For industrial capacitive sensor applications requiring a two wire 4..20 mA current loop output the C/V-converter CAV444 can be combined with the IC AM402. Sensor systems built with this combination are protected against permutation, short circuit and overload.

CAV444 is an integrated capacitance-to-voltage converter, which is able to convert a capacitive measurement head’s capacitance into an output voltage between 1 and 4 V. To realize a 4..20 mA current loop output in capacitive sensors Analog Microelectronics proposes the combination of CAV444 and AM402 shown in Figure 1. In this combination AM402 powers CAV444 and converts its differential output voltage into a 4..20 mA output current. Due to AM402’s protection functions the complete sensor system is protected against short circuit and overload and the pins \( V_S \) and \( I_{\text{OUT}} \) are protected against permutation.

The proposed system is designed for the industrial supply voltage of \( V_S = 24 \text{ V} \) (referenced to GND). The minimum supply voltage \( V_{S,\text{min}} \) depends on the used load \( R_L \) with \( V_{S,\text{min}} = 20 \text{ mA} \cdot R_L + 6 \text{ V} \) (see [2]), the maximum supply voltage \( V_{S,\text{max}} \) is \( V_{S,\text{max}} = 35 \text{ V} \).

Using the equations given in CAV444’s datasheet [1] and AM402’s datasheet [2] the output current \( I_{\text{OUT}}(C_M) \) of the sensor system, which is shown in Figure 1, is given by the following equation:

\[
I_{\text{OUT}}(C_M) = \frac{1}{R_0} \cdot V_{\text{DIFF}} + I_{\text{SET}} = \frac{1}{R_0} \left[ G \left( \frac{9}{16} \cdot \frac{C_M}{C_{M,\text{max}}} \right) + (B - 1) \cdot V_{\text{REF}} \right] + \frac{1}{2 \cdot R_0} \cdot \frac{R_7}{R_6 + R_7} \cdot 5\text{ V}
\]

with

- \( R_0 \): Sense resistor to adjust AM402’s gain (typ. \( R_0 = 36 \Omega \))
- \( I_{\text{SET}} \): Offset current (\( I_{\text{SET}} = 4 \text{ mA} \))
- \( V_{\text{DIFF}} \): CAV444’s differential output voltage (illustrated in Figure 1)
- \( G \): CAV444’s gain which can be adjusted using \( R_1, R_2, R_3, R_4 \) and \( R_5 \) (see [1])
- \( B \): CAV444’s offset adjustment coefficient (see [1])
- \( C_M \): Measurement capacitance value of the specific sensor head
- \( C_{M,\text{max}} \): Maximum measurement capacitance value of the specific sensor head
- \( V_{\text{REF}} \): Reference voltage generated by CAV444
- \( R_6, R_7 \): Resistors used to adjust the offset current (typ. \( R_6 = 133 \text{ k}\Omega, R_7 = 8.2 \text{ k}\Omega \))

**Figure 1: Capacitive sensor system with two wire 4..20 mA current loop output**
CAV444 AN02
Construction of capacitive sensors with 4..20 mA output

Dimensioning:

The dimensioning of the external components \(C_W, C_{F1}, C_{F2}, R_{CM}, R_{CW}, R_0, R_1, R_2, R_3, R_6\) and \(R_7\) in the circuit shown in Figure 1 depends on the used capacitive measurement head with its specific capacitive measurement range and the desired output current \(I_{OUT} = 4..20\) mA. The values for \(C_W, C_{F1}, C_{F2}, R_{CM}, R_{CW}, R_0, R_1\) and \(R_2\) which define CAV444’s operating point, can be calculated using the Excel-sheet Kali_CAV444 (see [3]). \(R_0\) defines AM402’s gain and \(R_6\) and \(R_7\) set the offset current. Using the special operating point for CAV444 described below \(R_0\), \(R_6\) and \(R_7\) can be chosen as fixed resistors for 4..20 mA (see note 1). A recommendation for these fixed values is given later on.

To set CAV444’s special operating point the following information has to be entered into step one (dimensioning and presetting) of the Excel-sheet Kali_CAV444 (see Figure 2):

- \(C_{M,\text{min}}\): Minimum measurement capacitance of the specific sensor head
- \(C_{M,\text{max}}\): Maximum measurement capacitance of the specific sensor head
- \(I_{CW} = 20\ \mu\text{A}\): Converter charge current. 20 \(\mu\text{A}\) is suitable for \(C_{M,\text{min}} < 1\ \text{nF}\) (see [3])
- \(I_{CM} = 20\ \mu\text{A}\): Charge current for \(C_{M}\). 20 \(\mu\text{A}\) is suitable for \(C_{M,\text{min}} < 1\ \text{nF}\) (see [3])
- \(V_{\text{DIFF(min)}} = 0\ \text{V}\): Minimum differential output voltage at \(C_{M,\text{min}}\)
- \(V_{\text{DIFF(max)}} = 0.576\ \text{V}\): Maximum differential output voltage at \(C_{M,\text{max}}\)

Using these input values the Excel-sheet Kali_CAV444 determines the corresponding dimensioning for \(C_W, C_{F1}, C_{F2}, R_{CM}, R_{CW}, R_0, R_1, R_2, R_3\) and \(R_A\), which is shown in Figure 3. The values given for \(R_{1(\text{meas})}\) and \(R_{3(\text{meas})}\) are standardized interim measurement resistances. They will be replaced or trimmed to their final values for each sensor system individually after the sensor systems have been assembled.

By choosing the above mentioned special operating point with \(V_{\text{DIFF(min)}} = 0\ \text{V}\) and \(V_{\text{DIFF(max)}} = 0.576\ \text{V}\), AM402’s offset and gain along with its output current range becomes independent from the measurement head’s capacitance range. To set the output current \(I_{OUT} = 4..20\) mA the following resistor values should be used:

\[R_0 = 36\ \Omega\]  
\[R_6 = 133\ \text{k}\Omega\]  
\[R_7 = 8.2\ \text{k}\Omega\]

With these values and the values calculated by the Excel-sheet Kali_CAV444 the sensor system’s dimensioning for the specific capacitive measurement head is complete. Using this dimensioning all sensor systems equipped with this kind of capacitive measurement head can be assembled\(^3\).

Due to tolerances in the system’s components each sensor built with this dimensioning has to be trimmed individually after the assembly. The trimming is described in step two of the Excel-sheet Kali_CAV444. For that purpose the specific sensor system has to be put into operation (with \(V_S = 24\) V). Using the interim resistors \(R_{1(\text{meas})}\) and \(R_{3(\text{meas})}\), CAV444’s differential output voltage \(V_{\text{DIFF}}\) has to be measured at \(C_{M,\text{min}}\) and at \(C_{M,\text{max}}\) and the measured values have to be entered into Excel-sheet Kali_CAV444 as \(V_{\text{DIFF(meas, min)}}\) and \(V_{\text{DIFF(meas, max)}}\) (see Figure 4). Based on these values the Excel-sheet Kali_CAV444 calculates the final values for \(R_1\) and \(R_3\). After setting \(R_1\) and \(R_3\) to their final values \(R_{1(\text{final})}\) and \(R_{3(\text{final})}\) the system is completely trimmed and ready for operation.

Notes:

1. In this trimming procedure AM402’s offset and gain are considered as ideal. For sensor systems with an error less than 1 % FS a fine trimming of \(R_0, R_6\) and \(R_7\) has to be done. To optimize the system’s offset \(R_6\) or \(R_7\) can be trimmed. A fine trimming of the system’s gain can be obtained using \(R_0\).
2. The tolerances for \(C_W, C_{F1}, C_{F2}, R_{CM}, R_{CW}, R_0, R_1, R_2, R_3\) and \(R_6\) are given in [3]. For \(R_7\) it is recommended to choose resistors with 0.1% tolerance. For \(R_0\) and \(R_6\) resistors with 1% tolerance can be used.

\(^1\) Using E12-series resistors \(R_0 = 36\ \Omega\) can be obtained by using a 33 \(\Omega\) and a 3 \(\Omega\) resistor in series.

\(^2\) Using E12-series resistors \(R_6 = 133\ \text{k}\Omega\) can be obtained by using a 100 \(\text{k}\Omega\) and a 33 \(\text{k}\Omega\) resistor in series.

\(^3\) \(R_{1(\text{meas})}\) and \(R_{3(\text{meas})}\) can be integrated in a measurement setup instead of soldering them to the pcb.

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Example:
To illustrate the dimensioning procedure a sensor system with $C_{M,\text{min}} = 100 \text{ pF}$ and $C_{M,\text{max}} = 1000 \text{ pF}$ is considered. The input values entered into the Excel-sheet Kali_CAV444 are shown in Figure 2.

<table>
<thead>
<tr>
<th>Input of user settings:</th>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Converter charge current:</td>
<td>$I_C$</td>
<td>$I_{CW}$</td>
<td>20.000</td>
<td>$\mu$A</td>
</tr>
<tr>
<td>Charge current for $C_M$</td>
<td>$I_{CM}$</td>
<td>20.000</td>
<td>$\mu$A</td>
<td></td>
</tr>
<tr>
<td>Min. measurement capacitance</td>
<td>$C_{M,\text{min}}$</td>
<td>100.00</td>
<td>pF</td>
<td></td>
</tr>
<tr>
<td>Max. measurement capacitance</td>
<td>$C_{M,\text{max}}$</td>
<td>1000.00</td>
<td>pF</td>
<td></td>
</tr>
<tr>
<td>Desired minimum output voltage</td>
<td>$V_{\text{DIFF(min)}}$</td>
<td>0.000</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Desired maximum output voltage</td>
<td>$V_{\text{DIFF(max)}}$</td>
<td>0.576</td>
<td>V</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2: Input of user settings**

The Excel-sheet Kali_CAV444 calculates the dimensioning of the external components shown in Figure 3:

<table>
<thead>
<tr>
<th>Output of dimensioning values:</th>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>f/V converter capacitor</td>
<td>$C_W$</td>
<td>1400.00</td>
<td>pF</td>
<td></td>
</tr>
<tr>
<td>Lowpass capacitor</td>
<td>$C_{F1(\text{min})}$</td>
<td>108.58</td>
<td>nF</td>
<td></td>
</tr>
<tr>
<td>Reference voltage capacitor</td>
<td>$C_{\text{VREF}}$</td>
<td>100.00</td>
<td>nF</td>
<td></td>
</tr>
<tr>
<td>Measurement osc. current resistor</td>
<td>$R_{CM}$</td>
<td>125.00</td>
<td>kΩ</td>
<td></td>
</tr>
<tr>
<td>Converter current resistor</td>
<td>$R_C$</td>
<td>125.00</td>
<td>kΩ</td>
<td></td>
</tr>
<tr>
<td>f/V stage biasing resistor</td>
<td>$R_A$</td>
<td>60.00</td>
<td>kΩ</td>
<td></td>
</tr>
<tr>
<td>Full-Scale resistor calibration start value</td>
<td>$R_{1(\text{meas})}$</td>
<td>33.00</td>
<td>kΩ</td>
<td></td>
</tr>
<tr>
<td>Offset resistor calibration start value</td>
<td>$R_{4(\text{meas})}$</td>
<td>100.00</td>
<td>kΩ</td>
<td></td>
</tr>
<tr>
<td>Output stage resistors</td>
<td>$R_2$, $R_4$, $R_5$</td>
<td>100.00</td>
<td>kΩ</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 3: Output of dimensioning values**

Since small variances to the calculated values are acceptable (see [3]) and $C_{F1}$, $C_{F2}$ have to be equal or larger than the values given in Figure 3 it is possible to use the following E12-series components:

- $C_W = 1500 \text{ pF}$
- $C_{F1} = C_{F2} = 220 \text{ nF}$
- $C_{\text{VREF}} = 100 \text{ nF}$
- $R_{CM} = R_C = 120 \text{ kΩ}$
- $R_A = 56 \text{ kΩ}$
- $R_{1(\text{meas})} = 33 \text{ kΩ}$ (0.1 %)
- $R_{2(\text{meas})} = R_4 = R_5 = 100 \text{ kΩ}$ (1 %)

Along with the following resistors

- $R_3 = 36 \Omega$ (1 %)
- $R_6 = 133 \kappa\Omega$ (1 %)
- $R_7 = 8.2 \kappa\Omega$ (0.1 %)

the dimensioning is complete for the desired output current range of 4..20 mA.

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To illustrate how the trimming step has to be done a real capacitive sensor system is considered, which was built with this dimensioning. For this sensor system CAV444’s differential output voltage $V_{\text{DIFF}}$ at $C_{\text{M,min}} = 99.75 \text{ pF}$ and $C_{\text{M,max}} = 1014.6 \text{ pF}$ was measured at AM402’s input and is given below:

\[
V_{\text{DIFF(meas,min)}} = 0.0984 \text{ V} \\
V_{\text{DIFF(meas,max)}} = 0.8299 \text{ V}
\]

These values are entered into the Excel-sheet to calculate the final trimming resistor values (see Figure 4).

<table>
<thead>
<tr>
<th>Input of measurements</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured min. output voltage</td>
<td>$V_{\text{DIFF(meas,min)}}$</td>
<td>0.0984</td>
<td>V</td>
</tr>
<tr>
<td>Measured max. output voltage</td>
<td>$V_{\text{DIFF(meas,max)}}$</td>
<td>0.8299</td>
<td>V</td>
</tr>
</tbody>
</table>

Replace $R_1 = 33 \text{ k}\Omega$ and $R_3 = 100 \text{ k}\Omega$ with the following:

<table>
<thead>
<tr>
<th>Output of calculated resistances</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final trimming resistor value $R_1$</td>
<td>$R_1$ (final)</td>
<td>12.61</td>
<td>k\Omega</td>
</tr>
<tr>
<td>Final trimming resistor value $R_3$</td>
<td>$R_3$ (final)</td>
<td>50.57</td>
<td>k\Omega</td>
</tr>
</tbody>
</table>

**Figure 4: Calculation of the final trimming resistor values**

After setting $R_1$ and $R_3$ to their final values (instead of the calculated values $R_1 = 12.6 \text{ k}\Omega$ and $R_3 = 50.6 \text{ k}\Omega$ were used) this real sensor system was put into operation and the output current as a function of $C_{\text{M}}$ was measured. *Figure 5* shows the measured output current signal along with the ideal transfer function. In addition the system’s total error is shown (round blue dots: before a fine trimming was done; square blue dots: after a fine trimming using $R_0$ and $R_7$ was done). As illustrated below the system’s error without fine trimming was found to be approximately 0.6 % FS and with fine trimming < 0.1 % FS.

**Figure 5: Output current signal and total error obtained for a sample sensor system**

References:

1.) Data sheet CAV444 (see [http://www.analogmicro.de](http://www.analogmicro.de))
2.) Data sheet AM402 (see [http://www.analogmicro.de](http://www.analogmicro.de))
3.) Excel-sheet Kali_CAV444 (Rev. 3.2) (see [http://www.analogmicro.de](http://www.analogmicro.de))