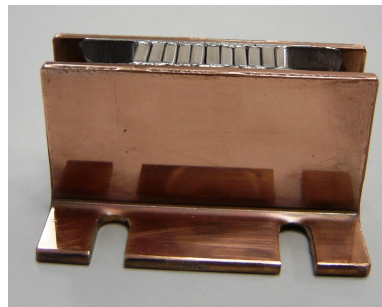


Application Notes: Power Capacitors

Ultra-Low ESR, High RF Power

In the RF world, one trend that continues to gain momentum is the need for higher RF output power in amplifier modules and systems. Associated to a growing demand for reduced unit size, the task for the designers and the component manufacturers is challenging.

First of all, the systems have to deal with higher RF power. At the component level, this means that a particular function which required only a single component previously has now to evolve to a sub-system made of several components to handle the total amount of power.



Moreover, the reduction of the unit size led to higher operating temperatures, adding severe requirements on the components. They have to survive higher temperatures, being able to dissipate the generated heat – small packages produce much higher thermal densities – maintain their performances among huge operating temperature variations and offer mechanical flexibility to accept significant PCB thermal expansion.

Now, when coming to the capacitor world, these new needs will affect the “single-chip” standard model. For instance, when one capacitor was enough to ensure the matching of a 100W RF transistor, the recent 1'000W transistors need “n” capacitors, even sometimes with an increased size.

In order to get a better understanding of these new requirements and to study the “n-chip” model, we will first look at the key parameters of high RF power systems. Then, depending on the key parameter(s) considered, we will see which Power Capacitor Solution is best-tailored to the designer needs.

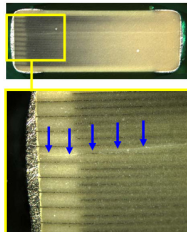
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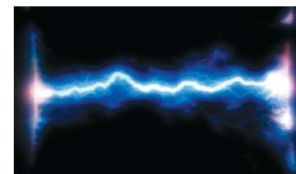
I. HIGH RF POWER

I.1. Voltage Rating

Maximum voltage ratings for ceramic capacitors (WVDC) are linked to two factors: strength of the dielectric and Paschen's law. The strength of the dielectric provides a maximum voltage above which the capacitor breaks and the Paschen's law provides another maximum voltage above which the air around the chip arcs.



Strength of Dielectric



Paschen's Law

The voltage rating of the ceramic capacitor is then defined as the lowest value when considering both limitations.

I.1.1. Dielectric Strength

The capacitor maximum voltage rating is determined predominantly by the dielectric strength or voltage breakdown characteristics. For instance, porcelain dielectrics exhibit a breakdown voltage that typically exceeds 1'000kV/inch of dielectric thickness.

Material	Dielectric Strength (kV/inch)
Vacuum	20
Air	20 to 75
Porcelain	40 to 200
Glass	2'000 to 3'000
Mica	5'000

For multilayer capacitors for instance, this means that one particular layer of standard dielectric—let's consider a theoretical 5 mils thick layer—will not crack until the voltage exceeds a value around 5'000V. In order to achieve even higher voltage ratings, specific internal electrode designs are used to split the voltage.

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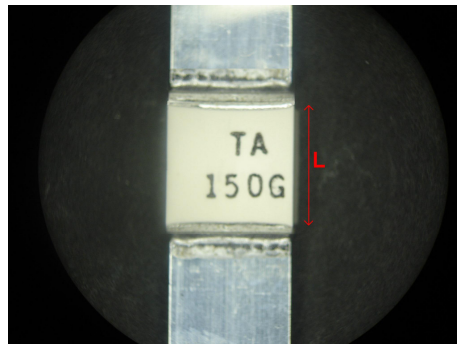
1.1.2. Paschen's Law

In 1889, F. Paschen published a paper (Wied. Ann., 37, 69) which set out what has become known as Paschen's Law. The law essentially states that the breakdown characteristics of a gap are a function (generally not linear) of the product of the gas pressure and the gap length, usually written as $V = f(pd)$, where p is the pressure (in Torr) and d is the gap distance (in cm):

$$V = \frac{365 \times p \times d}{1.18 + \ln(p \times d)}$$

Nota: 1 bar = 100'000 Pa = 750 Torr = 14.5 psi.

For instance, if we consider an E-type capacitor (CLE series with an EIA chip size of 4040), the length between the two terminations ("L" as shown below) is around 10.50mm.



This means, using the Paschen's law ($p=750$ Torr; $d=1.05$ cm), that if the voltage across such equivalent air gap exceeds 36'600V, an electric arc would be created. However, when dealing with the gap between the two capacitor terminations, another parameter has to be considered. Actually, as the dielectric material is charged, there is an ionization of air which influences the Paschen's law. Therefore, for the capacitor considered in this example, a voltage around 5'000V will probably create a short circuit on the capacitor external surface (carbon residues from the arcing). Moreover, the electric arc itself could damage nearby components.

For applications where very high voltages are needed, a specific coating would be applied on the capacitor, thus covering both terminations. In this case, the gap itself disappears and no electric arc could occur.

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I.2. Current Rating

The current rating assigned to a capacitor is stated in one of two ways: voltage limited or power dissipation limited. The rating that applies depends on the capacitance value and operating frequency. The voltage limited area is based on the voltage rating. The power dissipation limited area is based on the ability of the capacitor to dissipate the heat. The current rating of the ceramic capacitor is then the lowest value.

I.2.1. Voltage Limit

The maximum current for the voltage limited operating condition is directly proportional to the capacitor voltage rating and the impedance:

$$I_V = 2\pi \times WVDC \times f \times C$$

I.2.2. Power Dissipation Limit

The maximum current for the power dissipation limited operating condition is directly proportional to the maximum power dissipation of the device and the Equivalent Series Resistance:

$$I_P = \sqrt{\frac{Pd_{\max}}{ESR}}$$

Pd_{\max} is the maximum power dissipation of the device as defined in reference to a given mounting surface with known characteristics. The thermal resistance (θ_c) of a ceramic capacitor operating in a given application is a key factor to establish the device power rating:

$$Pd_{\max} = \frac{T_{\max} - T_{amb}}{\theta_c} = 4.186 \times \lambda \times (T_{\max} - T_{amb}) \times \frac{A}{L}$$

where

λ is the coefficient of thermal conductivity for the subject dielectric material

A is the cross-section area perpendicular to the heat path (cm^2)

L is the length of the thermal path (cm)

T_{\max} is the maximum rated operating temperature of capacitor ($^{\circ}\text{C}$)

T_{amb} is the application ambient temperature in operating conditions ($^{\circ}\text{C}$)

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I.3. Heat Transfer

I.3.1. Thermal Convection

Convection is heat transfer by mass motion of a fluid such as air or water when the heated fluid is caused to move away from the source of heat, carrying energy with it. Convection above a hot surface occurs because hot air expands, becomes less dense, and rises.

If volume increases, then density decreases, making it buoyant.

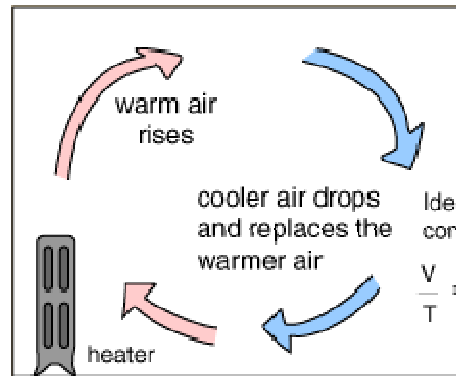
$$\rho = \frac{m}{V}$$

↓ ρ = m / V ↑

$$\frac{V}{T} = \text{constant}$$

↑ V ↑ T

If the temperature of a given mass of air increases, the volume must increase by the same factor.



Ideal gas law for constant pressure

$$\frac{V}{T} = \frac{nR}{P} = \text{constant}$$

I.3.2. Thermal Radiation

Radiation is heat transfer by the emission of electromagnetic waves which carry energy away from the emitting object. For ordinary temperatures, the radiation is in the infrared region of the electromagnetic spectrum. The relationship governing radiation from hot objects is called the Stefan-Boltzmann law:

$$P = e \times \sigma \times A \times (T^4 - T_C^4)$$

where:

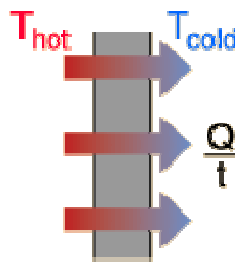
- P is the net radiated power
- e is the emissivity (1 for ideal radiator)
- σ is the Stefan's constant (5.6703.10⁻⁸ W/m².K⁴)
- A is the radiating area
- T is the temperature of radiator
- T_C is the temperature of surroundings

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1.3.3. Thermal Conduction

Conduction is heat transfer by means of molecular agitation within a material without any motion of the material as a whole. If one end of a metal rod is at a higher temperature, then energy will be transferred down the rod toward the colder end because the higher speed particles will collide with the slower ones with a net transfer of energy to the slower ones.



For heat transfer between two plane surfaces, such as heat loss through the wall of a house, the rate of conduction heat transfer is:

$$\frac{Q}{t} = \frac{\kappa \times A \times (T_{hot} - T_{cold})}{d}$$

where:

- Q is the heat transferred with the time t
- κ is the thermal conductivity of the barrier
- A is the conducting area
- T is the temperature
- d is the thickness of the barrier

Conceptually, the thermal conductivity can be thought of as the container for the medium-dependent properties which relates the rate of heat loss per unit area to the rate of change of temperature.

$$\frac{dQ}{dtA} = -\kappa \nabla T$$

The net heat transfer is in the direction of the negative of the temperature gradient.

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I.4. Global Power Model

All the above parameters have to be kept in mind when designing a high RF power function. The capacitors used in the application should be fine-tuned to make sure their voltage rating, their current rating and their heat transfer capabilities are in line with the required specifications. Moreover, the specifications do not only include the capacitor by itself, but also the PCB properties and the environment where the complete system operates.

Let's consider for instance the Global Power Model of a single capacitor mounted on a PCB studied at a working frequency of 50MHz.



The component characteristics are as-follows:

- type: Temex Ceramics CLE series;
- voltage rating: 7000V;
- capacitance value: 22pF.

First, the size of the component will give the capacitor thermal resistance—its ability to dissipate heat. Then, in the PCB specification, we will look for its thermal resistance properties. The environment—how the system is working in normal/maximum operation—will tell us the theoretical ambient temperature. Finally, the capacitor electrical parameters will be used—capacitance value, voltage rating and ESR.

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All these data are compelled in a simulation program which calculates the maximum current rating of the capacitor for the considered system, at one particular frequency:

Designation of the part: **702 CLE 220 GSL TK055**

Select the capacitor type:

Capacitor Length:	10.50 mm
Capacitor Width:	10.50 mm
Capacitor Height:	9.50 mm

5.5

Capacitor thermal resistance:	1.26 °C/W
PCB thermal resistance:	17 °C/W
Capacitor max operating temperature:	125 °C
Ambient temperature:	25 °C

Capacitance value:	22 pF
Rated DC voltage:	7 000 V

Frequency:	50 MHz
ESR @ Frequency	0.042 Ohm

I_v: 48.381 A

I_p: 11.420 A

The limitation is given by the:	Power
The maximum current is:	11.420 A

As previously written, the current rating assigned to a capacitor is stated in one of two ways: voltage limited or power dissipation limited. The software calculates both limitation: I_v for the voltage and I_p for the power. Finally, the smallest value is taken as it represents the first limitation the user will reach when using the system.

In the example above, the capacitor, according to its voltage limitation, should handle around 48A but the power dissipation will actually not allow it to handle more than 11A. If the capacitance function has to handle more current, then the designer has to switch to the “n-chip” model and to use a combination of several capacitors, .a.k.a as Power Capacitor Solutions.

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II. POWER CAPACITOR SOLUTIONS

More RF power means either a higher current or a higher voltage, sometimes both. As the current and voltage laws are quite fixed for capacitors—physical limitations give few options on dielectric thickness and number of electrodes which are key to handle more power in a single component—the only way to handle more power, for a given ultra-low ESR series, is to increase the number of capacitors.

This led to a new branch of capacitor knowledge dedicated to thermal and power analysis, mechanical assembly, high temperature PCB soldering and specific RF test procedures.

The Power Capacitor Solutions are especially dedicated to applications where high reliability, high operating voltages, high operating currents, ultra-low ESR and tighter tolerances are required. Most of these applications are found in the following markets:

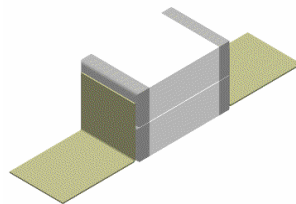
- Medical Electronics;
- Broadcasting Equipment;
- Semiconductor Manufacturing;
- Inductive Heating;
- LASER Power Supplies;
- MRI High Magnetic Environments;
- Military Systems.

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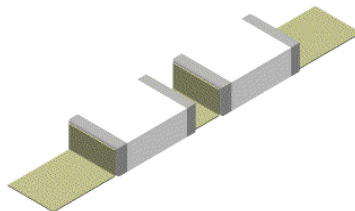
II.1. Parallel Combinations

To deal with a higher operating current or to further reduce our ultra-low ESR, one can use combinations of HiQ ceramic capacitors in parallel—current rating doubled.



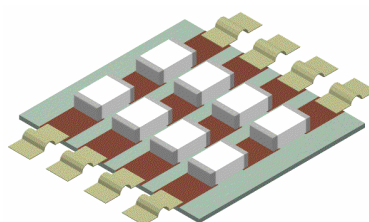
II.2. Series Combinations

To deal with a higher operating voltage, one can use combinations of HiQ ceramic capacitors in series, within the same dielectric die or using separate entities—voltage rating doubled.



II.3. Matched Sets

To achieve non-standard total capacitance values or ultra-tight tolerances, Temex Ceramics can match capacitors using computer specific software. Another use of matched sets is to reduce the overall purchasing costs; when several capacitors are used in parallel, a given tight tolerance can still be obtained on the final assembly while using wider tolerance single chips.



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III. GUIDELINES

Several factors have to be considered while designing high RF power applications and these factors are in fact all linked to the overall thermal management of the entire design. The main guidelines to lower the overall thermal load on the design are listed below:

- capacitors with ultra-low ESR provide a higher maximum current for power dissipation limited operating conditions – as $I_p = f\left(\frac{1}{ESR}\right)$ – allowing the overall design to handle more RF power. Of course, the dissipation factor characteristics also have to be compliant with this increased power;

- the thermal conductivity of all devices involved as well as board trace dimensions and material thickness have to be evaluated;

- the main part of the heat transfer is completed by thermal conduction. Actually, around 80% of the power is dissipated by conduction, 15% by convection and 5% by radiation. Therefore, the greater part of heat transfer is through the terminations of the capacitors. In order to further improve the thermal path of a porcelain capacitor, one should use leads such as non-magnetic micro-strip silver ribbons. The leads also offer another advantage: when the thermal expansion coefficients of the capacitor and the board are mismatched, they may act as a mechanical strain relief;

- to avoid reducing drastically the thermal conductivity at some specific locations within the circuit, one should avoid reducing the width of the board trace and using wires;

- heat sinks and blown cool air will also help to reduce the additional sources of heat generated by passive components, FETs and active gain blocks;

- Paschen's law defines the voltage rating for a given pressure. Therefore, depending on the operating conditions, the pressure parameter has to be considered (coating, voltage safety margin...);

- using Power Capacitor Solutions with parallel combinations will extend the RF power handling over a single chip. For instance, N capacitors in parallel will lead approximately to an ESR which is N-times lower than one capacitor, thus greatly increasing the maximum current handling capability by a factor of \sqrt{N} .



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IV. CONCLUSION

This article has described the major factors to consider while designing a Power Capacitor Solution for high RF power applications. The benefits of using Power Capacitor Solutions are numerous: high RF power, enhanced reliability with pre-tests, ultra-low ESR, reduced costs with matched sets, availability of specific capacitance values and tolerances, fewer assembly stages, customized styles...

To ensure the highest level of reliability in high RF power designs, factors such as heat transfer, maximum voltage and current ratings, thermal characteristics of the circuit devices and ways to remove the heat should be taken into account.

Temex Ceramics designs Application-Specific Solutions based on parallel and series combinations of designer-acclaimed capacitors. Customer requirements are addressed by computer matching sets, a wide range of mechanical configurations, a protective coating and adapted ribbons or wires which have enabled Temex Ceramics to extend overall performance while decreasing the total cost of ownership.

Temex Ceramics - by knowing the ESR and power dissipation of its capacitors at the application operating frequencies - helps the designers by simulating the thermal behavior of the assembly and proposing the optimum Power Capacitor Solution.