CAV444 AN02
Construction of capacitive sensors with 4..20 mA output

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_{OUT} are protected against permutation.

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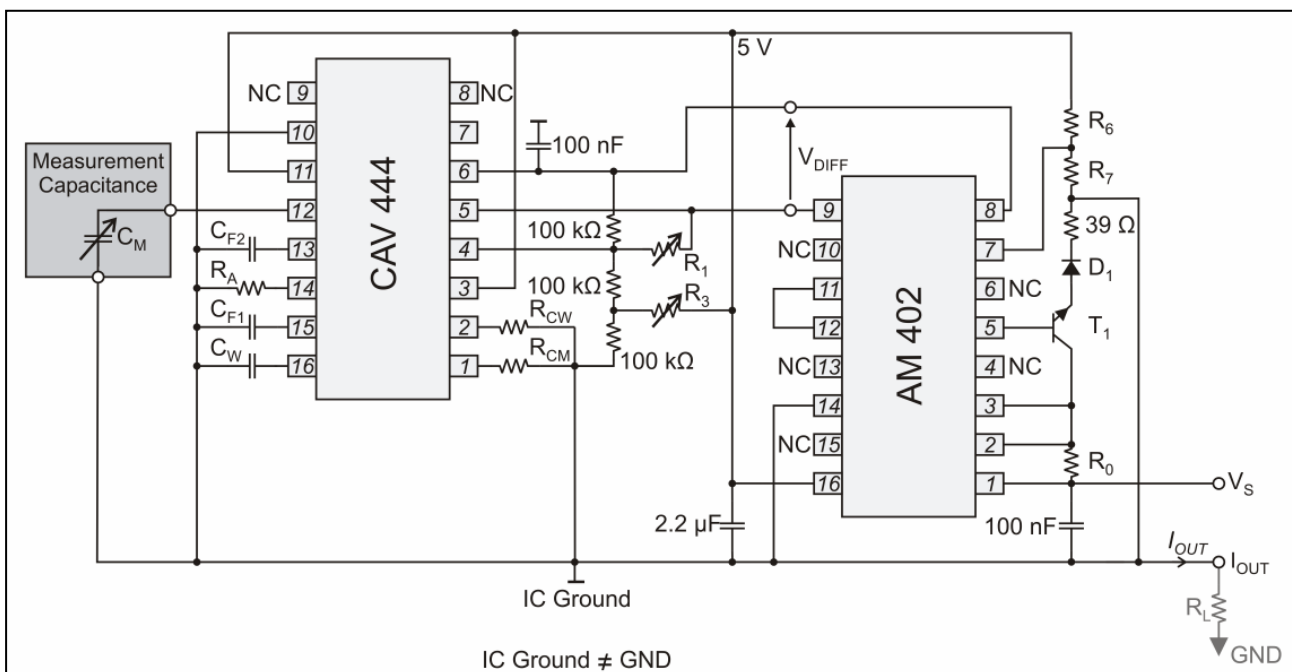

Figure 1: Capacitive sensor system with two wire 4..20 mA current loop output

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

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

with
	R_0	Sense resistor to adjust AM402's gain (typ. $R_0 = 36\ \Omega$)
	I_{SET}	Offset current ($I_{SET} = 4$ mA)
	V_{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
	$C_{M,max}$	Maximum measurement capacitance value of the specific sensor head
	V_{REF}	Reference voltage generated by CAV444
	R_6, R_7	Resistors used to adjust the offset current (typ. $R_6 = 133\ k\Omega$, $R_7 = 8.2\ k\Omega$)

Dimensioning:

The dimensioning of the external components (C_W, C_{F1}, C_{F2}, R_{CM}, R_{CW}, R_A, R_0, 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 current I_{OUT} = 4..20 mA. The values for C_W, C_{F1}, C_{F2}, R_{CM}, R_{CW}, R_A, R_1 and R_3, 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*):

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

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_1, R_3 and R_A, which is shown in *Figure 3*. The values given for $R_{1(meas)}$ and $R_{3(meas)}$ 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 $V_{DIFF(min)}$ = 0 V and $V_{DIFF(max)}$ = 0.576 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 range I_{OUT} = 4..20 mA the following resistor values should be used:

R_0 = 36 Ω[1] R_6 = 133 kΩ[2] R_7 = 8.2 kΩ

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 $R_{1(meas)}$ 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 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_A, R_1, R_2, R_3, R_4 and R_5 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.

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[1] Using E12-series resistors R_0 = 36 Ω can be obtained by using a 33 Ω and a 3 Ω resistor in series.
[2] Using E12-series resistors R_6 = 133 kΩ can be obtained by using a 100 kΩ and a 33 kΩ resistor in series.
[3] $R_{1(meas)}$ and $R_{3(meas)}$ 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 $C_{M,min} = 100\ pF$ and $C_{M,max} = 1000\ pF$ is considered. The input values entered into the Excel-sheet Kali_CAV444 are shown in *Figure 2*.

Input of user settings:			
Parameter	**Symbol**	**Value**	**Unit**
Converter charge current: *Range: 2 - 25 µA*	I_{CW}	20.000	µA
Charge current for C_M *Range: 20 - 50 µA*	I_{CM}	20.000	µA
Min. measurement capacitance *Range: 10 pF - 10,000 pF*	$C_{M,min}$	100.00	pF
Max. measurement capacitance *Range: 10 pF - 10,000 pF*	$C_{M,max}$	1000.00	pF
Desired minimum output voltage V_{DIFF} (=V_{OUT}-V_{REF}) @ $C_{M,min}$ *Range: -1.5V to 1.5V*	$V_{DIFF(min)}$	0.000	V
Desired maximum output voltage V_{DIFF} (=V_{OUT}-V_{REF}) @ $C_{M,max}$ *Range: -1.5V to 1.5V* $V_{DIFF(min)} < V_{DIFF(max)}$!	$V_{DIFF(max)}$	0.576	V

Figure 2: **Input of user settings**

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

Output of dimensioning values:			
Parameter	**Symbol**	**Value**	**Unit**
f/V converter capacitor	C_W	1400.00	pF
Lowpass capacitor	$C_{F1,F2(min)}$	108.58	nF
Reference voltage capacitor	C_{VREF}	100.00	nF
Measurement osc. current resistor	R_{CM}	125.00	kΩ
Converter current resistor	R_{CW}	125.00	kΩ
f/V stage biasing resistor	R_A	60.00	kΩ
Full-Scale resistor calibration start value	$R_{1(meas)}$	33.00	kΩ
Offset resistor calibration start value	$R_{3(meas)}$	100.00	kΩ
Output stage resistors	R_2, R_4, R_5	100.00	kΩ

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:

$C_W = 1500\ pF$ $C_{F1} = C_{F2} = 220\ nF$ $C_{VREF} = 100\ nF$
$R_{CM} = R_{CW} = 120\ k\Omega$ $R_A = 56\ k\Omega$ $R_{1(meas)} = 33\ k\Omega$ (0.1 %)
$R_{3(meas)} = 100\ k\Omega$ (0.1 %) $R_2 = R_4 = R_5 = 100\ k\Omega$ (1%)

Along with the following resistors

$R_0 = 36\ \Omega$ (1 %) $R_6 = 133\ k\Omega$ (1 %) $R_7 = 8.2\ k\Omega$ (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_{DIFF} at $C_{M,min} = 99.75\ pF$ and $C_{M,max} = 1014.6\ pF$ was measured at AM402's input and is given below:

$$V_{DIFF(meas,min)} = 0.0984\ V \qquad\qquad V_{DIFF(meas,max)} = 0.8299\ V$$

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

Input of measurements			
Parameter	**Symbol**	**Value**	**Unit**
Measured min. output voltage $V_{DIFF(meas,min)} = (V_{OUT}-V_{REF})@C_{M,min}$	$V_{DIFF(meas,min)}$	0.0984	V
Measured max. output voltage $V_{DIFF(meas,max)} = (V_{OUT}-V_{REF})@C_{M,max}$	$V_{DIFF(meas,max)}$	0.8299	V

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

Output of calculated resistances			
Parameter	**Symbol**	**Value**	**Unit**
Final trimming resistor value R_1	$R_{1\ (final)}$	12.61	kΩ
Final trimming resistor value R_3	$R_{3\ (final)}$	50.57	kΩ

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 $R_1 = 12.6\ k\Omega$ and $R_3= 50.6\ k\Omega$ were used*)* this real sensor system was put into operation and the output current as a function of C_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.
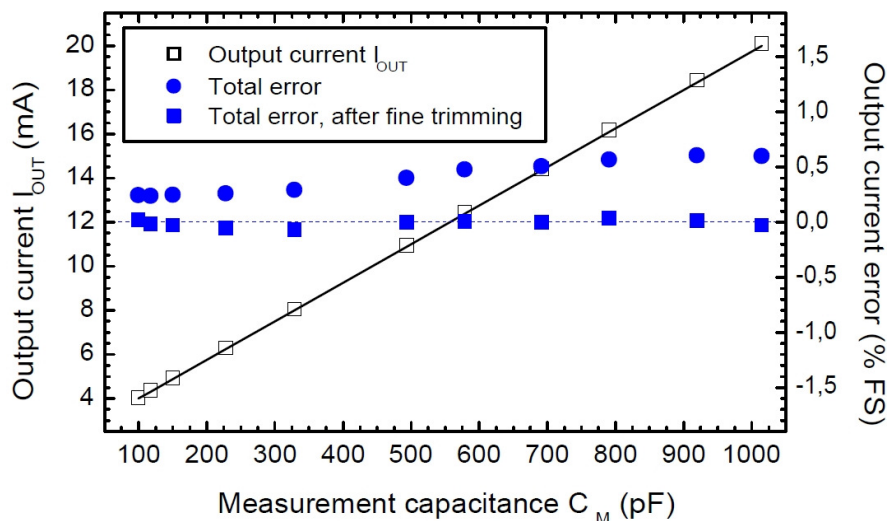

Figure 5: **Output current signal and total error obtained for a sample sensor system**

References:

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

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