Changes in a basic course of electrical measurement caused by development in microelectronics

V Haasz
Czech Technical University in Prague, Fac. of Electrical Eng., Dept. of Measurement, Technicka 2, 166 27 Prague, Czech Republic
E-mail: haasz@fel.cvut.cz

Abstract. Changes in electrical measurement and instrumentation caused by a development in microelectronics should be reflected also in education. This trend runs more than 50 years. At present it relates especially to substitution of analogue signal processing by digital processing of sampled signal in a number of measuring instruments. The actual essential changes in the basic course of electrical measurement at the Faculty of Electrical Engineering of the Czech Technical University (CTU) in Prague corresponding to this progress in last years are presented.

1. Introduction
The first changes in electrical measurement caused due to development in microelectronics appeared with coming of monolithic operational amplifiers and first analogue-digital converters in seventies of the last century. Their further development gradually leads to a replacement of analogue instruments for current and voltage measurement (ammeters, voltmeters etc.) and Wheatstone bridges for resistance measurement by digital multimeters, replacement of AC bridges for capacitance and inductance measurement by digital LCR meters etc. A higher sampling rate of AD converters made it possible to develop digitizing scopes and special methods of AD conversion improve accuracy of digital voltmeters so that they could replace potentiometers for a precise DC measurement [1], [2]. In addition, development of microcontrollers made possible to implement methods of digital signal processing directly in measuring instruments in the last years. Nevertheless the “classical” (out of date) methods remained partially in some courses or books till the first years of the 21st century [3], [4].

The progress mentioned above has influenced education of measurement and instrumentation and also evidently curricula of basic courses of electrical measurement and instrumentation before now. The changes made more than 20 years ago reflected this development, but analogue instruments (which were still used) remained as an indispensable part there. At present, when signal digitalization and digital signal processing are leading principles of a number of instruments [5] and industrial partners ask for this knowledge by graduates, curriculum of basic courses in measurement and instrumentation should be radically changed again. The actualised structure of the basic course, which it took into account, was implemented at the faculty of electrical engineering meanwhile in one study program three years ago and in the further two programs it is prepared for the academic year 2014-15.

The basic course Electrical measurement and instrumentation for students of the bachelor study stage at the Faculty of Electrical Engineering of CTU in Prague is offered in the study programs...
Communications, Multimedia and Electronics (in the 3rd semester) and Electrical Engineering, Power Engineering and Management (in the 2nd semester) in the amount 2 hours of lectures + 2 hours of labs per week. The course Sensors and measurement (in the 4th semester) intended for study program Cybernetics and Robotics in amount of 3 hours of lectures + 2 hours of labs per week covers in addition a significant part concerning sensors. This course arose after last re-building of study programs by combination of two previous (separated) courses Electrical measurement and Sensors and transducers [8] 3 years ago.

2. New approach to a structure of basic course in electrical measurement

In connection with the radically rebuilding of the study program Cybernetics and Robotics and creation of the new course Sensors and measurement, the new approach was implemented. The changes respected the requirement to give students the knowledge that they will need after finishing their master study, thus at 4 years or later after ending this course. Especially applications of digital signal processing in instrumentation were taken into account. Analogue instruments are mentioned only very briefly (from a historical point of view). Digital signal processing relates especially to methods and instruments for measuring of active electrical quantities. The chapters relating methods and instruments for measuring of resistance, capacitance and inductance were updated only less now (the main changes were done already before).

Compared to the classical approach from the end of last century (see e.g. [6], [7]), when the first part of the course was devoted to the instruments and methods for voltage, current and power measurement including principles of analogue instruments, the new approach started with signal digitalization and corresponding methods and devices. The principles of AD conversion are explained including their properties. It enables to apply the suitable kinds of ADC in different applications in measuring instruments and systems. Since the course is user-oriented, the teaching process remains based on the way “the knowledge of principle” → “properties of method” → “the area of their application”.

Principles of sampling and quantization are briefly explained initially including the Shannon theorem and a problem of an aliasing. Description of methods, which enables to convert analogue voltage signal to sequence of numbers follows. Three basic sorts of AD converters are explained:
- integrating (dual slope, voltage-frequency and Σ–Δ);
- successive approximation;
- parallel comparison (flash).

Their properties (sampling rate, resolution, disturbance immunity) and typical utilizations corresponding to them are mentioned. This knowledge is used in following lectures concerning electrical quantities measurement.

3. Changes in selected parts of the course

In the part concerning DC voltage or current measurement is accented a possibility of serial disturbance suppression using integrating principle that is used in a number of modifications in the most of multimeters as far as the integrating time is equal to period (or integer number of period) of a disturbing signal (usually from a power net). A typical application of the integrating ADC, which uses a voltage → frequency conversion is presented in the part concerning electrical energy measurement. It concerns of watt-hour meters with analogue multiplication of voltage and current, where output voltage of multiplier is proportional to the power while the number of output pulses is proportional to integral of it, thus the energy. Easy possibility of a change of the ratio resolution/sampling rate is underlined for Σ–Δ ADC in selected applications.

Since not only the analogue circuits for determination of parameters of AC or AC+DC signals (active rectifiers, RMS to DC converters, analogue multipliers) but a number of instruments utilize digital signal processing for measurement of RMS value, rectified mean value and DC component of voltage or current, active power etc., also typical algorithms for their calculation from the sampled
signal are presented in the part concerning AC voltage, current and power measurement. The describer simple algorithms are based on changes from integration to summation, accordingly

\[ U_{\text{RMS}} = \frac{1}{T} \int u^2(t) \, dt \Rightarrow U_{\text{RMS}} \approx \sqrt{\frac{1}{N} \sum_{i=1}^{N} u_i^2} \]  

(similarly for \( I_{\text{RMS}} \)) and using the same way, the resultant relation for the rectified mean value can be derived to be

\[ U_{\text{AVG}} = \frac{1}{N} \sum_{k=0}^{N-1} |u_k| \]  

for the DC component (mean value) it is

\[ U_{\text{DC}} = \frac{1}{N} \sum_{k=0}^{N-1} u_k \]  

and for active power is valid

\[ P = \frac{1}{T} \int u(t) i(t) \, dt \Rightarrow P \approx \sqrt{\frac{1}{N} \sum_{i=1}^{N} u_i i_i} \]  

where \( N \) is the number of samples per period or per integer number of periods.

Also the parts concerning frequency and phase shift measurement and voltage vector measurement were completed by corresponding algorithms for determination of measured values from a sequence of samples. In this case only the simplest methods are presented. At the same time it is underlined that while in the previous cases the mentioned methods can be used also for non-sinusoidal signals, the presented simplest methods of frequency and phase shift measurement are applicable only for limited types of signals. The period \( T \) and thus also the frequency \( f = 1/T \) can be calculated from a sequence of discrete values (samples) of \( u_k \) (see figure 1). The values \( T \) can be approximately determined as

\[ T = (k_2 - k_1) T_s \]  

where \( k_1 \) is the sample number after the 1\(^{\text{st}} \) zero crossing of \( u \), \( k_2 \) is the sample number after the 2\(^{\text{nd}} \) zero crossing of \( u \) (with the same sign of derivation) and \( T_s \) is sampling interval.

In the case of two sinusoidal signals the phase difference \( \varphi \) can be found as

\[ \varphi = \frac{2\pi t_0}{T} \text{ (rad)} , \quad \text{or} \quad \varphi = \frac{360 t_0}{T} \text{ (°)} \]  

where \( t_0 \) is the time delay (time shift) of the zero crossing (with the positive derivative) of the signals.

**Figure 1.** Determining the frequency from a sampled waveform

**Figure 2.** Determining the phase shift from sampled waveforms
$x_1(t)$ and $x_2(t)$ and $T$ is the period time. The ratio of $t_0/T$ can be calculated from a sequence of discrete values (samples) of $u_{1,k}$ and $u_{2,k}$. (see figure 2). The values of $t_0$ and $T$ can be approximately determined as

$$t_0 = (k_2 - k_1) T_S \quad \text{and} \quad T = (k_3 - k_1) T_S \quad (7)$$

where $k_1$ is the sample number after the 1\textsuperscript{st} zero crossing of $u_1$, $k_2$ is the sample number after the 1\textsuperscript{st} zero crossing of $u_2$ (with the same sign of derivation), $k_3$ is the sample number after the 2\textsuperscript{nd} zero crossing of $u_1$ (with the same sign of derivation) and $T_S$ is sampling interval. Then

$$\varphi = 2\pi \frac{t_0}{T} = 2\pi \frac{k_2 - k_1}{k_3 - k_1} \quad . \quad (8)$$

The Fourier transform which enables to determined the frequency spectrum of non-sinusoidal signals is mentioned only in brief.

Contemporary to the explanation of the methods mentioned above the students are got acquainted with the fact that they are implemented not only in professional up-to-date stand-alone measuring instruments (in digitizing oscilloscopes, power analyzers etc.) but they can be used also in small measuring systems with embedded microcontrollers designed for special applications (some examples of them developed for industrial partners are presented).

A separate chapter concerning applications of microcontrollers in instrumentation was also added to the curriculum. Principles of autocalibration and software calibration and a difference between these two methods are explained for example.

The new approach is used not only in lectures, but also in labs. E.g. a commercial digital clamp-on wattmeter that measures the active and apparent power, the RMS value of voltage and current, the power factor and the frequency based on signal sampling and following digital processing is used in comparison to classic analogue instruments. It shows possibility how to replace several classical instruments that use analogue signal processing by one instrument which use signal sampling and following digital processing.

An application of a digitizing scope in magnetic measurement is presented in another task. Permeability and the iron loss of a ferromagnetic material (ring specimen) are measured by the sinusoidal voltage magnetizing (thus by τε: non-sinusoidal magnetizing current). The peak value of the magnetizing current (necessary for $H_{\text{max}}$ calculation) is determined from the peak-peak value of a voltage drop on a serial resistor, which is measured automatically by a digitizing scope. Similarly is determined the value of induced voltage, which is necessary for $B_{\text{max}}$ determination. It is currently used application, of course. However, the embedded microcontroller in the digitizing scope with a corresponding firmware enables also the iron loss measurement because a number of digitizing scopes enable multiplication of signals of two input channels and following determination of the mean value of the result, thus the active power.

4. Conclusion

Knowledge of methods used for digital signal processing in up-to-date commercial measuring instruments is important. It enables not only to understand their principles, advantages and disadvantages, but also their usage in non-traditional applications, e.g. active power measurement using a digitizing scope mentioned above etc. These methods, which are now presented already in the basic course of electrical measurement, can be applied also in simple PC measuring systems based on a multifunction AD module or in embedded systems using a microcontroller with one or more analogue inputs, too.

The positive response of this last actualization of curricula of basic course of electrical measurement and instrumentation in the study program Cybernetics and Robotics both of industrial partners and of students confirm eligibility of this way. Therefore these changing are implementing now also in the further two programs and will be applied already in the academic year 2014-15.
5. References

[1] Coombs C F 1995 *Electronic Instrument Handbook* (New York: McGraw-Hill, Inc)
[2] Witte R A 1993 *Electronic Test Instruments* (Englewood Cliffs: Prentice Hall PTR)
[3] Biesen L V 2009 Metrology Education in the Curriculum of the Accredited Bachelor in
   Engineering Programme of the “Vrije Universiteit Brussel” *Fundamental and Applied
   Metrology: Proc. XIX IMEKO World Congress* (Lisbon Portugal, 6-11 September 2009)
   pp 10-14
[4] Northrop R B 2005 *Introduction to Instrumentation and Measurements (2nd edition)* (New York:
   Taylor & Francis)
[5] Placko D *Fundamentals of Instrumentation and Measurement* (London: ISTE Ldt)
[6] Schrüfer E *Grundpraktikum Elektrische Messtechnik* (Munich: Technische Universität
   München)
[7] Zwicky R, Weiler J 1987 *Messtechnik I, II* (Zürich: AMV Verlag)
[8] Haasz V 2002 Changes in Education of Measurement and Instrumentation at CTU in Prague
   Caused by Implementation of Bologna Declaration *Proc 12th IMEKO TC4 International
   Symposium Electrical Measurements and Instrumentation* (Zagreb, Croatia 25–27
   September, 2002) pp 535-538