



The use of inexpensive, inferior capacitors in passive filter networks often brings unsatisfactory results, especially when the network design calls for values of capacitance greater than a microfarad. When capacitance of a few microfarads is needed, many designers seek to lower production costs by using the cheaper bi-polar electrolytic or metalized-film capacitors instead of the superior film-and-foil variety. In high-current use, however, the bi-polar electrolytic and metalized-film types cause severe problems arising from their higher equivalent series resistance (ESR).

Significant ESR has a two-fold effect on capacitor performance: First, as we indicated in our earlier white paper, "Considerations for a High Performance Capacitor: The REL MultiCap™" (June 1990), the losses are very high. Look at Figure 1; note that under identical values and test conditions, the current available (the vertical scale shows 5 amperes per division) to a load through the bi-polar electrolytic capacitor is only about one-third the current passed by a REL MultiCap™. In addition, in this particular example, current passage or release takes five times longer in the bi-polar electrolytic capacitor than it does in the MultiCap™. (This MultiCap™ type is optimized for the time-domain response.)

What are the Audible Effects?

In an application such as that shown in Figure 1, the bi-polar electrolytic cap greatly compresses and smears the signal. This leads to the loss of dynamic range and sonic detail. As the current is increased, losses produce heat within the capacitor; this further increases the ESR losses in a non-linear manner. When this occurs, signal compression is increased. At low frequencies, this compression may even cause modulation of the ESR, which in turn gives rise to phase and magnitude instability.

Looking Beyond the Magnitude of Impedance to Phase

The second effect of high ESR is that it causes a phase shift away from the expected ideal of 90 degrees between voltage and current at all frequencies.

Some designers assume that if the resonant frequency is high compared to the frequency of interest, all will be well - the capacitor can be used up to the natural self-resonant frequency or, when the capacitor maker does not give that information, as high a frequency as possible as long as the impedance curve remains fairly linear in appearance. This is not a valid assumption for many capacitor applications, however. It can be true for power-supply by-passing, but for many circuit applications, the useful frequency range of the capacitor is limited by its phase response rather than its impedance. The phase response is degraded well below the capacitor's natural or self-resonant frequency when series losses are added. These losses may arise from the construction of the capacitor itself, or they may arise externally, usually from wire or cable losses and the driving source impedance.

## Phase Response

In Figures 2 and 3, we show that filter circuits (e.g., loudspeaker crossovers, RIM equalization, D/A filters, etc.) cannot be thoroughly designed without integrating the actual, measured in-circuit performance of the capacitors (and inductors as well) into the over-all system design.

Figure 2 shows the phase/magnitude of a 4.4 mfd/100v bi-polar electrolytic capacitor. The capacitor itself has a resonance at 450 kHz with 1-inch lead length, which looks as if it is well out of the audible range. But because of the capacitor's high ESR, phase was down 5 degrees to -85 at only 4.0 kHz and -10 degrees at 14 kHz. When this capacitor was measured in-circuit (with 12 inches of circuit wire), the phase had degraded from -89 degrees at 100 Hz to -85 at approximately 800 Hz, and -55 degrees at 10 kHz! If this designer had doubled the lead length from the capacitor to the load, phase would have begun to sour at a very low frequency, even though the resonance would still be at a relatively high frequency! For the most effective designs, it is necessary to keep losses both in the capacitor and outside it to a minimum. Filter networks, for example, could, with good effect, be located as close as possible to the load they supply a signal to. They might be distributed rather than lumped together in one location. These practices will keep the lead lengths as short as possible and any series wiring/cable resistance to a minimum. This might suggest that distributed driving sources are also needed. In this way, the resonance will be as high as possible, and the phase response will be maintained to the highest possible frequency.

## MIT's film-and-foil type MultiCap

way out to its natural resonance. With this capacitor, designers will find fewer differences between their theory and the actual practice than with inferior capacitors. Less fudging and tweaking of the network component values will be needed to make the design "look right" - such adjustments at best give only a compromised performance.

## Audible Effects

When capacitors do not maintain a 90-degree current phase relationship to voltage at the frequency of interest (and for a couple of octaves beyond), proper music-signal summation becomes difficult to achieve. Image blurring and ambience retrieval suffer. And the relationships of harmonics to fundamental will be altered.

For those who strive to produce the best possible performance, only the most linear and ideal capacitors can be acceptable.