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Economic Voltage Measurement With the MSP430 Family

Application Report

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Economic Voltage Measurement With the MSP430 Family

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ABSTRACT

This application report describes voltage and current measurement methods using the MSP430 universal timer/port module. The report explains the two measurement methods (charge and discharge) and shows how to measure voltage and current. The equations for the calculations are also given.

Further sections show additional applications such as the measurement of two voltage inputs, bridge arrangements, and R/2R configurations. Equations are given for all examples.

1 Voltage Measurements With the Universal TImer/Port Module

Voltage measurements with the universal timer/port module require the least amount of hardware, and deliver a very precise result if a two-point calibration is used with two voltages at the limits of the input voltage range. Application of this method produces the following results:

- Accuracy between 1 V and 3.7 V, better than $\pm 10^{-3}$ (±0.1%). A two-point calibration is used.
- Temperature deviation between –20°C and 30°C, better than 45 ppm/°C

1.1 The Universal Timer/Port Module

The universal timer/port module was conceived to measure resistive sensors, such as temperature sensors. The module consists of two independent parts which work together to measure resistors and voltages:

- **Counter with Controller:** two 8-bit counters, which may be connected in series to form a 16-bit counter. Additionally, there is a controller, a comparator input CMPI, and an input CIN with Schmitt trigger characteristics.
- **Input/Output Port:** five outputs (TP0.0...TP0.4), which can be switched to Hi-Z, and an I/O-port (TP0.5).

The comparator input (CMPI), which is normally used on voltage measurement, has a threshold voltage $V_{ref(com)}$ which is nominally $0.25 \times V_{cc}$ with small tolerances. $V_{ref(com)}$ is temperature independent. The comparator hardware consumes approximately 300 µA, and should be switched off when not in use.

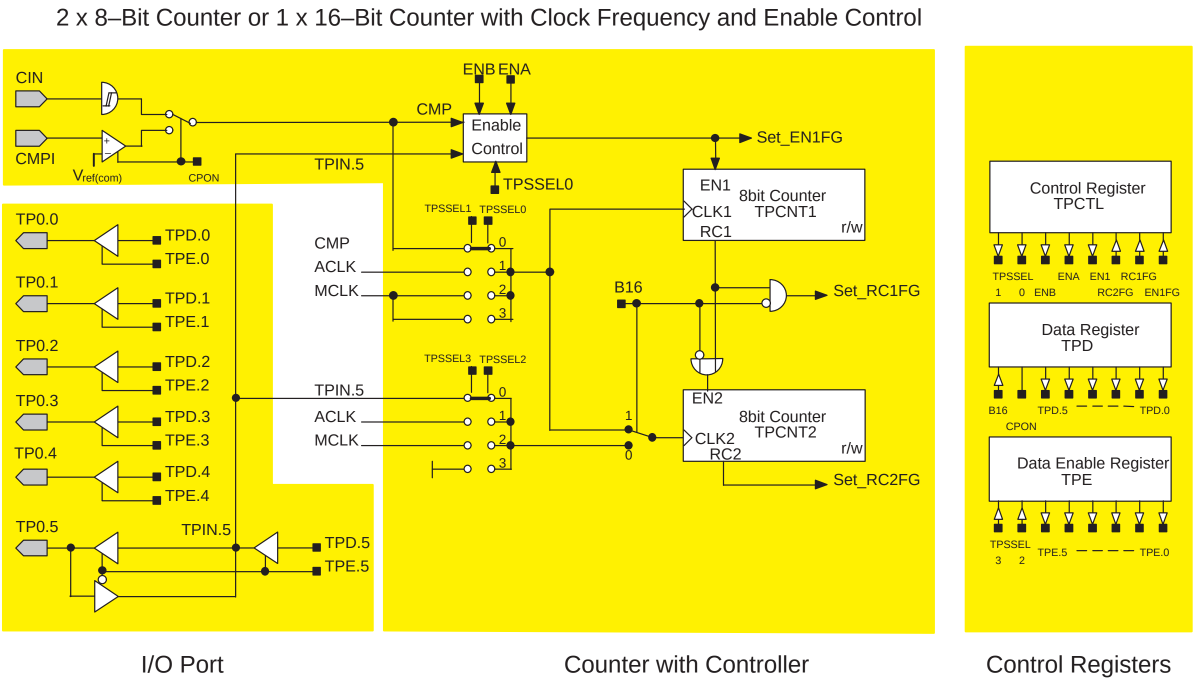


Figure 1. Block Diagram of the Universal Timer/Port Module

1.2 Measurement Principle

The universal timer/port module of the MSP430 family allows measurement of a restricted voltage range. Normally, a second circuit (analog-to-digital converter) is utilized for this task. The measurement principle is explained using the circuit of Figure 2.

When measuring voltage with the MSP430x3xx family, the comparator input CMPI, with its well-defined 0.25×Vcc threshold voltage, is used instead of the analog input CIN, with its Schmitt trigger characteristic. The comparator input CMPI has different names with different MSP430 family members because it normally uses the same pin as the highest numbered LCD-select line (for instance, S29 with the MSP430x33x).

The LCD pin is switched from the select function to the comparator function by a control bit located in the universal timer/port module (CPON, TPD.6, address 04Eh).

Figure 2 shows a voltage-measurement circuit with two different input stages for the input voltage Vmeas. Referring to this circuit:

- Input voltages with relatively low impedance are connected directly to the input Vmeas0. The input impedance of the circuit is approximately $10^5\ \Omega$ to $10^6\ \Omega$ (see example in Figure 4).
- Input voltages with very high impedance are connected to the noninverting input of the op amp (Vmeas1), which has an approximate input impedance of $10^9\ \Omega$.

Only one of the two input stages described in Figure 2 can be used. If more than one input voltage is to be measured, one of the circuits shown in further sections should be used.

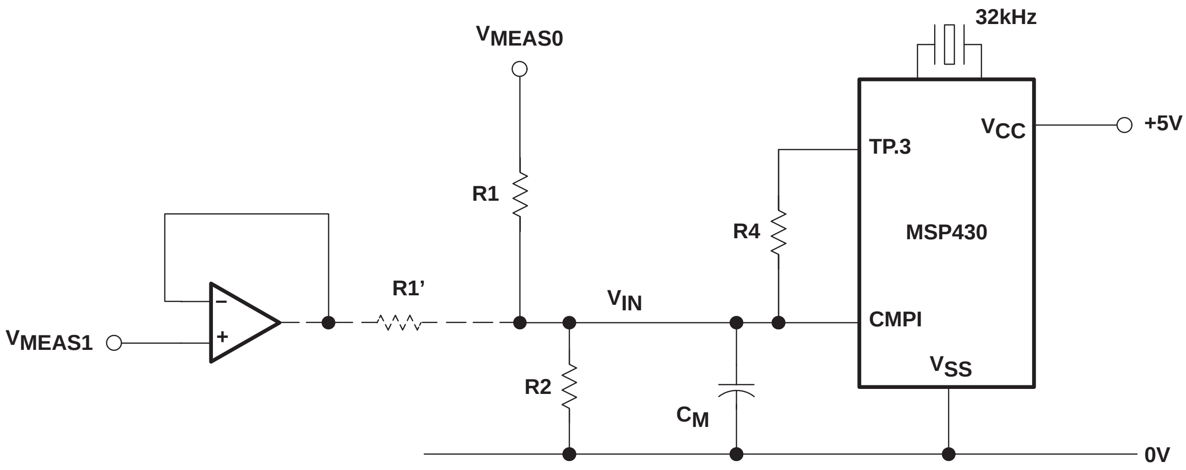


Figure 2. Voltage Measurement With the Universal Timer/Port Module

The range of input voltage Vin (as seen at the input CMPI) that can be measured with the circuit of Figure 2 is restricted to:

$$V_{ref(com)max} < Vin \leq Vcc \tag{1}$$

This implies that for a supply voltage Vcc = 5 V, voltages between 0.26 × 5 V = 1.3 V and 5 V can be measured ($V_{ref(com)max}$ = 0.26 × Vcc).

With a resistor divider consisting of resistors R1 and R2, a nominal input voltage range for Vmeas0 results in:

$$V_{ref\,(com)} \times \frac{R1 + R2}{R2} < Vmeas0 \leq Vcc \times \frac{R1 + R2}{R2} \tag{2}$$

The following is the sequence for the measurement of Vmeas. The numbers used correspond to the numbers of the *conversion states* shown in Figure 3. The software is contained in Section 1.5.1 of this report.

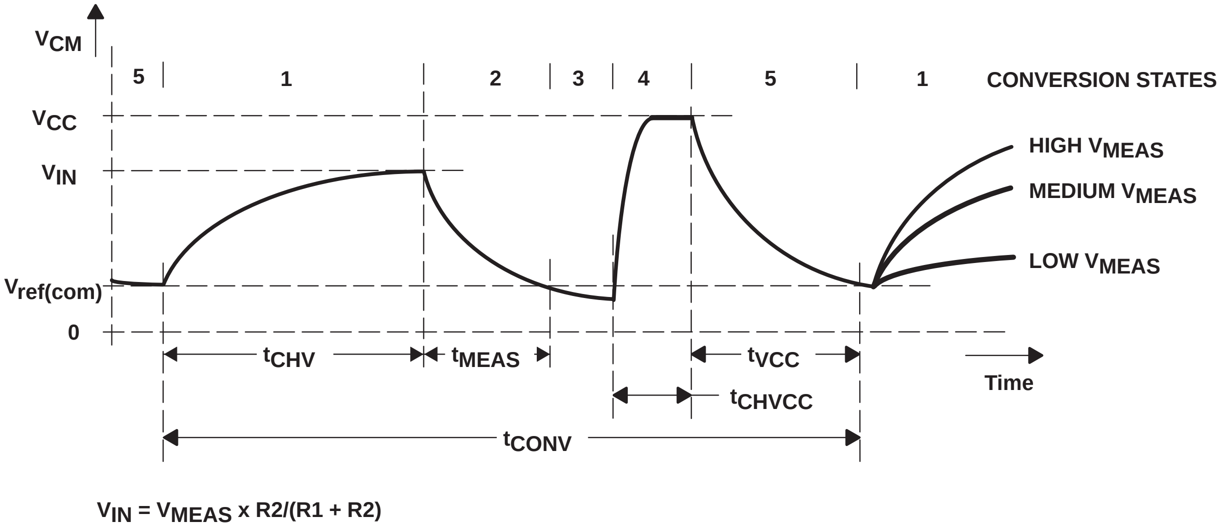


Figure 3. Voltage Measurement Sequence

1. Output TP.3 is switched to Hi-Z. Measurement capacitor Cm charges to the divided input voltage Vmeas during the time interval tchv between two voltage measurements.

2. The voltage measurement starts. TP.3 is switched to 0 V and discharges capacitor Cm. At the same time, the measurement of the time (tmeas) starts with the 16-bit counter of the universal timer/port module. When threshold voltage $V_{ref(com)}$ is reached, the time measurement is automatically stopped.
3. The measured time (tmeas) is stored.
4. TP.3 is switched to Vcc and charges capacitor Cm to the supply voltage Vcc. The time required (tchvcc) ranges from 5τ to 7τ, depending on the accuracy required. (τ ≈ R4 × Cm).
5. The reference measurement starts. TP.3 is switched to 0 V and discharges capacitor Cm. At the same time, the measurement of the time (tvcc) starts with the 16-bit counter. When the threshold voltage $V_{ref(com)}$ is reached, the time measurement is automatically stopped.
6. The measured time (tvcc) is stored.

> **NOTE:** All formulas show measured time intervals only. These time intervals *tx* can be converted into the measured counts *nx* using the formula:
>
> $$tx = \frac{nx}{fMCLK}$$
>
> Where fMCLK represents the CPU frequency MCLK of the MSP430.

The voltage Vmeas can be calculated from the two time intervals measured (tmeas and tvcc) using the following formula:

$$V_{meas} = Vcc \times \frac{R1 + R2}{R2} \times e^{\frac{tmeas - tvcc}{\tau}} \tag{3}$$

Where:

Vmeas = Input voltage to be measured [V]
Vcc = Supply voltage of the MSP430 (used for reference) [V]
R1, R2 = Input resistor divider at input CMPI [V]
tmeas = Discharge time of the divided Vmeas until $V_{ref(com)}$ is reached [s]
tvcc = Discharge time from Vcc to $V_{ref(com)}$ [s]
τ = Time constant of the discharge circuit (τ ≈ R4 × Cm) [s]
$V_{ref(com)}$ = Threshold voltage of the comparator input CMPI [V]
tconv = Time between two complete voltage measurements [s]

To get a constant value for τ, an expensive, highly stable capacitor Cm is necessary. This can be avoided by deriving the value of τ from equation (4) (for the discharge of capacitor Cm) to obtain equation (5). This value of τ is then substituted into equation (3) to obtain equation (6) for the value of Vmeas. Equation (6) is also used with the software example shown in Section 1.5.1.

$$V_{ref\,(com)} = Vcc \times e^{-\frac{tvcc}{\tau}} \tag{4}$$

τ is calculated:

$$\tau = \frac{tvcc}{\ln \frac{Vcc}{Vref\,(com)}} \quad where \quad \frac{Vcc}{Vref\ (com)} = 4 \tag{5}$$

Inserted into equation (3) this leads to:

$$V_{meas} = Vcc \times \frac{R1 + R2}{R2} \times e^{\frac{tmeas - tvcc}{tvcc} \times ln \frac{Vcc}{Vref\,(com)}} \qquad (6)$$

It is only important that the capacitor Cm used on the voltage measurement has constant or very high isolation resistance. The isolation resistor of capacitor Cm is connected in parallel with resistor R2, and thus affects the resistor ratio if it changes, for example, due to changes in temperature.

Equation (6) shows the dependence of the voltage measurement on the supply voltage Vcc (which is the reference), the threshold voltage $V_{ref(com)}$, the accuracy of resistors R1 and R2, and the temperature drift of these values. To get a measurement accuracy of ±1% for Vmeas without calibration, the following basic requirements must be met:

- The supply voltage Vcc must be stable. Vcc needs to be within ±25 mV of the defined temperature range. The absolute value of Vcc is not important if a two-point calibration is used.
- CMPI must be used for the comparator input. The fairly well defined threshold voltage $V_{ref(com)}$ (0.25×Vcc) allows better results than the normal Schmitt trigger input CIN with its large threshold voltage tolerances.
- Temperature drift of the resistor divider must not be greater than ±50 ppm/°C.
- Sufficient charge-up time must be allowed to measure capacitor Cm:
  - For 1.0% accuracy, approximately 5τ are necessary ($e^5 = 148.41$).
  - For 0.1% accuracy, approximately 7τ are necessary ($e^7 = 1096.63$).

If a two-point calibration is used, the values calculated for slope and offset are stored in an external EEPROM; if the battery is continuously connected to the MSP430 system, they are stored in the internal RAM.

1.3 Resolution of the Measurement

The resolution for one counter step nmeas of the voltage measurement is:

$$\frac{dVmeas}{dnmeas} = \frac{Vmeas}{\tau \times fMCLK} \approx \frac{Vmeas}{R4 \times Cm \times fMCLK} \qquad (7)$$

For the circuit shown in Figure 4 this means (worst case, Vmeas = $Vmeas_{max}$)

$$\frac{dVmeas}{dnmeas} \approx \frac{3.7}{47 \times 10^3 \times 82 \times 10^{-9} \times 3 \times 10^6} = 0.32 \times 10^{-3}$$

The resolution for the worst case is 0.32 mV for Vmeas = 3.7 V, Cm = 82 nF, R4 = 47 kΩ, f_{MCLK} = 3 MHz. This is equivalent to an analog-to-digital converter with a bit length *a* of:

$$a = ld\,\frac{3.7\ V}{0.32\ mV} = 13.49 \qquad (8)$$

With *ld* = $\log_2$. The result above means that the resolution of this circuit ranges between a 13-bit and a 14-bit analog-to-digital converter.

For the voltage range of interest at input CMPI ($V_{ref(com)}$ to Vcc), the nonlinear characteristic of the exponential function can be approximated by a hyperbola. The advantage of this method is that the time-consuming exponential function is replaced by just one division:

$$Vmeas = \frac{A}{(tmeas–tvcc) + B} + C \tag{9}$$

The values for A, B, and C can be determined by solution of three equations (see Section 5.5, *Coefficient Calculation for the Equations*, in the *MSP430 Application Report*), or with the aid of a software application such as Mathcad™.

The MSP430 floating point package FPP4 is ideally suited for the calculation of all the previous formulas. The package contains all the necessary functions, such as exponential and logarithmic. An example of its use is given in Section 1.5.1.

1.4 Measurement Timing

The worst-case time interval tconv for a complete voltage measurement can be calculated using the previous formulas. This time interval determines the highest repetition rate for a complete voltage measurement. The time interval tconv is the sum of all time intervals shown in Figure 3.

$$tconv = tchv + tmeas + tchvcc + tvcc \tag{10}$$

The worst case value for the complete measurement time tconv can be calculated using the values that determine the time intervals of equation (10). The accuracy required is assumed to be 1%. If a higher accuracy is required, then *ln100* in equation (11) must be substituted by the logarithm of the required accuracy, for example, by ln1000 for 0.1%. The time interval tmeas is assumed to be the maximum; for Vin = Vcc this implies the following:

$$\begin{aligned} tconv = {} & ln100 \times Cm \times R1 \parallel R2 + \tau \times ln\, \frac{Vcc}{Vref\ (com)} + \tau \times ln100 \\ & + \tau \times ln\, \frac{Vcc}{Vref\ (com)} \end{aligned} \tag{11}$$

With the components of Figure 4 (right-hand circuit) the time interval tconv between two complete voltage measurements is ($\tau \approx R4 \times Cm$):

$$tconv = Cm \times \left(ln100 \times R1 \parallel R2 + 2 \times R4 \times ln4 + ln100 \times R4 \right)$$

$$\begin{aligned} tconv = {} & 82 \times 10^{-9} \times (4.6 \times 300 \times 10^{3} \parallel 470 \times 10^{3} + 2 \times 47 \\ & \times 10^{3} \times 1.386 + 4.6 \times 47 \times 10^{3}) \end{aligned} \tag{12}$$

$$tconv = 0.0975s$$

If 0.1% (10^{-3}) accuracy is required, the time interval tconv becomes 141 ms. By modifying the values of R1, R2, R4, and Cm, the time interval between two complete measurements can be widely changed. The component values of Figure 4 were chosen for a high-precision voltage measurement. The values of the components may be changed if lower accuracy is acceptable.

Mathcad is a registered trademark of MathSoft, Inc.

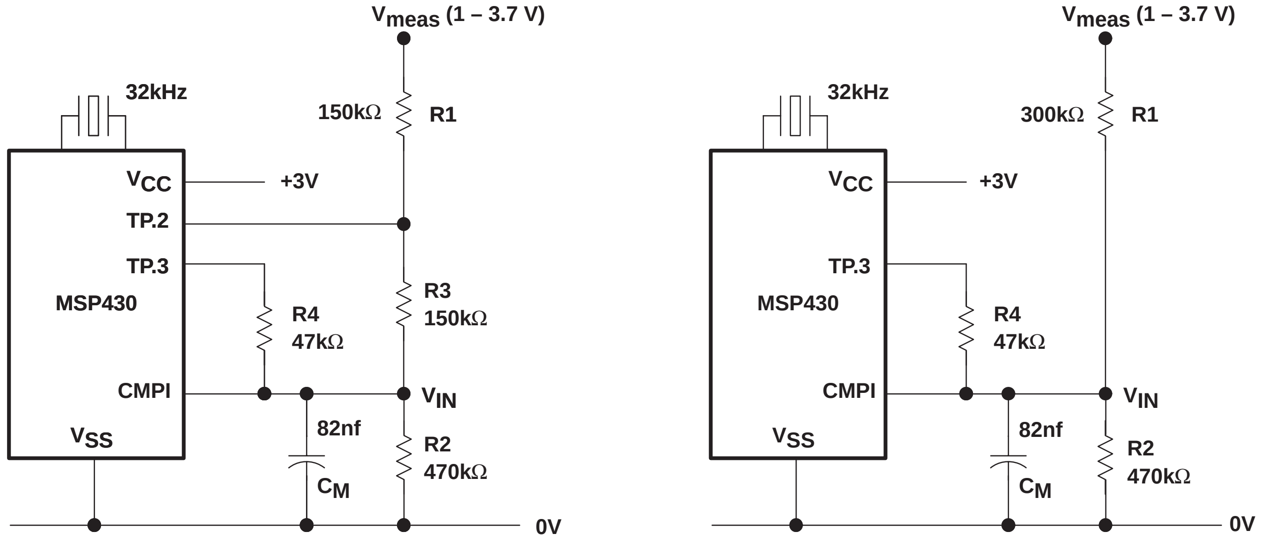
1.5 Applications

This section shows how to connect other voltage sources to the universal timer/port module. Different hardware configurations are necessary, depending on the structure of the external voltage source.

1.5.1 Voltage Measurement

Figure 4 shows two circuits to measure an external voltage Vmeas. As with all other circuits, the voltage reference is the supply voltage Vcc, which may be between 3 V and 5 V. If the supply voltage changes from 3 V, only resistor R1 needs to change. Two different circuits are shown; the influence of input voltage Vmeas is different during the conversion:

- For the right-hand circuit of Figure 4, the input voltage Vmeas also shows its influence during the reference measurement with Vcc (approximately R4/R1 here).
- For the left-hand circuit, the output TP.2 isolates the input voltage Vmeas from the reference measurement: TP.2 is always switched the same way as TP.3 (0 V, 3 V, Hi-Z). Once Cm is charged, the input voltage Vmeas has no influence on the conversion.



Voltage Measurement without influence by V_{meas}

Voltage Measurement

Figure 4. Voltage Measurement Circuits

Software Example: a voltage calculation is performed for the right-hand circuit shown in Figure 4. The measurements of tmeas and tvcc are performed as described above. Equation (6) is implemented in software.

The MSP430 floating-point package FPP4 is used for the calculations (32-bit format). All subroutines call FPP4 functions. See *The Floating Point Package* chapter in the MSP430 application report.

RAM word ADCref contains the 16-bit result (tvcc) of the Vcc measurement.

RAM word ADCmeas contains the 16-bit result (tmeas) of the Vmeas measurement.

Both time intervals are measured with MCLK cycles.

```
; Voltage measurement of Vmeas:
; Vmeas = factor * exp(((tmeas/tvcc) –1)* ln(Vcc/ Vref(com)))
; Where   factor = Vcc x (R1+R2)/R2
;
; Input:      ADCref:       Measured reference value Vcc: tvcc
;             ADCmeas:      Measured voltage value: tmeas
; Output:     Act. Stack    Calculated voltage Vmeas:  @SP
;
Calc_Volt     SUB   #4,SP              ; Reserve stack
       MOV    #ADCmeas,RPARG           ; ADC value of voltage tmeas
       CALL   #CNV_BIN16U              ; Convert to unsigned number
       MOV    @RPRES+,x                ; Store result to x. MSBs
       MOV    @RPRES+,x+2              ; LSBs
       MOV    #ADCref,RPARG            ; ADC value of Vcc tvcc
       CALL   #CNV_BIN16U              ; Convert to unsigned number
       MOV    #x,RPRES                 ; Address tmeas
       CALL   #FLT_DIV                 ; tmeas/tvcc
       JN     Calc_Error               ; Error
       MOV    #FLT1,RPARG              ; Address 1.0
       CALL   #FLT_SUB                 ; (tmeas/tvcc) – 1.0
       MOV    #FLTLN4,RPARG            ; Address Ln(Vcc/ Vref(com))
       CALL   #FLT_MUL                 ; [(tmeas/tvcc)–1]*ln(Vcc/Vref(com))
       CALL   #FLT_EXP                 ; exp[(tmeas/tvcc) – 1)*ln4]
       JN     Calc_Error
       MOV    #factor,RPARG            ; Address Vcc x (R1+R2)/R2
       CALL   #FLT_MUL                 ; Vmeas = factor * exp[...]
;
; Correction of Vmeas with calculated slope and offset
; Vmeas’ = factor*exp[(tmeas/tvcc)–1)*ln4]*slope + offset
;
       MOV    #Slope,RPARG             ; Address slope
       CALL   #FLT_MUL                 ; Vmeas * slope
       MOV    #Offset,RPARG            ; Address offset
       CALL   #FLT_ADD                 ; Vmeas’ = Vmeas * slope + offset
;
       MOV    @RPRES+,6(SP)            ; Corrected Vmeas on Stack
       MOV    @RPRES+,8(SP)            ; LSBs
       ADD    #4,SP                    ; Release stack
       RET                             ; Return with N = 0
;
; Calculation error (N = 1 after return): FFFF,FFFF result
;
Calc_Error MOV      #0FFFFh,6(SP)
       MOV    #0FFFFh,8(SP)
       ADD    #4,SP                    ; Correct stack
       SETN                            ; Set N–bit for error indication
       RET                             ; Return with N = 1
;
; factor describes supply voltage Vcc and resistor divider
;
factor .float 4.9148936                ; 3V * (300k+470k)/470k
FLTLN4 .float 1.38629436               ; ln Vcc/ Vref(com).  (nom. ln 4.0)
FLT1   .float 1.0                      ; Constant 1.0
```

1.5.2 Current Measurement

Current flowing through a shunt resistor can also be measured with the universal timer/port module. The voltages generated are small because of the normally-low resistance of the shunt (this is due to the dissipated power $I^2 \times$ Rshunt). In order to attain full resolution, there is no resistor divider to split the voltage across the shunt.

Figure 5 shows the current measurement circuit. The voltage across the shunt resistor ranges from –0.3 V to $V_{ref(com)}$ ($V_{ref(com)}$ is 0.25×Vcc for the MSP430). The value –0.3 V is the most negative voltage allowed as an MSP430 input. To be able to measure currents or voltages around the zero point (0 V), an inversion of the previous measurement method is necessary. Capacitor Cm is discharged to the voltage to be measured with respect to the 0 V potential. Then Cm is charged. The time interval is then measured during the charging until the comparator threshold $V_{ref(com)}$ is reached again. This measurement method shows a smaller resolution than the previous method (due to the smaller charge voltage range available), but it can also measure voltages around the zero point.

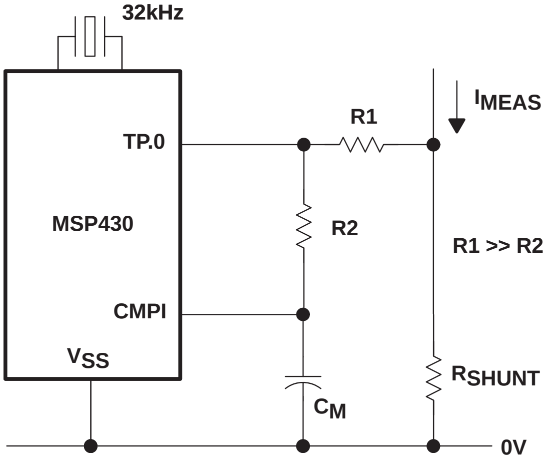


Figure 5. Circuit for the Current Measurement

Figure 6 shows the voltage across capacitor Cm during the measurement of two currents: Vin0 corresponds to a positive current, and Vin1 to a negative current. As described before, the measured time interval tvcc is used for reference purposes. The supply voltage Vcc is measured. The circuit above the voltage curve shows the influence of the TP0.0 state (Vss, Vcc, Hi-Z). The equation for the calculation of the current Imeas is:

$$Imeas = \frac{Vcc}{Rshunt} \times \left(1 - e^{\left(1 - \frac{tmeas}{tvcc}\right) \times ln\left(1 - \frac{vref\ (com)}{Vcc}\right)}\right) \tag{13}$$

Equation (13) looks complicated, but it can be substituted by the form:

$$Imeas = a + b \times e^{\frac{tmeas}{tvcc} \times 0.2876821} \tag{14}$$

where a and b are constants given by the values of the supply voltage and the shunt resistor.

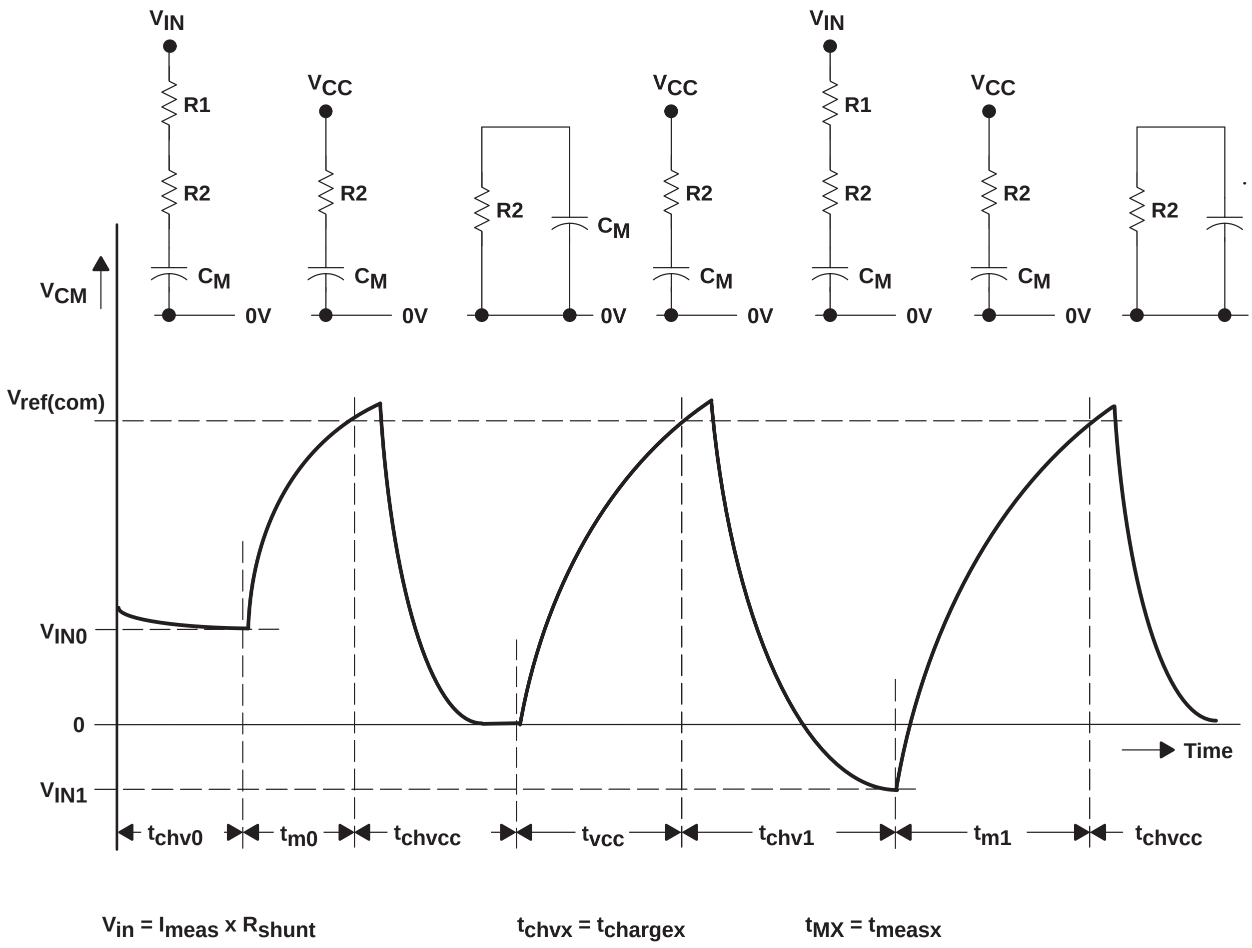


Figure 6. Current Measurement

The advantage of the circuit shown in Figure 5 is that the measurement value that represents the voltage 0 V (Vss) is exactly known: it is the value tvcc. This means that no additional measurements are necessary to find the zero point (Imeas = 0) of the circuit.

The resolution of the current measurement may be calculated using equation (15). For the current Imeas, the difference between the counter steps Δnin results in:

$$\Delta nin = \tau \times fMCLK \times \left(ln\left(1 - \frac{Vref\ (com) - Imeas \times Rshunt}{Vcc - Imeas \times Rshunt}\right) - ln\left(1 - \frac{Vref\ (com)}{Vcc}\right)\right) \quad (15)$$

The first logarithmic function shows the counter steps for the current Imeas; the second one shows the counter steps for a zero current. With R2 = 47 kΩ, Cm = 33 nF (τ = 1.55 ms), and fMCLK = 3.3 MHz, equation (15) results in 1036 counter steps per volt. This means that if a 1-A current flows through a 0.1 Ω, shunt resistor, the resolution is approximately 10 mA.

1.6 Conclusion

Despite being developed for the measurement of resistive sensors, the universal timer/port module also allows very accurate voltage and current measurements. The hardware necessary to implement this task is minimal: two resistors and one capacitor. Two different measurement methods were presented: the discharge method with its higher resolution, and the charge method with the possibility of measuring voltages around the zero point.

1.7 References

1. *MSP430 Family Architecture Guide and Module Library*, 1996 Literature Number SLAUE10B
2. MSP430 Application Report, 1998, Literature Number SLAAE10C
3. Data Sheet *MSP430x31x*, 1998, Literature Number SLAS165A

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