICATION.

more of the changes may dominate and be more likely to affect the outcome. The standard deviations are not equal, and the data for standard deviation is sometimes unavailable. In actual practice, the maximum or worst-case total change would probably fall at 1.67 to 3.8%. Another source of error may result from using the data sheet to define maximum changes. For mature resistor-product lines, the application engineer may be able to provide more realistic maximum-change data. For example, whereas the product's data sheet may give 0.5% for load life, an accumulation of load-life data may yield

an average change of 0.18% with a standard deviation of 0.05%. Using, for example, ± 4 standard deviation would give 99.99% certainty that the maximum change would be 0.18%+4(0.05%), or 0.38%. Most resistor applications do not merit this much attention. The major point is that you must account for more than just initial tolerance and TCR in allowing for resistance change in a critical circuit application. **EDN**

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Gene Howell is an electrical engineer at TT Electronics, IRC Boone Division (Boone, NC), where he has worked in the resistor-component business since 1965. He has also taught at Appalachian State University (Boone, NC). He is currently responsible for thick-film-development projects at IRC. Howell holds a bachelor's degree in electrical engineering from North Carolina State University—Raleigh and a master's in education from Appalachian State University. He is a registered professional engineer in North Carolina and a member of the IEEE.

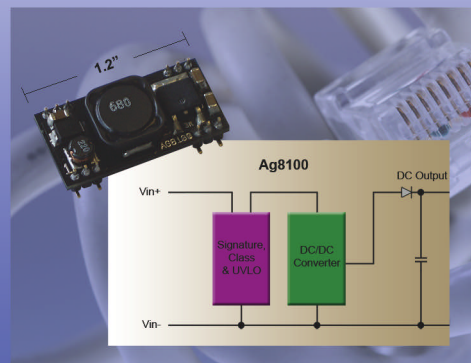
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