# Testing and Certification (01NNKOQ)

**Date of the examination: 28 January 2019**

**Student:**

Surname ______________________________

Name ______________________________

Code ______________________________

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## Question 1

The electrical network of an industrial plant (nominal length 2 km) has to be monitored to estimate the current harmonic distortion. The current that flows through the network has a root mean square (rms) value in the range (2 ÷ 50) A and a crest factor (peak to rms ratio) of 4.0. The available current sensors have a bandwidth of 2.5 kHz and an output voltage expressed as:

$$v_{\text{out}} = S \cdot i_{\text{IN}} + v_{\text{OFF}}$$

where $S$ = 0.1 mV/A, 0.05% and $v_{\text{OFF}} = 0 \pm 2\ \mu\text{V}$.

The main requirements are:

- current resolution: 40 mA
- current uncertainty: 200 mA
- measuring nodes 100 m away from each other;
- samples acquired at each node sent to a central PC, which is located at one end of the plant, where an FFT algorithm is implemented that has to provide a frequency resolution of 50 Hz;
- data has to be updated every 2 s.

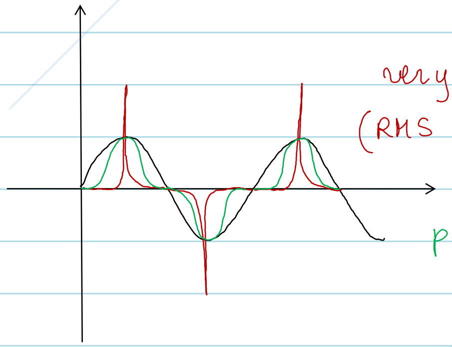
Design the data acquisition system providing details about conditioning circuitry, Analogue-to-Digital Converter and data-communication bus.

for the design problem multiple solutions exists
⇨ you have too meet the requirements

input quantity $I_{rms} = 2 \div 50 \text{ mA}$ ; $CF \triangleq \dfrac{I_{peak}}{I_{rms}} = 4$

for a sine wave as
$V_{rms} = \dfrac{V_{peak}}{\sqrt{2}}$ ⇨ $CF_{\substack{\text{sine}\\\text{wave}}} = \sqrt{2} \simeq 1.41$

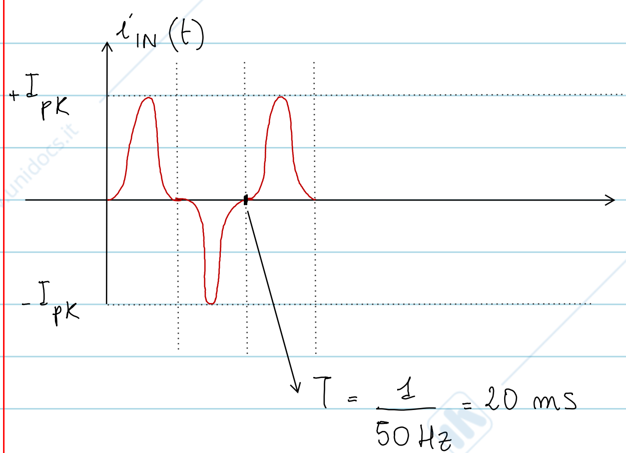
the crest factor is used to highlight the distortion of the signal



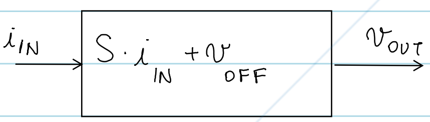
very high CF
(RMS related to energy of the signal ⇨ area beneath the waveform)
possible waveform with $CF \approx 4$

from the crest factor and RMS value it is possible to evaluate the peak value
$I_{peak} = CF \cdot I_{rms}$ ⇨ $I_{peak} \; (8 \div 200) \text{ A}$

the expected signal




we are working with an alternate signal
the current $i_{IN}$ at the input of the sensor has to be considered in the following range
$i_{IN} = (-200 \div 200) \text{ A}$




nominal estimation of the voltage output (nominal ⇨ $v_{OFF} = 0$)
$v_{OUT} = (-20 \div 20) \text{ mV}$

is it necessary to have something in between the output of the sensor and the input of the ADC ?

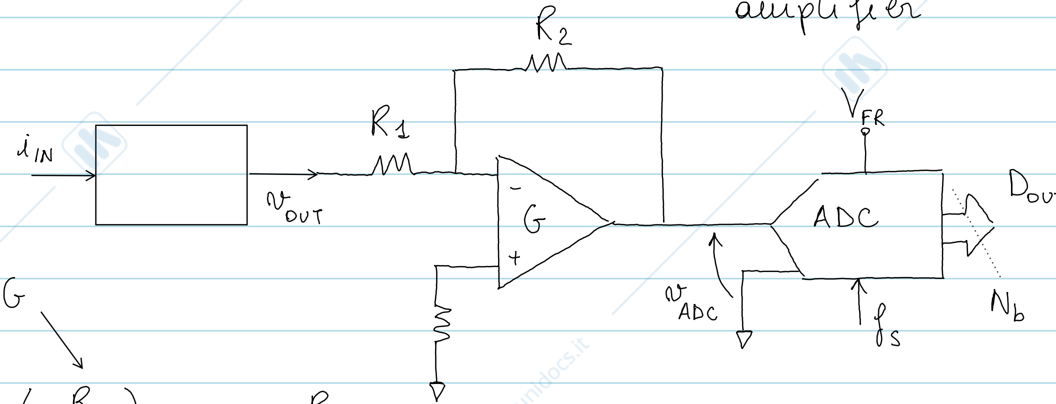
⇨ consider the amplitude of the output of the sensor convenient that the signal at the input of ADC is matched as well as possible to the input range of the ADC ⇨ ADC with full range similar to $(-20 \div 20)$ mV

common ADC full ranges $V_{FR}$ (both for unipolar / bipolar)

- 0.1 V
- 0.2 V
- 0.25 V
- 0.5 V
- 1 V
- 2 V
- 2.5 V
- 5 V
- 10 V

for this problem it could be fixed $V_{FR} \triangleq 2\,V$ bipolar (full scale $V_{FS} \triangleq 1V$)

convenient to put an amplifier between the sensor and ADC ⇨ inverting amplifier




$$v_{ADC} = v_{OUT} \cdot \overbrace{\left(-\frac{R_2}{R_1}\right)}^{G} = -v_{OUT}\frac{R_2}{R_1}$$

the minus sign corresponds to a phase inversion as we are interested in amplitudes value it is not a problem

$$|G_{MAX}| = \frac{V_{FS}}{\max\{v_{OUT}\}} = \frac{1\,V}{0{,}02\,V} = 50$$

fixing the resistors $R_1, R_2$ in order to obtain $|G| < |G_{MAX}|$

$R_1 \triangleq 1\,k\Omega$ , $R_2 \triangleq 47\,k\Omega$ ⇨ $G = 47$

for $R_3$ to minimize the offset at the output of the amplifier $R_3 \triangleq R_1 /\!/ R_2$

fixing the sampling rate of the ADC
⇨ maximum frequency content of the signal ⇨ sensor bandwidth
$f_{MAX} \simeq BW = 2.5\ KHz$

as $f_S \geq 2.5\, f_{MAX}$ ⇨ $f_S \triangleq 4\, f_{MAX} = 10\ K\frac{Sa}{s}$ large $f_S$ has consequences
(Nyquist)

estimation of $v_{ADC}$ range
$v_{ADC} = v_{OUT} \cdot |G| = v_{OUT} \cdot 47 = (-0.94 \div 0.94)\ V$

estimation of Nb ⇨ we need to fix $V_q$
$v_{ADC} = (S \cdot i_{IN} + v_{OFF})$

$$\Delta v_{ADC} = \left| \frac{\partial v_{ADC}}{\partial i_{IN}} \right| = \Delta i_{IN}$$ design requirement current resolution ⇨ $\Delta i_{IN} = 0.04\ A$

$\Delta v_{ADC} = S G \Delta i_{IN} \cong 0.19\ mV$
so the ADC has to assure a resolution $V_q \leq \Delta v_{ADC}$

as $V_q = \frac{V_{FR}}{2^{Nb}} \leq \Delta v_{ADC}$ ⇨ $2^{Nb} \geq \frac{V_{FR}}{\Delta v_{ADC}} \sim 10638$ levels

$Nb = \lceil \log_2 2^{Nb} \rceil = 14$

I/O relationship $D_{OUT} = \frac{v_{ADC}}{V_q} = \frac{S \cdot i_{IN} + v_{OFF}}{V_q} \cdot \frac{R_2}{R_1}$

$$\max\{D_{OUT}\} = \frac{\max\{v_{ADC}\}}{V_q} = \frac{0.94}{2/2^{14}} \simeq 7700\ LSB$$

comparing to the 14 bit bipolar ADC range $(-2^{13} \div 2^{13} - 1)$ LSB
which corresponds to $(-8096 \div 8095)$ LSB

uncertainty requirements ⇨ calibration function

$$i_{IN} = \frac{1}{S} D_{OUT} \cdot V_q \cdot \frac{R_1}{R_2} - v_{OFF}$$ this represents the measuring model

worst case approach for the design problem as requirements on the input must be assured

$$\delta i_{IN} = \left|\frac{\partial i_{IN}}{\partial S}\right| \delta S + \left|\frac{\partial i_{IN}}{\partial D_{OUT}}\right| \delta D_{OUT} + \left|\frac{\partial i_{IN}}{\partial R_1}\right| \delta R_1 + \left|\frac{\partial i_{IN}}{\partial R_2}\right| \delta R_2 + \left|\frac{\partial i_{IN}}{\partial v_{OFF}}\right| \delta v_{OFF}$$

sensitivity coeff. can be computed

$\delta S$, $\delta v_{OFF}$ are known value

design requirements ⇨ $\delta i_{IN} \leq 0{,}2\ A$

computing $\left|\frac{\partial i_{IN}}{\partial S}\right| \delta S$ and $\left|\frac{\partial i_{IN}}{\partial v_{OFF}}\right| \delta v_{OFF}$ and take into account that $\delta i_{IN} \leq 0{,}2\ A$ we have a residual uncertainty to split between $\left|\frac{\partial i_{IN}}{\partial R_1}\right| \delta R_1$, $\left|\frac{\partial i_{IN}}{\partial R_2}\right| \delta R_2$, $\left|\frac{\partial i_{IN}}{\partial D_{OUT}}\right| \delta D_{OUT}$

as the sens. coeff. are known

$$\left|\frac{\partial i_{IN}}{\partial D_{OUT}}\right| = \frac{V_q}{S} \cdot \frac{R_1}{R_2} = 0.026\ \frac{A}{LSB} \triangleq C1$$

$$\left|\frac{\partial i_{IN}}{\partial R_1}\right| = \frac{\max\{D_{OUT}\}\, V_q}{S\, R_2} = 0.2\ \frac{A}{\Omega} \triangleq C2$$

$$\left|\frac{\partial i_{IN}}{\partial R_2}\right| = \frac{\max\{D_{OUT}\}\, V_q\, R_1}{S\, R_2} = 4.3 \cdot 10^{-3}\ \frac{A}{\Omega} \triangleq C3$$

$$\left|\frac{\partial i_{IN}}{\partial S}\right| = \frac{\max\{D_{OUT}\}\, V_q}{S^2} \frac{R_1}{R_2} = 2 \cdot 10^{6}\ \frac{A}{V/A} \triangleq C4$$

$$\left|\frac{\partial i_{IN}}{\partial v_{OFF}}\right| = \frac{1}{S} = 1 \cdot 10^{4}\ A/V \triangleq C5$$

$$\delta i_{IN} = c_1 \delta D_{OUT} + c_2 \delta R_1 + c_3 \delta R_2 + c_4 \boxed{\delta S} + c_5 \boxed{\delta v_{OFF}} \leq 0.2\ A$$

known

design requirement

$$c_4 \delta S = c_4 \frac{0.05}{100} \cdot S = 0.1\ A$$

$$c_5 \delta v_{OFF} = c_5 \cdot \frac{1}{S} = 0.02\ A$$

so it must be $c_1 \delta D_{OUT} + c_2 \delta R_1 + c_3 \delta R_2 \leq (0.2\,A - 0.12\,A) = 80\ mA$

by considering $c_1 \delta D_{OUT} + c_2 \delta R_1 + c_3 \delta R_2 = 80\ mA$

so now we must assign values for $c_1 \delta D_{OUT}$, $c_2 \delta R_1$, $c_3 \delta R_2$
as the ADC is normally the largest uncertainty contribution
$0.5 \cdot 80\,mA = c_1 \delta D_{OUT}$, $0.25 \cdot 80\,mA = c_2 \delta R_1 = c_3 \delta R_2$

$$\delta D_{OUT} = \frac{c_1 \delta D_{OUT}}{c_1} = \frac{0.5 \cdot 80\,mA}{c_1} \cong 1.5\ LSB$$

$$\delta R_1 = \frac{0.02\,A}{c_2} = 0.1\ \Omega \Rightarrow \varepsilon_{R_1\%} = 0.01\%$$

$$\delta R_2 = \frac{0.02\,A}{c_3} \simeq 4.7\ \Omega \Rightarrow \varepsilon_{R_2\%} = 0.01\%$$

different abs. uncertainty as it depends to the resistor value

same relative uncertainty as the same residual uncertainty was assigned to the two resistors of the amplifier

for the ADC $\Rightarrow \delta D_{OUT} \leq 1.5\ LSB$
it's possible to actuate zero/gain compensations

implementation of the BUS
$\Rightarrow$ how many bits each node has to transmit to the central unit? $\Rightarrow$ transmission rate?

starting with the nuber of nodes $\Rightarrow N_{NODES} = \dfrac{L}{\Delta L} = \dfrac{2\ Km}{0.1\ Km} = 20$

processing of the unit ⇨ FFT algorithm resolution $\Delta f = 50\ Hz$
the frequency resolution is the reciprocal of the acquisition interval
each node must acquire samples of the current signal for
$\Delta t = \frac{1}{\Delta f} = 20\ ms$

number of samples collected at each node
$N_{samples} = f_s \cdot \Delta t = 200\ Sa$

converting samples ⇨ bits
$N_{bit} = N_{samples} \cdot N_b = 200 \cdot 14 = 2800$ bit (no protocol overhead)

transmission rate $TR = \frac{N_{nodes} \cdot N_{bit}}{\text{update rate}} = \frac{20 \cdot 2800}{2} = 28\ Kbit/s$
sys requirem.

$f_s$ (ADC) ↑ , $N_b$ (ADC resolution) ⇨ TR ↑
minimize $f_s$, $N_b$ ⇨ minimize TR

as TR < 31.25 Kbit/s ⇨ $\begin{cases} \text{Fieldbus} \\ \text{Profibus PA} \end{cases}$

possible choice: Fieldbus NB max 1 Km, max 10 nodes
⇨ 2 sections (10 nodes / section of 1 Km)
1 repeater