For industrial capacitive sensor applications requiring an analog output voltage range of 0..5 V or 0..10 V the C/V-converter CAV444 can be combined with the IC AM411. Sensor systems built with this combination are protected against short circuit.

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 an analog output voltage range of 0..5 V or 0..10 V in capacitive sensors Analog Microelectronics proposes the combination of CAV444 and AM411 shown in Figure 1. In this combination AM411 powers CAV444 and converts its differential output voltage into a 0..5 V or 0..10 V output voltage\(^1\). Due to AM411’s protection functions the complete sensor system is protected against short circuit.

The proposed system is designed for the industrial supply voltage of \(V_S = 24\) V, which is included in the overall supply voltage range \(V_S = 10..35\) V for an output of 0..5 V or \(V_S = 15..35\) V for an output of 0..10 V.

\[
V_{OUT}(C_M) = 5 \cdot \left(1 + \frac{R_6}{R_7}\right) \cdot V_{DIFF} = 5 \cdot \left(1 + \frac{R_6}{R_7}\right) \cdot G_{CAV444} \cdot \left(\frac{9}{16} \cdot \frac{C_M}{C_{M,max}}\right) + (B-1) \cdot V_{REF}
\]

with

- \(R_6, R_7\): Resistors used to choose the output voltage range
- \(V_{DIFF}\): CAV444’s differential output voltage (illustrated in Figure 1)
- \(G_{CAV444}\): 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
- \(C_{M,max}\): Maximum measurement capacitance value of the specific sensor head
- \(V_{REF}\): Reference voltage generated by CAV444

\(^1\) Instead of AM411 it is also possible to use the IC AM401. The small changes needed to connect CAV424 to AM401 can be derived from AM401’s data sheet.
Construction of capacitive sensors with 0..5 V/0..10 V output

Dimensioning:

The dimensioning of the external components (C_W, C_F1, C_F2, R_CM, R_CW, R_h, R_1, 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 voltage range. Using the Excel-sheet Kali_CAV444 (see [3]) the values for C_W, C_F1, C_F2, R_CM, R_CW, R_h, R_1, R_3, R_6 and R_7, which define CAV444’s operating point, can be calculated for the application specific kind of measurement head. R_6 and R_7 define AM411’s gain and the system’s output voltage range. Using the special operating point for CAV444 described below the sensor systems can be trimmed individually. 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. Using the interim resistors R_1(meas) and R_3(meas) CAV444’s differential output voltage V_DIFF has to be measured at C_M,min and at C_M,max and the measured values have to be entered into Excel-sheet Kali_CAV444 as V_DIFF(meas,min) and V_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(final) and R_3(final) the system is completely trimmed and ready for operation.

Notes:

1. In this trimming procedure AM411’s gain is considered as ideal. For sensor systems with an error less than 1 % FS a fine trimming of R_6 and R_7 might be necessary. To optimize the system’s gain R_6 or R_7 can be trimmed.
2. The tolerances for C_W, C_F1, C_F2, R_CM, R_CW, R_h, R_1, R_3, R_6 and R_7 are given in [3]. For R_6 and R_7 it is recommended to choose resistors with 0.1% tolerance.

2 Using E12-series resistors R_6 = 44 kΩ can be obtained by using two 22 kΩ resistors in series.
3 Using E12-series resistors R_6 = 84.7 kΩ can be obtained by using a 2.7 kΩ and a 82 kΩ resistors in series.
4 R_1(meas) and R_3(meas) are interim measurement resistors, which can be integrated in a measurement setup instead of soldering them to the pcb.
Example:

To illustrate the dimensioning procedure a sensor system with a desired 0..5 V output voltage and $C_{M,\text{min}} = 100 \text{ pF}$ and $C_{M,\text{max}} = 1000 \text{ pF}$ is considered. Figure 2 shows the input values, which have to be entered into the Excel-sheet Kali_CAV444.

<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>$I_{CW}$</td>
<td>20.000</td>
<td>μA</td>
<td></td>
</tr>
<tr>
<td>Charge current for $C_M$</td>
<td>$I_{CM}$</td>
<td>20.000</td>
<td>μA</td>
<td></td>
</tr>
<tr>
<td>Min. measurement capacitor</td>
<td>$C_{M,\text{min}}$</td>
<td>100.00</td>
<td>pF</td>
<td></td>
</tr>
<tr>
<td>Max. measurement capacitor</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>0.00</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Desired maximum output voltage</td>
<td>$V_{\text{DIFF(max)}}$</td>
<td>0.56</td>
<td>V</td>
<td></td>
</tr>
</tbody>
</table>

$V_{\text{DIFF}} (=V_{\text{OUT}}-V_{\text{REF}}) \@ C_{M,\text{min}}$

Range: -1.5V to 1.5V

$V_{\text{DIFF}} (=V_{\text{OUT}}-V_{\text{REF}}) \@ C_{M,\text{max}}$

Range: -1.5V to 1.5V

$V_{\text{DIFF(min)}} < V_{\text{DIFF(max)}}$

---

**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>1/V converter capacitor</td>
<td>$C_W$</td>
<td>1400.00</td>
<td>pF</td>
<td></td>
</tr>
<tr>
<td>Lowpass capacitor</td>
<td>$C_{F1,F2(\text{min})}$</td>
<td>108.58</td>
<td>nF</td>
<td></td>
</tr>
<tr>
<td>Reference voltage capacitor</td>
<td>$C_{VREF}$</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>$R_{CW}$</td>
<td>125.00</td>
<td>kΩ</td>
<td></td>
</tr>
<tr>
<td>1/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>$R_{2(\text{meas})}$</td>
<td>100.00</td>
<td>kΩ</td>
<td></td>
</tr>
<tr>
<td>Output stage resistors</td>
<td>$R_2, R_4, R_6$</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:

- $C_W = 1500 \text{ pF}$
- $C_{F1} = C_{F2} = 220 \text{ nF}$
- $C_{VREF} = 100 \text{ nF}$
- $R_{CM} = R_{CW} = 120 \text{ kΩ}$
- $R_A = 56 \text{ kΩ}$
- $R_{3(\text{meas})} = 100 \text{ kΩ (0.1 %)}$
- $R_{2(\text{meas})} = R_4 = R_5 = 100 \text{ kΩ (1 %)}$
- $R_3 = 44 \text{ kΩ (0.1 %)}$
- $R_7 = 56 \text{ kΩ (0.1 %)}$

Along with the following resistors

- $R_2 = 44 \text{ kΩ (0.1 %)}$
- $R_7 = 56 \text{ kΩ (0.1 %)}$

the dimensioning is complete for the desired output voltage range of 0..5 V.
To illustrate how the trimming step has to be done a real sensor system is considered, which was built with this dimensioning. For this sensor system the differential output voltages at \( C_{M,\text{min}} = 99.75 \text{ pF} \) and \( C_{M,\text{max}} = 1014.6 \text{ pF} \) were measured and are given below:

\[
V_{\text{DIFF(meas, min)}} = 0.0989 \text{ V} \\
V_{\text{DIFF(meas, max)}} = 0.8366 \text{ V}
\]

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

<table>
<thead>
<tr>
<th>Parameter</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)}} = (V_{\text{OUT}} - V_{\text{REF}}) \times C_{M,\text{min}} )</td>
<td>0.0989</td>
<td>V</td>
</tr>
<tr>
<td>Measured max. output voltage</td>
<td>( V_{\text{DIFF(meas, max)}} = (V_{\text{OUT}} - V_{\text{REF}}) \times C_{M,\text{max}} )</td>
<td>0.8366</td>
<td>V</td>
</tr>
</tbody>
</table>

Replace \( R_{1(\text{meas})} = 33 \text{ k\Omega} \) and \( R_{3(\text{meas})} = 100k\text{\Omega} \) with the following:

<table>
<thead>
<tr>
<th>Parameter</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 \text{(final)} )</td>
<td>10.00</td>
<td>k\Omega</td>
</tr>
<tr>
<td>Final trimming resistor value ( R_3 )</td>
<td>( R_3 \text{(final)} )</td>
<td>43.70</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 value for \( R_3(\text{final}) \), \( R_3 = 43.6 \text{ k\Omega} \) was used) this real sensor system was put into operation and the output voltage signal as a function of \( C_M \) was measured. **Figure 5** shows the output voltage 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 \( R_6 \) was done). As illustrated below the system’s error without fine trimming was found to be approximately 0.7 % FS and with fine trimming < 0.3 % FS.

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

References:

1.) CAV444’s data sheet (see [http://www.analogmicro.de](http://www.analogmicro.de))
2.) AM411’s data sheet (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))