

High-Current, High-Frequency Filtering With Feedthrough Caps

Critical factors unique to high current feedthrough filter applications: through current and shunt current dissipation, as well as the associated temperature rise.

High performance high current filtering can be defined as insertion loss above 30 dB, frequency to 1 GHz, and through currents exceeding 30 amperes. Selecting a filter requires analysis of the noise frequency profile, and then selecting the appropriate capacitance, current and voltage ratings to reduce this noise to acceptable levels. In some cases, discrete components might be efficient in filtering noise below 10 MHz, while a feedthrough capacitor must be used for higher frequencies.

The filtering effectiveness of a typical feedthrough technology is compared to a discrete or leaded capacitor in *Fig. 1*. A 0.22 μ F feedthrough filter can easily provide over 40dB of insertion loss above 10 MHz. The leaded capacitor will achieve an insertion loss peak, in this case shown by the blue line, at about 3MHz; but the insertion loss drops dramatically at higher frequencies. A feedthrough capacitor will maintain good performance to over 1 GHz. In most cases, a film feedthrough capacitor (either metalized or foil types), as shown by the purple line, will show an insertion loss dip or reduction (in this example at about 17 MHz); due to internal resonance. This dip is more pronounced with higher capacitance values. The deficit in filtering for a film type can exceed 30 dB at this dip. An X7R ceramic filter, shown in red, will generally continue to increase performance as frequencies go higher. High current low-pass feedthrough capacitors are used to pass high currents through a shielding enclosure. This can eliminate further propagation of unwanted electrical energy, which is required to meet susceptibility or emission or interference requirements. NexTek high current feedthroughs (*Fig. 2*) are amongst the most compact filters capable of high-frequency performance in this type of application. Feedthrough capacitors do not contain significant series inductance, which could be susceptible to saturation. Therefore, the filtering performance is not affected by the level of through current.

Aside from filtering performance considerations, there are several factors that make these applications different from lower current filtering applications. High current and high power applications cause stress from elevated levels of both through current and shunt RF current. Both the through current and the RF shunt current create power dissipation, which leads to temperature rise of the filter. Excessive temperature rise can cause failure or malfunction.

Fig. 2. Typical Compact High Current Low-pass Feedthrough capacitor

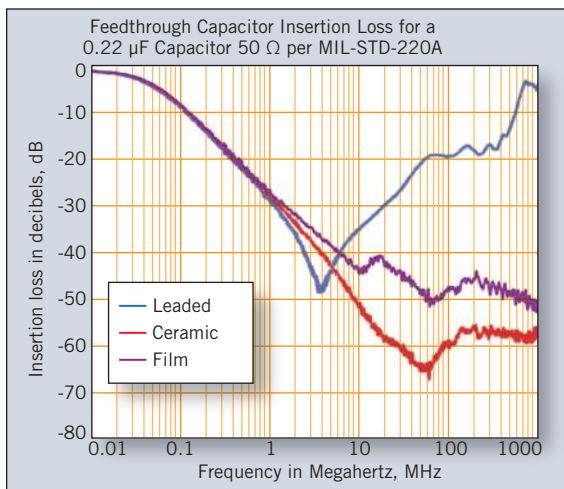
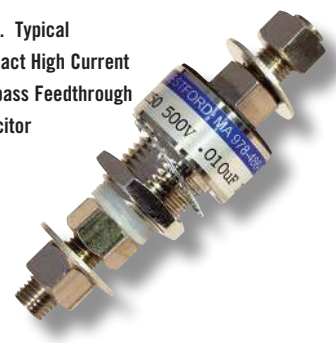


Fig. 1. Comparison of Filtering Capacitors.

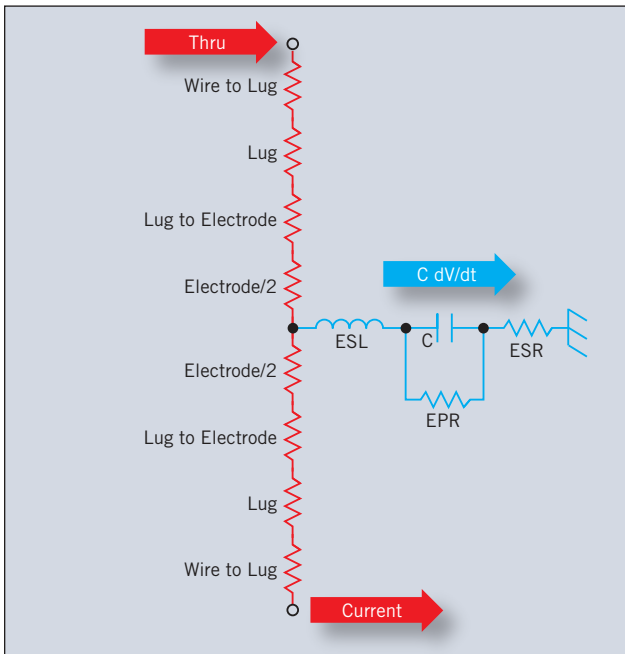


Fig. 3. Simplified Circuit for a Feedthrough Capacitor

EQUIVALENT CIRCUIT

A simplified, but useful, equivalent circuit of a feedthrough filter capacitor is shown in Fig. 3. The main current travels through the various resistances shown along the red vertical path. Note that the resistances of the wire or bus bar attachment elements are included. The through electrode resistance is divided in approximately half, since the capacitor is usually about midway along the length of the center electrode. The through current is a function of the power source and load impedances (or control). The through current can be dc, single frequency ac, or a more complex waveform.

The equivalent circuit of the filtering capacitor element is shown in blue in Fig. 3. The desired capacitance is the value C. There is an equivalent series inductance (ESL), which is the cause of the rapid decline in a leaded capacitors' filtering action as frequency increases. The ESL is nearly eliminated in a feedthrough filter due to the absence of leads and other construction geometry. There is also an equivalent series resistance (ESR), which is usually a func-

TABLE 1. THROUGH RESISTANCE AND WATTS FOR TYPICAL FEEDTHROUGHS		
CURRENT RATING (A)	THROUGH RESISTANCE ($\mu\Omega$)	WATTS DISSIPATED (W)
30	8000	7.2
100	1000	10.0
400	100	16.0



Fig. 4. Measuring Total Voltage Drop

tion of frequency. The ESR is predominately defined by the material properties of the dielectric and conductive surfaces. There is also an equivalent parallel resistance (EPR) which affects leakage current, or insulation resistance, but does not normally have an effect on filtering performance. A shunt or bypass current, from the electrode through the capacitor to ground, is related to the rate of change of the applied voltage. Complex applied voltage or current waveforms during PWM control are possible. In some applications, ac voltage produces leakage current which may have safety-oriented limits. Ripple voltage can exist existing on otherwise dc buses and will produce significant shunt ac current through the capacitor C.

THROUGH CURRENT DISSIPATION

The through current causes series voltage drop and associated power dissipation. As filters approach and exceed 50A, variations in the through resistance play a more and more important role in contributing to power dissipation. The entire through resistance is represented by the vertical resistances in Fig. 3. Typical values for feedthroughs of three different current ratings and three dissipation capabilities are shown in Table 1. The through electrode resistance can be under 10m Ω for the 30A filter, but might have to be below 100 $\mu\Omega$ for a 400A filter in order to control the power dissipation and associated temperature rise.

Table 1 shows that variation of electrode resistance of 100 $\mu\Omega$ (as compared to 8000 $\mu\Omega$) would be acceptable, or even insignificant, for a 30 Ampere rated filter. However, a variation of the same level could be disastrous for a 400A filter, because of the 100% increase in power dissipation. For any high current installation, the goal is to minimize the total voltage drop within and near the feedthrough capacitor. Each application requires attention to the wire, lug and associated interfaces. As current increases to higher levels, these application-dependent voltage drops tend to be larger than the electrode's, and thus are more influential in increasing power dissipation and temperature rise.

Since a feedthrough capacitor introduces very little series inductance, the through current power dissipation (in watts) can usually be accurately estimated as the voltage drop times the current. The through current can be measured by any traditional means, but non-contact

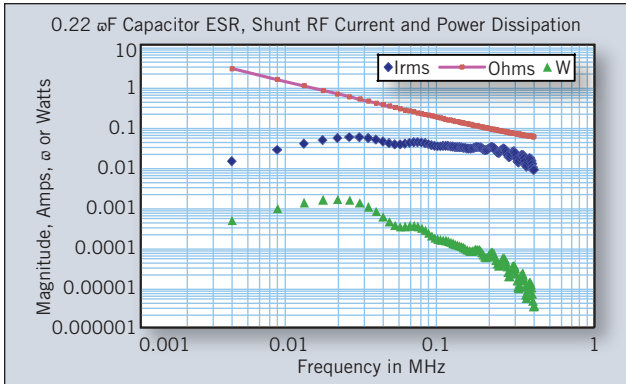


Fig. 5. ESR, Current and Dissipation

current transformers or hall effect probes are usually the most convenient. The preferred measuring points to measure voltage drop are shown in Fig. 4, which would span all of the resistances in Fig. 3. Sometimes, it is necessary to pierce the insulation with a test point to make contact with the wire near the lug.

To estimate dissipation or temperature rise, it is unnecessary to estimate the individual resistances in Fig. 3. However, if you are troubleshooting a design or manufacturing problem; comparing one side of the electrode wire or bus bar to the other may be required. For example, in Fig. 4, the voltage drop from the feedthrough electrode to the aluminum bus bar at the top of the filter could be less than the voltage drop from the opposite feedthrough electrode to the copper wire at the bottom, because of the additional copper lug. Measurement of the voltage drop at high current should be used to control variables such as interface surface preparation/oxidation, tightening torque; lug crimp quality, wire insertion and preparation, and material or plating variations.

The voltage drop measurement can be somewhat sensitive to electrical noise. In cases where the bus voltage is

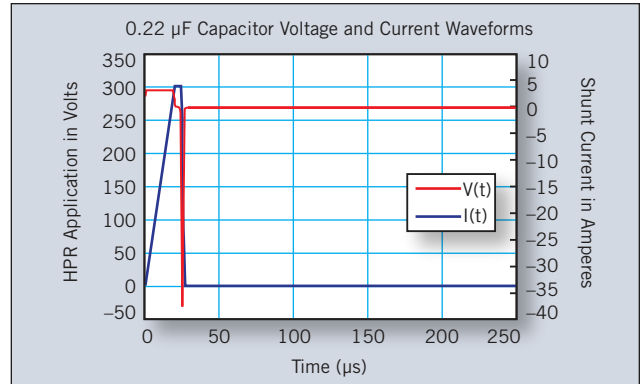


Fig. 6. Applied Voltage and Shunt Current

in an environment with high electrical noise, it may be necessary to measure the RMS through current. Then, apply the equivalent dc or 50/60 Hz through current from another low noise source to measure voltage drop(s) with less error. The same method of applying an equivalent current might be necessary if the voltage on the filter exceeds the measurement or meter capabilities. Always use safe measurement practices, appropriate to the voltage and current present.

RF SHUNT CURRENT DISSIPATION

The shunt current through the capacitor is the current bypassed to ground, and is related to the rate of change of voltage on the center conductor and the capacitance of the filter. For example, if a single frequency AC voltage is applied with a value of 50Vrms at a frequency of 100 kHz, to a 220nF capacitor; the capacitor would represent a reactive impedance of about 7Ω. The RF shunt current would be about 7A. The ESR of a typical ceramic capacitor with a value of 220nF is shown as the magenta data in Fig. 5. In this example, ESR decreases at higher frequencies. After reaching a minimum value, the ESR will typically begin to rise at frequencies above 10 MHz. The ESR of the capacitor at 100kHz is about 0.12 Ohms, so the power dissipation ($i^2 \times \text{ESR}$) would be 5.7W. Most large format RF filters can safely handle several amperes of current, particularly at frequencies where ESR is of a low value.

If the voltage waveform is complex, then the harmonics should be analyzed; with each constituent part evaluated for $i^2 \times \text{ESR}$. These harmonic dissipation powers are summed to confirm that the entire waveform content is within the dissipation level of the capacitor.

The 220nF filter could be exposed to a trapezoidal voltage waveform as shown in Fig. 6. This waveform has a rise time of 20μs to 300V, a dwell time of 5μs, a fall time to 0 volts of 1 μs, and an overall waveform period of 250μs (or 4kHz repetition rate). This voltage waveform is shown in the blue line in Fig. 6.

The shunt current is calculated from:

TIPS ON CONNECTING TO HIGH CURRENT FEEDTHROUGH FILTERS

- At high current and full load, measure the wire to wire total voltage drop to confirm design and manufacturing performance. No-load testing with an ohmmeter or for continuity, even using four wire test methods, will not provide adequate interface stress.
- Measure or model the applied voltage to estimate the shunt current power dissipation. (see RF Shunt Current Dissipation below)
- Estimate or measure the electrode temperature rise, taking applied voltage waveforms and through current into account.
- Have a budget or goal for voltage drop, to assist in qualification or inspection.

$$i=C dv / dt$$

The RF shunt current is shown in the magenta line on Fig. 6. It would be approximately 3.3A during the voltage ramp up time and about -38A during the voltage fall time. While the average current would be about 1.13A, the RMS current would be about 3.0A. There is a high current crest factor of 12.5 in this example, which indicates a significant harmonic content. The time domain shunt current data can be transformed to the frequency domain by use of Fourier techniques and is represented by the blue data points in Fig. 5.

These harmonic currents also cause shunt dissipation because of the ESR. This dissipation (for each harmonic) can be calculated from $W = ESR(\text{freq}) \times I(\text{freq})^2$, and is shown by the green data points in Fig. 6. If these power dissipations are plotted cumulatively, as shown in Fig. 7, one will notice that the largest contributions are at frequencies below 100kHz, and the dissipation approaches an asymptote just below 20mW. Total power dissipation of less than 20mW is considered trivial for large filters.

Models are very useful in understanding the principals and tendencies in filter applications. Variations in ESR values and waveform consistency will require qualification testing to confirm acceptable performance; particularly in cases of predictions close to the limits of a design. Since shunt current is produced by the derivative of the voltage waveform, and the impedance of the capacitance is lower at higher frequencies, shunt current harmonics are usually higher in frequency than the through current waveform.

TEMPERATURE RISE

Given moderately effective air cooling, a filter installation with significant metal section geometry and low and distributed power dissipation would be nearly isothermal. Testing at NexTek confirms that the temperature of the through conductor and adequate attaching hardware all generally remain within a range of one or two degrees C. Therefore, total dissipation and any resulting temperature rise can be represented as a singular value.

Testing at NexTek has also suggested a departure from traditional linear models of temperature rise. Many components can use a linear “ θ ” or “dissipation factor” model to describe the relationship between temperature rise and power dissipation. While linear dissipation temperature rise models may be acceptable for component forced convection cooling, the thermal resistance of a high current feed through is heavily dependent upon convection heat transfer effects. While relationships are nearly linear for forced convection applications, most capacitor applications are more in a free convection cooling environment, which are non-linear. For more information, see the sidebar “High Frequency Current on Large Conductors”.

As a simplified but reasonably accurate model (in free

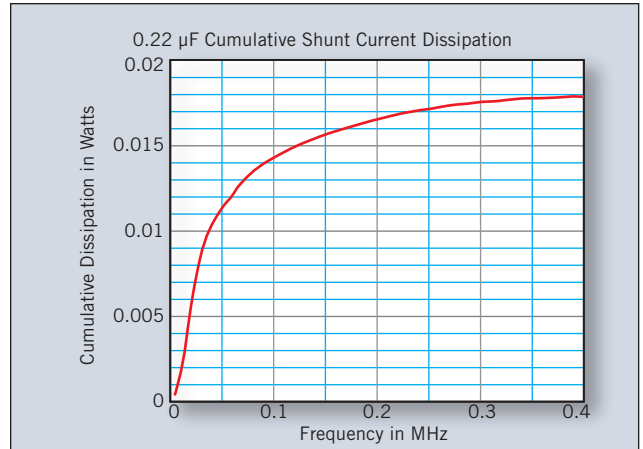


Fig. 7. Cumulative Power Dissipation

convection mode), the power law relationship is widely accepted to be a good approximation. NexTek suggests using this model, which can provide its customers with accurate temperature estimates.

The temperature rise due to power dissipation for a free convection cooled feedthrough filter is given by:

$$\Delta T = C_1 \times W^{C_2} \quad (2)$$

Where:

C_1 = Empirical constant

C_2 = Empirical power constant

Using the NexTek 400 A filter as an example, C_1 is typically in the range of 2.0 to 3.0 and C_2 is the range of 0.80 to 0.85. W is the total power dissipation of the feedthrough filter, including conductor attachments. The value of C_1 is dependent upon the cooling capability of the mounting bulkhead and the size and surface area of the attaching lugs, wire or bus bar.

Measuring and controlling the voltage drop across the filter installation is the most effective way to qualify

HIGH FREQUENCY CURRENT ON LARGE CONDUCTORS

In extreme cases of large conductors with high frequency current, the current is constrained more to the outer surface of the conductor. This can render the material on the interior ineffective in reducing the loss and dissipation due to through current.

The skin depth can be considered as the limit of current penetration into the conductor. Skin depth will cause the through electrode resistance to increase from the dc value, if the conductor thickness is close to or greater than the skin depth. Appropriate through current de-rating would be required for these conductors.

the designs of the feedthrough and attachments. When using a high current feedthrough, ask the manufacturer for the expected total voltage drop at full current, or the param-

eters to predict temperature rise versus total power dissipation. Despite advances in modeling dissipation and temperature rise, it is best to measure actual temperature rise during design

qualification. See the sidebar “Safety Tips” for safety information on high-current feedthroughs.

EFFECTIVE ABOVE 10 MHz

High current feedthrough capacitors can provide the most compact, effective method of filtering noise, particularly above 10 MHz. In addition, filter capacitor performance is insensitive to the effects of through current. High-current applications over 100 amperes require special attention to connection techniques in order to minimize voltage drop and the associated power dissipation. Moreover, the applied voltage waveform can be modeled or measured in order to estimate the shunt current and associated power dissipation. Combined, these two factors can be used to estimate the temperature rise of the feedthrough. For more information, see the sidebar “Tips on Connecting To High Current Feedthrough Filters”.

Measuring total power dissipation is the easiest and most effective way to control a high current feedthrough, including the effects of connections.

Attention to these details is essential to creating a simple filtering and wiring system that is highly reliable, easy to verify, and capable of the highest temperature operation. ⏻

SAFETY TIPS

High current feedthroughs are usually connected to high voltage and high energy circuits.

1. Consult safety codes for wire type, enclosure and other design and test requirements.
2. Use safe practices when working on or measuring these devices.
3. Use devices and equipment rated for the application.
4. Cover exposed electrodes and bare terminals and conductors.