CAV444 AN01
Construction of capacitive sensors with 0..5 V/0..10 V output

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.

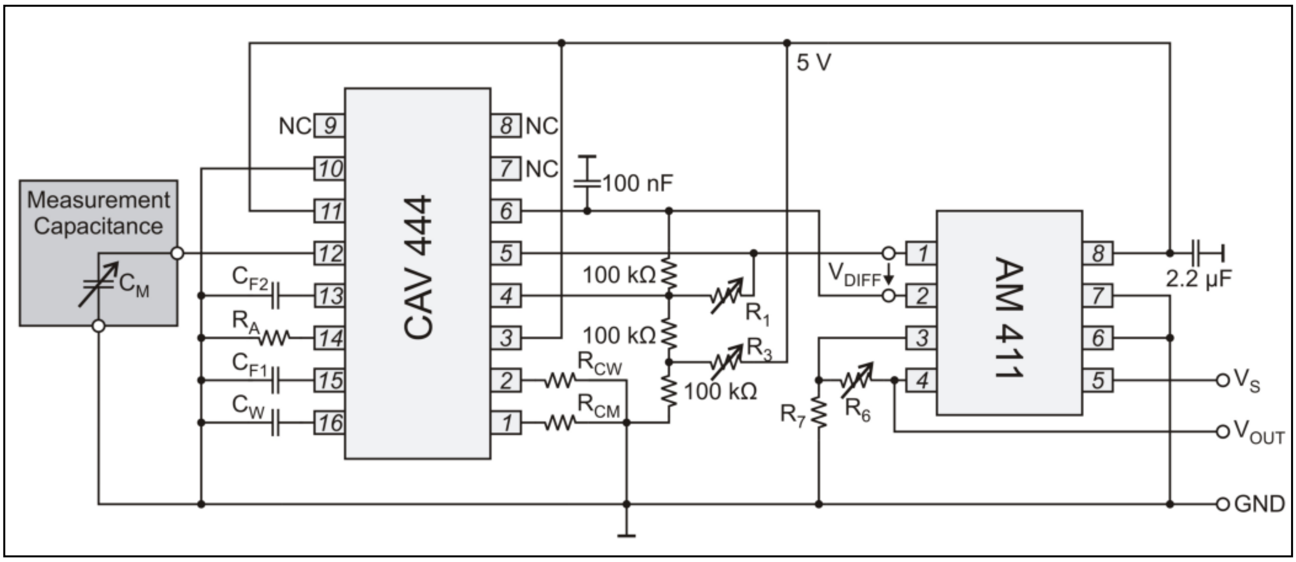

Figure 1: Capacitive sensor system with industrial output voltage range 0..5V or 0..10V

Following CAV444's datasheet [1] and AM411's datasheet [2] the output voltage $V_{OUT}(C_M)$ of the sensor system, which is shown in *Figure 1*, can be calculated by:

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

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.

Dimensioning:

The dimensioning of the external components (C_W, C_{F1}, C_{F2}, R_{CM}, R_{CW}, R_A, 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_A, R_1 and R_3, 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 R_6 and R_7 can be chosen as fixed resistors for the specified voltage range. 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
$I_{CW} = 20\ \mu A$	Converter charge current. 20 µA is suitable for $C_{M,min} < 1\ nF$ (see [3])
$I_{CM} = 20\ \mu A$	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 $C_{M,min}$
$V_{DIFF(max)} = 0.56\ V$	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}, $R_{1(meas)}$, $R_{3(meas)}$ 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 $V_{DIFF(max)} = 0.56\ V$, AM411's gain becomes independent from the measurement head's specifications. It only depends on the desired output voltage range V_{OUT}.

To select the specific industrial output voltage range the following resistor values can be used:

$R_6 = 44\ k\Omega$[2] and $R_7 = 56\ k\Omega$ for $V_{OUT} = 0..5\ V$

$R_6 = 84.7\ k\Omega$[3] and $R_7 = 33\ k\Omega$ for $V_{OUT} = 0..10\ V$

With these values for C_W, C_{F1}, C_{F2}, R_{CM}, R_{CW}, R_A, R_1, R_3, R_6 and R_7 the sensor system's dimensioning for the specific capacitive measurement head is complete. All sensor systems equipped with this kind of capacitive measurement head can be assembled using this dimensioning[4].

Due to tolerances in the system's components each sensor system built with this dimensioning has to 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_A, R_1, R_2, R_3, R_4 and R_5 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 $R_6 = 44\ k\Omega$ can be obtained by using two 22 kΩ resistors in series.
[3] Using E12-series resistors $R_6 = 84.7\ k\Omega$ 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 $C_{M,min} = 100\ pF$ and $C_{M,max} = 1000\ pF$ is considered. *Figure 2* shows the input values, which have to be entered into the Excel-sheet Kali_CAV444.

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 capacitor *Range: 10 pF - 10,000 pF*	$C_{M,min}$	100.00	pF
Max. measurement capacitor *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*	$V_{DIFF(min)}$	0.00	V
Desired maximum output voltage V_{DIFF} (=V_{OUT}-V_{REF}) @ $C_{M,max}$ *Range: -1.5V to 1.5V* $V_{DIFF(min)} < V_{DIFF(max)}$!	$V_{DIFF(max)}$	0.56	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:

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

Along with the following resistors

$R_6 = 44\ k\Omega\ (0.1\ \%)$ $\quad$ $R_7 = 56\ k\Omega\ (0.1\ \%)$

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 $C_{M,min} = 99.75\ pF$ and $C_{M,max} = 1014.6\ pF$ were measured and are given below:

$V_{DIFF(meas,min)} = 0.0989\ V$ $\qquad$ $V_{DIFF(meas,max)} = 0.8366\ V$

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 $V_{DIFF(meas,min)} = (V_{OUT}-V_{REF})@C_{M,min}$	$V_{DIFF(meas,min)}$	0.0989	V
Measured max. output voltage $V_{DIFF(meas,max)} = (V_{OUT}-V_{REF})@C_{M,max}$	$V_{DIFF(meas,max)}$	0.8366	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	$R_{1\ (final)}$	10.00	kΩ
Final trimming resistor value R_3	$R_{3\ (final)}$	43.70	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 value for $R_{3(final)}$ R_3= 43.6 kΩ 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.

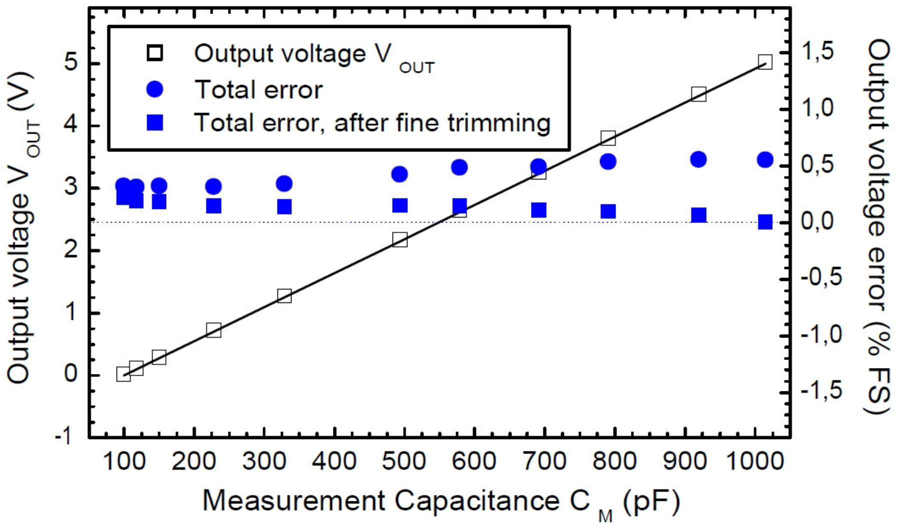

Figure 5: **Output voltage signal and error obtained for a sample sensor system**

References:

1.) CAV444's data sheet (see http://www.analogmicro.de)
2.) AM411's data sheet (see http://www.analogmicro.de)
3.) Excel-sheet Kali_CAV444 (Rev. 3.2) (see http://www.analogmicro.de)