Capacitor amplifier reduces ripple without dc loss

Filter capacitors reduce ripple in power-supply circuits or provide pulse energy at a constant dc voltage. In both applications, there is fundamental conflict. The circuit needs constant voltage, but capacitor energy-storage and -delivery capability is a function of capacitance and of voltage-change squared. To achieve a low-ripple output, therefore, the circuit needs a large, costly capacitance.

Early attempts to use active circuits to reduce capacitor size were effective but had a hitch: The circuits were not dc-efficient. Designers could not use such circuits in applications in which efficiency was critical or in high-power applications.

The active circuit in shows a simple example of using an active circuit to reduce capacitor size. The filter capacitor connects to the base of an emitter follower. The capacitor's effectiveness in reducing ripple at the output increases by a factor equal to the transistor's beta value. A transistor-induced loss of dc output voltage and power accompanies the improved ripple reduction, however. Low-dropout linear regulators produce similar ripple reductions but also demonstrate a dc loss.

The active circuit in attacks the problem by reducing ripple without dc loss. The circuit acts as a small two-terminal device that is a direct replacement for a large, high-value, two-terminal capacitor (Reference 1). Associates have affectionately dubbed the circuit the "Kanner Kap."

The voltage to be filtered powers the circuit. Capacitor $C_2$ couples the line ripple to the amplifier. The amplifier both amplifies the ripple and inverts its phase. Capacitor $C_3$ couples the amplified and inverted ripple back to the dc supply line. The gain of the amplifier ($A$) multiplies capacitor $C_3$'s effectiveness in reducing ripple.

Design avoids dc loss
Study of the circuit reveals two important factors. First, the dc source connects to the load without going through the active circuit element, therefore without incurring dc loss. Second, the negative ripple level across \( C_3 \) is a factor \( A \) times greater than the ac ripple on \( C_1 \). \( C_3 \), therefore, reduces the output ripple as if \( C_3 \) had the value \( A \times C_3 \). This increase in capacitor effectiveness allows designs to use smaller capacitors to achieve lower ripple levels. The circuit produces its expected performance when the amplifier bandwidth is consistent with the power source's maximum ripple frequency or greater than the load's pulse-loading frequencies.

As with any active circuit, the amplifier's supply voltage and current limits put a bound on magnitude of \( A \) and the corresponding increase in \( C_3 \)'s effectiveness. As shows, separating the amplifier supply voltage from the filtered dc source eliminates the rail limitations. This configuration is particularly useful for filtering low-voltage levels, in which the amplifier rails otherwise would severely limit the increase in capacitor effectiveness.

The capacitor amplifier does have losses but not the major dc loss of circuit. The capacitor amplifier's losses are simply the sum of the amplifier's housekeeping power and the negative ripple power. If the original ripple power is 1 or 2%, then the circuit loss is 1 or 2% plus the nominal housekeeping loss.

The circuit in resolved a critical space-station video-system problem. A test for audio susceptibility revealed a severe disturbance in the system's video output. Engineers traced the problem to a power-supply output voltage that used an 80-µF output-filter capacitor. Although the supply's ripple was less than 1%, the video system needed a ripple 20 times smaller, or 0.05%, for satisfactory performance. Normally, achieving this ripple level would require an extremely large, 1600-µF capacitor.

Addition of such a large capacitor would have severely impacted packaging on a design that engineering had already released. Instead, designers applied a circuit with the topology of circuit.
shows the circuit’s schematic detail with the test-setup's schematic. The amplifier (IC₁) is an LM 386, eight-pin DIP op amp. This device is ideal for the application, because the amplifier automatically biases its output signal to the midrails and references the input signals to ground without external resistors.

**Capacitance boost**

A single 10-µF capacitor (C₄) sets the amplifier's open-loop gain to 200. The positive amplifier-input signal (pin 3) references to ground, and a 0.1-µF capacitor (C₃) ac-couples the ripple to the negative-amplifier input line. The circuit serves to amplify the effect of a 22-µF capacitor (C₅) that connects back to the input line through a high-frequency stabilizing network (a 1/8W, 4.7V resistor (R₁) in series with a miniature 1.0-µH choke (L₁)).

A test of the circuit's performance applied a variable-frequency ripple across a 50-µF capacitor (C₂) as the circuit's input signal. The signal generator established a 100-mV ripple level at frequencies ranging from 100 to 100,000 Hz. The ripple-level reduction when the test circuit connected across the 50-µF capacitor provided a measure of the capacitor amplifier's performance. Ideally, the circuit should amplify C₅’s effectiveness by 200, therefore acting as a 4400-µF capacitor.

Table 1 shows the capacitor amplifier's frequency response. The IC's bandwidth limits the circuit's high-frequency performance. Still, the results remain impressive out to 100 kHz, where the 22-µF capacitor acts better than a standard 1500-µF filter capacitor. Although the circuit does not demonstrate the theoretical capacity of 4400 µF, the amplification from 22 to 3400 µF more than exceeds the 1600 µF required to solve the critical space-station problem.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Ripple level at 50-µF cap without amp (µV rms)</th>
<th>Ripple level at 50-µF cap with amp (µV rms)</th>
<th>Effective cap (µF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>100</td>
<td>1.47</td>
<td>3400</td>
</tr>
<tr>
<td>1000</td>
<td>100</td>
<td>1.51</td>
<td>3311</td>
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<tr>
<td>10,000</td>
<td>100</td>
<td>3.22</td>
<td>1553</td>
</tr>
<tr>
<td>100,000</td>
<td>100</td>
<td>2.95</td>
<td>1694</td>
</tr>
</tbody>
</table>

The amplifier's input and output waveforms remain 180° out of phase except at low ripple frequencies. At 100 Hz, the input capacitor (C₃) and the IC’s input impedance act to delay the input signal, but ripple reduction remains excellent. Increasing the value of C₃ would have reduced the circuit's low-frequency cutoff. As designed, however, the circuit's low-frequency ripple reduction exceeds requirements.

The circuit has an important application in high-frequency switching power supplies. As supply designers increase switching frequency, they typically reduce the size of output-filter capacitors. These smaller capacitors cost less but still maintain the supply's self-generated ripple at acceptable levels. Reducing capacitor size also reduces energy-storage capability, however. The supply needs energy storage to handle load perturbations or audio susceptibility. Thus, the power-supply vendor or the user quickly puts large capacitors back into the circuit to provide the missing storage. Such capacitors can compete in size with the power supply itself. The Kanner Kap design provides the energy storage needed and uses a small capacitor.
Recently, large-capacitance ceramic capacitors have become available for high-frequency, switching power supplies. The techniques described permit application of these ceramic capacitors at much higher power levels than is possible in a conventional filter-capacitor configuration.

Author's biography

Martin Kanner is a consultant in the fields of motion control, switching supplies, and feedback and feedforward control systems. He has three degrees, a BS in Aeronautical Engineering, a BSEE, and an MSEE, from New York University (New York). He is a member of Eta Kappa Nu and Tau Beta Pi honorary societies and holds three patents, including Patent No. 4,710,861 for the capacitor amplifier.

Reference