Electronically-variable capacitor with wide range and high value

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Electronically-variable capacitors, whether used for T&M or in an end circuit, usually have a maximum capacitance of a few hundred picofarads, and a limited adjustment range. This Design Idea demonstrates a wide-range, variable, high-valued capacitor.

Figure 1 The circuit in the dashed box illustrates the variable capacitor topology.

Here are the relevant equations:
\[ V_i = -I_c \times R_{sh} \times k_i \]

\[ V_d = -k_d \times \frac{dV_c}{dt} \]

\[ V_o = k \times (V_d - V_i) = k \times \left( -k_d \times \frac{dV_c}{dt} + I_c \times R_{sh} \times k_i \right) = V_c - I_c \times R_{sh} \]

\[-k_d \times k \times \frac{dV_c}{dt} + I_c \times R_{sh} \times k_i \times k = V_c - I_c \times R_{sh} \]

Rearranging we get:

\[ I_c \times R_{sh} \times (k_i \times k + 1) = V_c + k_d \times k \times \frac{dV_c}{dt} \]

Because \( k_i \times k \gg 1 \) we can ignore the 1; thus:

\[ I_c = \frac{k \times k_d}{R_{sh} \times k_i \times k} \times \frac{dV_c}{dt} + \frac{V_c}{R_{sh} \times k_i \times k} \]

Simplifying, and neglecting the last term due to the very high value of the denominator, we get:

\[ I_c = \frac{k_d}{R_{sh} \times k_i} \times \frac{dV_c}{dt} \]

This resembles the displacement current of a capacitor: \( I_c = C \times \frac{dV_c}{dt} \)
I used the **OPA189** due to its very low offset voltage, and the **OPA633** due to its high output current.

With the values shown in the schematic:

\[ k_i = 1 \]

\[ k_d = C1 \times (P1+R7) \]
Changing the value of the potentiometer we get a capacitance of 100 nF to 4.8 µF.

**Figure 3** Simulation results for P1 = 3.2 kΩ.
As a further test, I connected a 2.2 mH coil between $V_c$ and ground. The circuit rings at 1.87 kHz, which agrees well with the expectation.
**Figure 5** Ringing (1.87 kHz) of 2.2 mH and 3.3 µF.

**Influence of op-amp common-mode rejection**

Considering the error sources at the outputs of U1 and U3 due to the mismatches in R3-R6 and R8-R11, we get:
\[ V_i = -I_c \times R_{sh} \times k_i + V_{err1} \]

\[ V_d = -k_d \times \frac{dV_c}{dt} \]

\[ V_o = k \times (V_d - V_i) + V_{err2} = k \times \left( -k_d \times \frac{dV_c}{dt} + I_c \times R_{sh} \times k_i - V_{err1} \right) + V_{err2} = V_c - I_c \times R_{sh} \]

\[ -k_d \times k \times \frac{dV_c}{dt} + I_c \times R_{sh} \times k_i \times k - k \times V_{err1} + V_{err2} = V_c - I_c \times R_{sh} \]

Rearranging, simplifying, and ignoring the “1”, we get:

\[ I_c \times R_{sh} \times (k_i \times k + 1) = k_d \times k \times \frac{dV_c}{dt} \times \frac{V_c - V_{err2}}{R_{sh} \times k_i \times k} + \frac{V_{err1} \times k}{R_{sh} \times k_i \times k} \]

\[ I_c = \frac{k_d \times \frac{dV_c}{dt} \times \frac{V_c - V_{err2}}{R_{sh} \times k_i \times k} + \frac{V_{err1}}{R_{sh} \times k_i \times k}}{R_{sh} \times (k_i \times k + 1)} \]

We can neglect the second term due to very high value of denominator.

But, the error due to the CMRR of U1 cannot be neglected. The differential input voltage of U1 is very small \((V_c - V_o)\), while the common input voltage is high, namely \(V_c\).

The CMRR due to resistor mismatch is:

\[ \text{CMRR} = \frac{0.5 \times (G_d + 1)}{\Delta R / R} \]

where \(G_d\) is the differential gain.

Using 0.1% resistors for R3-R6, the CMRR will be 54 dB.

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References


Related articles:

- [A guide to using FETs for voltage controlled circuits](https://www.designideas.com/articles/guide-to-using-fets-for-voltage-controlled-circuits)
• Sensing current on the high side
• Dramatically increase the frequency range of RC-based voltage-controlled oscillators
• Light-controlled oscillator uses solar cell junction capacitance
• Circuit simulates a loudspeaker's impedance curve
• Smart ripple canceller offers near-zero dropout

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