Chapter 4

VOLTAGE AND CURRENT CALIBRATORS

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4.1. Introduction

The first idea of the voltage calibrator was presented in the IEC document (IEC 443, 1974), where the calibrator was named a *stabilized supply apparatus for measurement*, whose scheme is presented in Fig. 4.1. This scheme explains the construction and

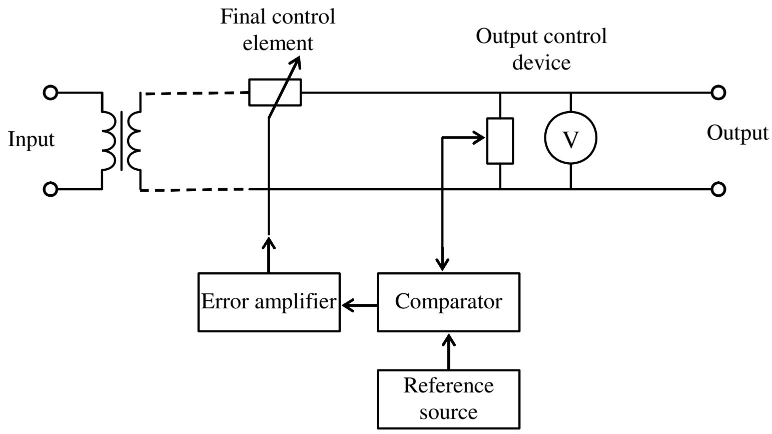

Fig. 4.1. Functional component diagram of a supply apparatus with a stabilized voltage by closed loop stabilization (scheme of the voltage calibrator)

"energetic" definition of the calibrator – the calibrator is an apparatus which takes electrical energy from a supply source and supplies the electrical energy, in a modified form, to one or more loads and in which one or more of the output quantities are stabilized. The input of the calibrator is connected to a power network.

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The calibrator consists of the following items:

- the final control element, which controls the output voltage to a specified value,
- the reference source – a source of voltage to the value of which the output in closed loop stabilization is referred,
- the comparator, which compares the value of the output voltage with a reference voltage and produces a difference signal,
- the error amplifier, which amplifies a difference signal (error signal),
- the output control device, which measures the output voltage.

This chapter presents the main ideas and theoretical problems which were solved by the authors to implement multifunction calibrators, three-phase power calibrators and industrial signals calibrators.

4.2. Static model of the voltage calibrator

4.2.1. Definitions of the calibrator

The Polish DC and AC voltage calibrator definitions were published in the instructions issued by the Polish Central Office of Measures at the end of 1970 (DzNiM, 1978). The voltage calibrator is an electronic control voltage source which has possibility to obtain the output voltage with a specified value and accuracy without the necessity of carrying out measurements and manual corrections. This “information” definition of the calibrator is up-to-date and may be expanded for electrical values calibrators such as current calibrators, phase angle calibrators, power and energy calibrators, and even resistance, capacity and inductance calibrators.

In the next calibrator definition (DzNiM, 1984) – voltage, current, power and resistance calibrators are devices which have the possibility to obtain the output quantities value according to digital setting without the necessity of performing measurements and corrections. A general and simple functional scheme of the calibrator is shown in Fig. 4.2 and consists of the following blocks:

- the Digital to Analogue Converter, DAC, which converts the input quantity value X (input setting) in a digital form to the output quantity value Y (output quantity) in an analogue form,
- the readout device for the indication of the input setting X or the output quantity value Y,
- the supply source, which, according to the “energetic” definition, takes electrical energy from a power network or battery and supplies it to the DAC and the readout device.

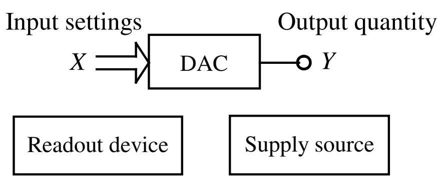


Fig. 4.2. Simple functional scheme of the calibrator according to the definition

4.2.2. Model of the multifunction (DC and AC voltage and current) calibrator

A block scheme of the voltage and current calibrator model (Olencki, 1991; Olencki and Szmytkiewicz, 1999; Szmytkiewicz, 2000) is shown in Fig. 4.3. It consists of digital and analogue parts. The forward branch, which transfers the input setting X to the output quantity Y, consists of two converters: the digital to digital converter (control system) and the multi range digital to analogue converter (digitally programmed voltage and current source).

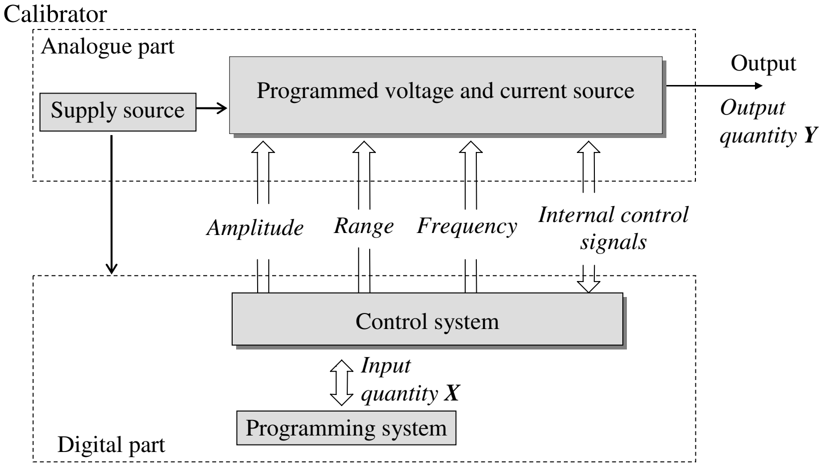


Fig. 4.3. Block scheme of the calibrator model

The transfer function, which describes mathematically the relationship between output and input signals of both converters, is linear, therefore the nominal transfer function $Y_N = f(X)$ of the calibrator model is (Olencki and Szmytkiewicz, 1999):

$$Y_N = X. \tag{4.1}$$

The real transfer function $Y_R = f(X)$ of the calibrator is

$$Y_R = (\delta_M Y + 1)X + \Delta_A Y, \tag{4.2}$$

where $\Delta_A Y$ is the additive part of the error, and $\delta_M Y$ is the multiplicative part of the error.

The error equation of the calibrator is the subtraction of the real and nominal transfer functions:

$$\delta Y = \delta_M Y + (\Delta_A Y / X), \tag{4.3}$$

and describes static features of the calibrator.

4.2.3. Open structure of the calibrator

The typical open structure of the DC and AC voltage and current calibrator is illustrated in a block diagram form in Fig. 4.4 and consists of the digital to analogue converter DAC and the Output System OS. The output system can be

- a voltage amplifier in DC voltage calibrators,
- a transconductance amplifier in DC current calibrators,
- a DC to AC converter plus an AC voltage amplifier in AC voltage calibrators,
- a DC to an AC converter plus AC transconductance amplifier in AC current calibrators.

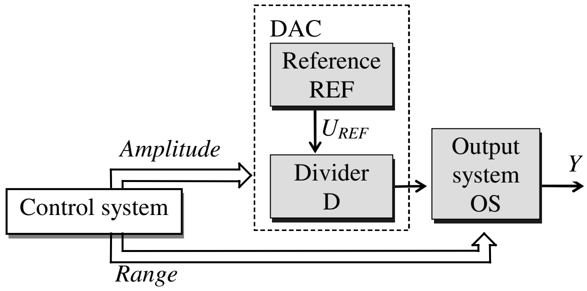


Fig. 4.4. General block diagram for an open structure calibrator with a DAC

The nominal transfer function and error equation of the open structure are (Olencki and Szmytkiewicz, 1999):

$$Y = U_{\mathrm{REF}}\, K_{\mathrm{D}}\, K_{\mathrm{OS}}, \tag{4.4}$$

$$\delta Y = \delta U_{\mathrm{REF}} + \delta K_{\mathrm{D}} + \delta K_{\mathrm{OS}} + \frac{\Delta U_{\mathrm{D}} + \Delta U_{\mathrm{OS}}}{U_{\mathrm{REF}}\, K_{\mathrm{D}}}, \tag{4.5}$$

where δU_{REF} is the error of the reference voltage U_{REF}, δK_{D} is the multiplicative error of the divider D, ΔU_{D} is the additive error of the divider D referenced to its output, δK_{OS} is the multiplicative error of the output system, and ΔU_{OS} is additive error of the output system OS referenced to its input.

The open structure is very simple but the error equation contains errors of all blocks of the structure, particularly output system errors: δK_{OS} and ΔU_{OS}.

4.2.4. Closed loop structure of the calibrator and error analysis

The closed loop structure of the AC calibrator is illustrated in Fig. 4.5 and consists of the DAC and the output system OS, as presented in Fig. 4.3. The output system OS uses a single-loop control system with a comparison of DC signals. The DAC's output voltage, proportional to the amplitude setting, is compared with a DC voltage proportional to the output quantity Y from a feedback branch. The feedback consists of the sense system SS and the AC to DC converter (in the AC calibrator). The sense system measures the output voltage or current Y, by means of precision voltage dividers or current shunts. Any difference between the two comparator inputs is amplified by the controller CTR, to produce a controlling signal for driving the output converter DC to AC (DC/DC in the DC calibrator) and the power amplifier PA. The output of the DC/AC converter consists of a generator G, which generates a fixed, low-distortion sine wave, and a modulator M, which is a voltage controlled divider.

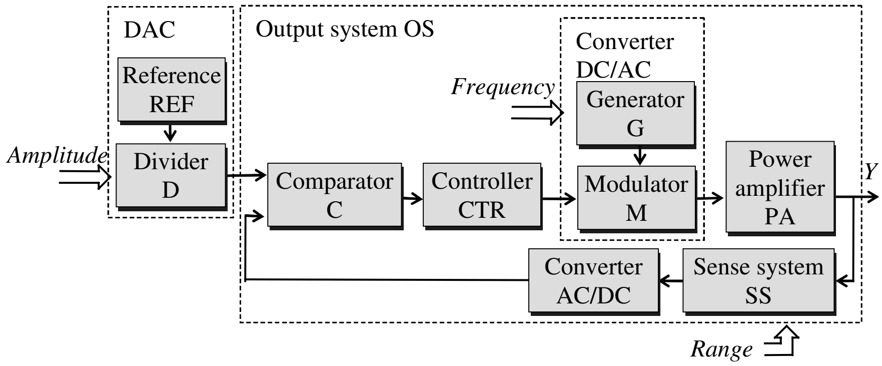


Fig. 4.5. AC calibrator's block diagram for a closed loop structure

In proportional plus integral feedback control systems with astatic control characteristics, the controller CTR consists of an integrator. The error equation of this system is

$$\delta Y = \delta U_{\mathrm{REF}} + \delta K_{\mathrm{D}} - \delta K_{\mathrm{SS}} - \delta K_{\mathrm{ACDC}} + \frac{\Delta U_{\mathrm{D}} + \Delta U_{\mathrm{C}} - \Delta U_{\mathrm{SS}}\, K_{\mathrm{ACDC}} - \Delta U_{\mathrm{ACDC}} + \Delta U_{\mathrm{CTR}}/K_{\mathrm{C}}}{U_{\mathrm{REF}}\, K_{\mathrm{D}}}, \tag{4.6}$$

where δU_{REF}, δK_{D}, ΔU_{D} are multiplicative errors of the voltage reference and divider and additive error of the divider, which represents the accuracy of the DAC, ΔU_{C} is the additive error of the comparator C with reference to its input, δK_{UN}, ΔU_{UN} are multiplicative and additive errors of the sense system SS with reference to its output, δK_{ACDC}, ΔU_{ACDC} are multiplicative and additive errors of the AC to DC converter, ΔU_{UC} is the additive error of the controller (integrator), and K_{C} is the amplitude gain of the comparator C.

The relation (4.6) shows that errors of blocks between the controller and the calibrator output are absent. This is the property of proportional plus integral feedback control systems with astatic control characteristics.

4.3. Dynamic properties of calibrators using the closed loop structure

The AC voltage calibrator may be presented as an automatic control system illustrated ln Fig. 4.6 (Olencki and Szmytkiewicz, 1999), where U_{DAC} is the DAC's output voltage, T_{CTR} is the controller's time constant, T_{ACDC} is the AC/DC converter's time constant.

The best output transient is when

$$\frac{K_{\mathrm{C}}\, K_{\mathrm{DCAC}}\, K_{\mathrm{SS}}\, K_{\mathrm{ACDC}}}{T_{\mathrm{CTR}}} = \frac{1}{4\, T_{\mathrm{ACDC}}}. \tag{4.7}$$

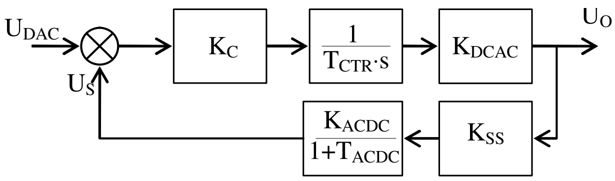


Fig. 4.6. AC voltage calibrator as an automatic control system

Settling time (transient recovery time) as an answer to a step change of the setting is computed from the AC calibrator dynamic equation:

$$t_{\mathrm{O}} \geq \frac{K_{\mathrm{C}}}{f\ \mathrm{THD}}, \qquad \text{for } K_{\mathrm{C}} \gg 1, \tag{4.8}$$

$$t_{\mathrm{O}} \geq \frac{1}{2f\sqrt{\mathrm{THD}}} \ln\frac{4}{\delta}, \quad \text{for } K_{\mathrm{C}} \approx 1, \tag{4.9}$$

where f is the frequency of the output signal, THD is the total harmonic distortion of the output signal, and δ represents error limits placed around rated output value.

From the following DC calibrator dynamic equation the settling time of the DC calibrator using a DC/AC/DC converter in the output system of the calibrator can be calculated:

$$t_{\mathrm{O}} \geq \frac{2K_{\mathrm{C}}}{f_{\mathrm{G}}\mathrm{PARD}}, \qquad \text{for } K_{\mathrm{C}} \gg 1, \tag{4.10}$$

$$t_{\mathrm{O}} \geq \frac{1}{f_{\mathrm{G}}\mathrm{PARD}} \ln\frac{4}{\delta}, \quad \text{for } K_{\mathrm{C}} \approx 1, \tag{4.11}$$

where f_{G} is the converting frequency of the DC/AC/DC converter, and PARD is the periodic and random deviation of an output quantity from its average value.

The equations of dynamic properties (4.8)–(4.11) (Olencki and Szmytkiewicz, 1999) describe limitations and settling time short cut possibilities for calibrators made by means of one closed loop, closed tracking structure with PI control and output stage designed by means of a DC/AC converter for an AC calibrator and a DC/AC/DC converter for a DC calibrator.

4.4. Digital to analogue converters used in calibrators

4.4.1. Basic requirements

Errors of the DAC's reference and divider are included in the error equations (4.5) and (4.6) of the calibrators, which work on the basis of open and closed loop structures. DACs used in multifunction calibrators have high resolution, from 18 to 24 bits, and are built by means of applying the precision DC voltage reference source and of the digitally programmed precision divider.

In the first calibrators there were applied D/A converters with a resistive divider. Today, those converters are used as integrated circuits in calibrators with low and medium resolution of settings up to 16 bits e.g. in industry signals calibrators, or with low and medium accuracy up to 0,01%, e.g. in three phase power calibrators.

4.4.2. PWM DACs

Most calibrators use D/A converters based on Pulse-Width Modulation, PWM, (Fluke, 1979; Grimbleby, 2004) idea illustrated in Fig. 4.7. The DAC consists of digital and analogue sections. The digital section uses a PWM converter to generate a digital waveform with a mark/space ratio (duty cycle τ/T) proportional to the input setting S_{IN}. This waveform is converted to an analogue signal by a fast switch with precisely known resistance, and law-pass filtered by a τ/T to DC converter.

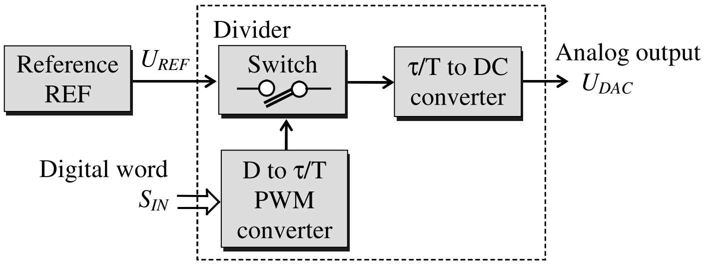


Fig. 4.7. Block diagram of the PWM DAC

The average analogue output voltage U_{DAC} is

$$U_{\mathrm{DAC}} = U_{\mathrm{REF}} \frac{\mathrm{SIN}}{2^n}, \tag{4.12}$$

where S_{IN} is a n-bit binary word. The frequency of the PWM waveform is

$$f_{\mathrm{PWM}} = f_{\mathrm{C}}/2^n, \tag{4.13}$$

where f_{C} is the frequency of a clock. Components at the f_{PWM} frequency must be removed by low-pass filtering. Filter cutt-off frequency must be much less than PWM frequency the f_{PWM} to achieve sufficient rejection of PWM component. The largest AC component occurs, when the input setting S_{IN} is 2^{n-1} and the amplitude of the fundamental component is (Grimbleby, 2004):

$$A + 1 = \frac{1}{\Pi} \int_0^{\Pi} U_{\mathrm{REF}} \sin t \,\mathrm{d}t = \frac{2U_{\mathrm{REF}}}{\Pi}. \tag{4.14}$$

PWM DACs are simple to implement and have very good linearity. The relation (4.13) shows that the increasing resolution will decrease the PWM frequency. Good solution is a PWM weighted-resistor DAC, which uses few PWM DACs with low resolution and sums the PWM waveforms. PWM weighted-resistor DACs have very good linearity and can handle higher f_{PWM} frequency than PWM DACs.

By applying the three PWM DACs with 7-bit precision it is possible to achieve a PWM weighted-resistor DAC with 21-bit precision and 16 384 times higher PWM frequency. Integral linearity errors (maximum difference between the actual analogue voltage and the straight line between endpoints) of PWM weighted-resistor DACs are presented in Fig. 4.8 (Szmytkiewicz, 2000) and were obtained in the C101 multifunction calibrator (Olencki, 1998).

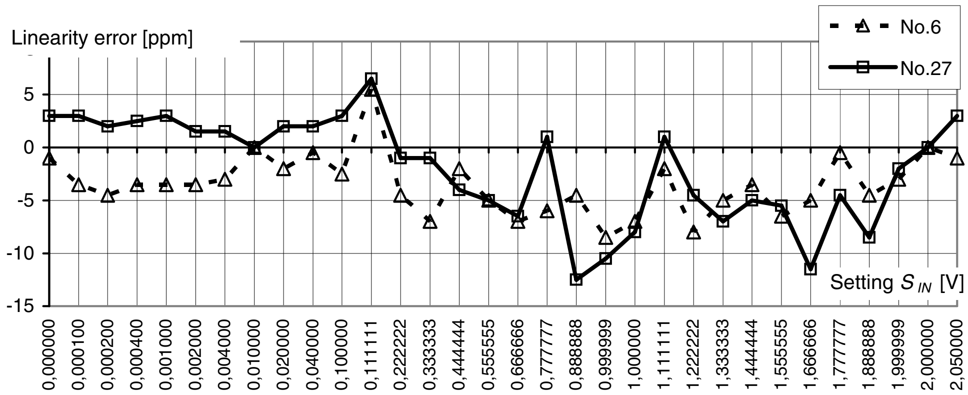


Fig. 4.8. Measurement results of the DAC's integral linearity errors

4.4.3. DACs with inductive voltage dividers

In the first Polish multifunction calibrators: model GA1 (Olencki, 1982) and the model SQ10 (Szmytkiewicz, 1990), there were applied D/A converters with a 20-bit precision inductive voltage divider (Olencki, 1983; 1984), in which there were achieved 10 ppm of Full Scale (FS) integral linearity and errors at the same level, too. The DAC's divider (see Fig. 4.9) consists of a DC/AC converter, an inductive voltage divider and an AC/DC converter. The DC/AC converter is used to generate a trapezoidal bipolar waveform with a precision peak to peak value (Lange and Olencki, 1986a). The amplitude of this waveform is divided with the use of the precision inductive divider. The peak to peak value of an output divider voltage is converted do the proportional DC output voltage U_{DAC} (Lange and Olencki, 1986b).

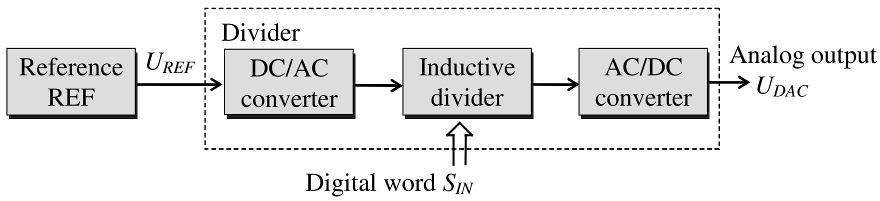


Fig. 4.9. Block diagram of the DAC with an inductive voltage divider

The method used in this DAC, like differential methods, has very good immunity from law frequency disturbances. The disturbances between the DC/AC converter output and the AC/DC converter input are rejected with a Disturbance Rejection

Ratio, DRR, calculated from the formula (Olencki, 1984):

$$\mathrm{DRR} = \frac{f_{\mathrm{TW}}}{2\Pi f_{\mathrm{D}}}, \tag{4.15}$$

where f_{TW} is a trapezoidal waveform frequency and f_{D} is a sinusoidal disturbances frequency. From (4.15) it is clear that the DC and Low Frequency (LF) parts of disturbances are many times rejected.

4.5. Increasing the accuracy of calibrators

One of the calibrators development directions is improving their metrological parameters and, above all, decreasing the output error. The output error of calibrator is the sum of the reference source error and other analog circuit errors. The reference source error δU_{REF} ((4.5) and (4.6)) defines a theoretical low limit of calibrator accuracy.

There are two groups of methods which can decrease the output error: design or technological methods, and structural-algorithm methods. If the difference between the value of the output error and the reference source error is close to zero, then there is only one way to increase the accuracy – improvement design or technology. These can be implemented by the application of higher quality parts or materials, better design of calibrator construction, and protection against influence quantities.

Structural-algorithm methods are divided into the statistical method and the correction of influence quantity effects. The statistical method permits to reduce only random errors, which do not have a conclusive consequence for calibrator accuracy. But the correction of influence factors effects involves the implementation excess of electrical circuits or time. Depending on the participation digital part of the calibrator in the execution of structural methods of automatic correction, we can divide those methods into analogue methods and digital methods.

Depending on the type of reference standard application we can divide digital methods of error correction into

- methods which are called digital adjust with the use of the outside standard,
- methods which are called autocalibration with the use of the inside standard.

Both of these methods consist of two stages: the stage of correction calculating and the stage of error correction. In digital adjustment methods the corrections are calculated by the outside standard. Then the digital adjustment completely substitutes the analogue adjustment. In autocalibration methods, the corrections are calculated by the internal standard. Then the autocalibration can be done by users themselves. In both methods the correction coefficients are first calculated and then applied to error correction.

The corrected value of the setting X_K is calculated in such a way that the real output value Y_R, for any setting, reconstructs the nominal profile of the process. It means that the real output value Y_R meets the following requirement:

$$Y_R = X_K. \tag{4.16}$$

On the basis of the equation (4.3) we can calculate the value of X_K from the following equation:

$$X_K = (\delta_M Y + 1)\ \ X + \Delta_A Y, \tag{4.17}$$

where $\Delta_A Y$ is the additive component of the error related to the output, $\delta_M Y$ is the multiplicative component of the error related to the output, and X is the setting.

The coefficients $\Delta_A Y$ and $\delta_M Y$ are calculated from the following set of equations (Szmytkiewicz, 1998):

$$\begin{aligned} X_O &= (\delta_M Y + 1)\, X_1 + \Delta_A Y, \\ X_M &= (\delta_M Y + 1)\, X_2 + \Delta_A Y, \end{aligned} \tag{4.18}$$

where Y_O and Y_M are the values of output quantity, for which the adjust is executed (points of adjustment), and X_1 and X_2 are the settings, which are modified settings X_O and X_M. The settings X_O and X_M are set via keyboard and they are modified in such a way that the results of the measurement are equal Y_O and Y_M.

When we solve the above set of equations and we substitute $X_M = Y_M$ and $X_O = Y_O$, we can calculate the coefficients $\Delta_A Y$ and $\delta_M Y$:

$$\delta_M Y + 1 = \frac{X_M - X_O}{X_2 - X_1} \quad \text{and} \quad \Delta A_Y = X_O - X_1 \frac{X_M - X_O}{X_2 - X_1}. \tag{4.19}$$

The coefficients are calculated and stored in the digital part of the calibrator. At the stage of correction, on the basis of coefficients calculated from the system of equations (4.19), the corrected values of the settings from the equation (4.17) are calculated.

In Fig. 4.10 are presented the nominal $Y_N(X)$ and the example of a real $Y_R(X)$ profile of the calibration process. This figure describes the algorithm of digital adjustment. In the figure the are the following symbols: Y_O and Y_M are the values of the output quantity chosen as the measurement point for which the adjust is executed (points of adjustment), X_O and X_M are the values of the setting fit the values of the output quantity Y_O and Y_M when the calibrator works according to the nominal profile of the process, X_1 and X_2 are the values of the setting fit the values of the output quantity Y_O and Y_M when the calibrator works according to the real profile of the process, X and Y represent any value of the setting and the fitting value of the

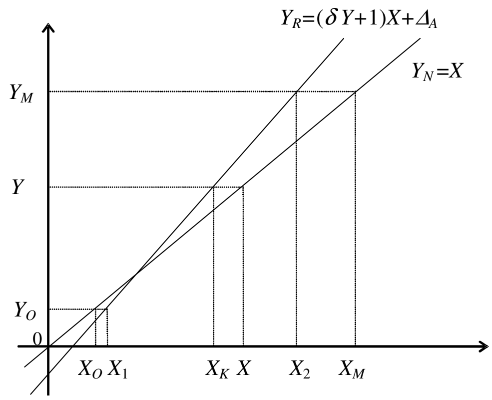


Fig. 4.10. Nominal Y_N and sample real Y_R profile of the process

output quantity when the calibrator works according to the nominal profile, and X_K is calculated at the stage of the correction value of X.

The realization of the adjustment is a laborious and responsible task. The stage of calculating correction determines the laboriousness of the adjustment. Then the ergonomics of adjustment needs special attention when the algorithm is worked out. There are two possible ways to design the stage of calculating correction:

- first – manual from the calibrator keyboard, implemented in the C101 multifunction calibrator (Szmytkiewicz, 1998; 2000),
- second – half automatic from the computer via an interface connection, implemented in the C300 three phase power calibrator (Calmet, 2006).

The advantage of the first selection is the possibility to perform the calibrator adjustment in different laboratories without using computer equipment or special software. The advantage of the second selection is

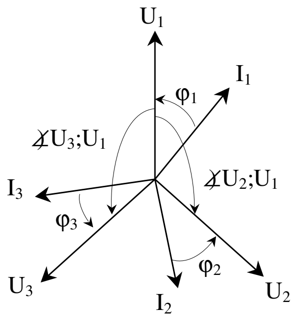
- decreasing the probability of mistakes when the stage of calculating correction is reached,
- saving in memory the correction coefficients allows, after a few years, using these memorizes coefficients to be used for the analysis of the change of calibrator errors,
- after any damage of the digital part of the calibrator it is enough to recall the correction coefficient from computer memory.

4.6. Multiple output calibrators

Typical multifunction calibrators can generate only one quantity at a time – a voltage or a current (Fluke, 1979; Olencki, 1983). For many applications are needed precision sources with more than one channel with an accurately generated value of the voltage or the current (Carullo *et al.*, 1998). Practically in laboratories the are used two or six channel calibrators. The so-called “one phase” power calibrator has two outputs and can generate at the same time an AC voltage and current (Fluke, 2006a; Rotek, 1989). Also the phase angle between them can be set with high accuracy, so we get the possibility of power simulation. The six channel version can generate three voltages shifted usually by 120° and 240° and three currents shifted like the voltages plus an additional phase shift between the voltage and the current. Such a system allows simulating a three phase power network (Calmet, 2006).

One phase and three phase calibrators can be used for adjustment and checking measurement equipment, especially electricity meters and power analyzers, etc (Coombes, 2006; Fluke, 2006b; 2006c). They can generate reference vectors of the voltage and current, which is shown in Fig. 4.11.

Figure 4.12 presents a block structure of the one phase calibrator (Olencki and Urbański, 1998). The structure can be divided into a digital part with control unit CU and an analogue part. This part consists of a generator G, a phase shifter PS, a voltage power amplifier VP and a current power amplifier CP. At the output of calibrator terminals, active power P is simulated according to the equation (4.20) and



U_1; U_2; U_3	sinusoidal phase voltage
I_1; I_2; I_3	sinusoidal phase current
φ_1; φ_2; φ_3	phase angle shift
$\measuredangle U_2$; U_1	angle shift between voltage U_2 and U_1
$\measuredangle U_3$; U_1	angle shift between voltage U_3 and U_1
f	frequency of voltage and current

Fig. 4.11. Vector diagram of three phase power calibrator output

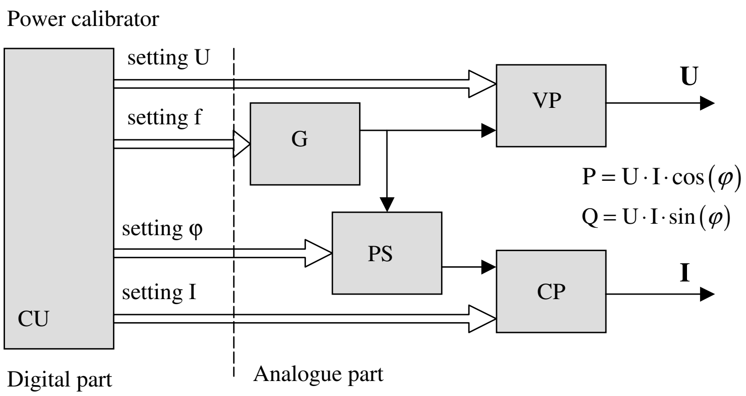


Fig. 4.12. Structural scheme of a power calibrator

reactive power (Q) according to the equation (4.21):

$$P = UI\cos(\varphi), \tag{4.20}$$

$$Q = UI\sin(\varphi), \tag{4.21}$$

where U is the setting value of the sinusoidal voltage, I is the setting value of the sinusoidal current, f is setting value of the frequency, and φ is the setting value of the phase shift between U and I.

From the control unit CU to the analogue part of the calibrator there are connected signals as follows: the setting of the voltage (U), the setting of the current (I), setting of the phase shift (φ), and setting of the frequency (f).

The nominal characteristics (4.20) and (4.21) describe the relationship between the output quantity (power) and the settings at the input. The real characteristics P_R and Q_R of the power calibrator have a systematic error of adjustment and are given by the equations (4.22) and (4.23):

$$P_R = \left[(\delta U + 1)\,U + \Delta U\right]\left[(\delta I + 1)\,I + \Delta I\right]\cos(\varphi + \Delta\varphi)\,, \tag{4.22}$$

$$Q_R = \left[(\delta U + 1)\,U + \Delta U\right]\left[(\delta I + 1)\,I + \Delta I\right]\sin(\varphi + \Delta\varphi)\,, \tag{4.23}$$

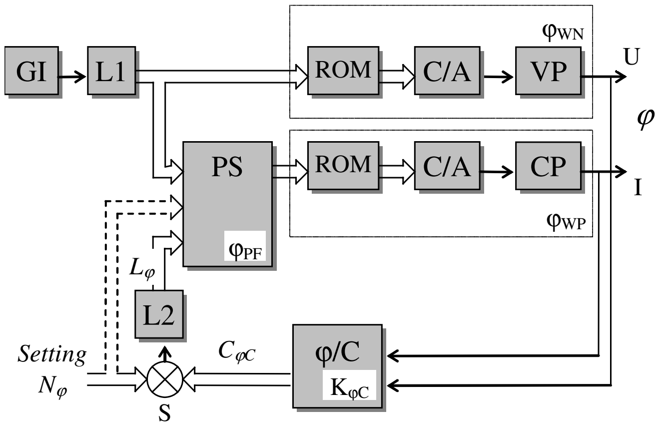


Fig. 4.13. Block diagram of a power calibrator with a closed tracking structure and error corrections

where δU, ΔU represent the multiplicative and the additive part of the voltage U error, δI, ΔI represent the multiplicative and the additive part of the current I error, and $\Delta\varphi$ is the error of the phase shift angle φ.

The difference between real and nominal characteristics gives an active power error δP and a reactive power error δQ of the power simulated at the output of the calibrator. The equations of these errors are (Urbański, 2001):

$$\delta P = \frac{P_R - P}{P} = \delta U + \frac{\Delta U}{U} + \delta I + \frac{\Delta I}{I} + \frac{\cos(\varphi + \Delta\varphi) - \cos\varphi}{\cos\varphi}, \tag{4.24}$$

$$\delta Q = \frac{Q_R - Q}{Q} = \delta U + \frac{\Delta U}{U} + \delta I + \frac{\Delta I}{I} + \frac{\sin(\varphi + \Delta\varphi) - \sin\varphi}{\sin\varphi}. \tag{4.25}$$

The equations (4.22)–(4.25) describe the static properties of the power calibrator by connecting the output quantities P or Q with the settings U, I, φ and f.

Figure 4.13 presents a block diagram of a real power calibrator developed by means of a closed tracking structure with error corrections (Olencki and Urbański, 1994a; 1994b). The signal of the setting N_φ is compared with the output signal φ converted by the phase shift angle converter (φ/C) to a digital code. The result of the comparison, as a coefficient L_φ, is added by the phase shifter PS to the main signal (output of the counter L1). The presented structure consists of a voltage channel (U), which contains an impulse generator GI, a counter L1, memory ROM with a stored shape of the signal, a digital to analog converter C/A and a voltage power amplifier VP. The second channel I consists of phase shifter PS (as a code adder), read only memory ROM, a digital to analog converter C/A and a current power amplifier CP. Astatic characteristics of control are delivered by means of a counter L2 connected to the correction path and additionally, the adder S and a phase shift angle to digital code converter (φ/C). In a stable state there is given set of equations (Urbański, 2001):

$$\begin{cases} C_{\varphi\mathrm{C}} = N_\varphi, \\ C_{\varphi\mathrm{C}} = \varphi\, K_{\varphi\mathrm{C}}, \end{cases} \tag{4.26}$$

which allows us to describe the nominal characteristics of the calibrator and its error by the equations

$$\varphi = \frac{N_\varphi}{K_{\varphi\mathrm{C}}}, \tag{4.27}$$

$$\Delta\varphi = R_{\mathrm{PF}} - \delta K_{\varphi\mathrm{C}}\, N_\varphi - \Delta_{\varphi\mathrm{C}} - R_{\varphi\mathrm{C}} + R_{\mathrm{L2}}, \tag{4.28}$$

where $K_{\varphi\mathrm{C}}$ is the converting coefficient of the phase shift angle converter φ/C, $\delta K_{\varphi\mathrm{C}}$ is the φ/C converter multiplicative part of the error, $\Delta_{\varphi\mathrm{C}}$ is the φ/C converter additive part of the error, $R_{\varphi\mathrm{C}}$ is the resolution of the φ/C converter, R_{PF} is the resolution of the adder PS, and R_{L2} is the resolution of the counter L1.

In the equation (4.28), there are no parasitical phase shifts φ_{WN} and φ_{WP} of output amplifiers, which is an advantage of this structure. The phase shifter PS and the counter L2 are made as digital circuits, and their resolution R is related to the frequency of the impulse generator GI according to the equation

$$R\,[^\circ] = \frac{360 f}{f_{\mathrm{GI}}}, \tag{4.29}$$

where f is the frequency of the output signals, and f_{GI} is the frequency of the impulse generator GI. So errors caused by the limited resolution R_{PF} and R_{L2} of the phase shifter PS and the counter L2 can be made considerably small.

4.7. Calibrator as a test system

The idea of a connection three phase calibrator and additional meters with a computer equipped with specialized software gives a new kind of device – a three phase power calibrator and an electric equipment automatic tester (Olencki, 2006). In Fig. 4.14. this calibration and test system is presented. It consists of a calibrator and a computer with software. The calibrator has a precision three phase generator and a set of additional inputs and meters:

- impulse counter S0 for counting the output impulses from electricity meters,
- direct current ammeter Idc for checking industrial transducers,
- DC voltmeter Udc for checking industrial transducers or DC current clamps,
- AC ammeter Iac for checking current clamps or current transformers for measurements,
- timer t_O for starting relay time measurements.

This idea is applied to design a three phase automatic calibration system model C300 (Calmet, 2006) called the "calibrator". This calibrator can be used for measurements of two kinds of calibration characteristics:

- error curves (see Fig. 4.15(a)) of electricity meters, measurement industrial transducers, current clamps and current transformers in a fully automatic way,

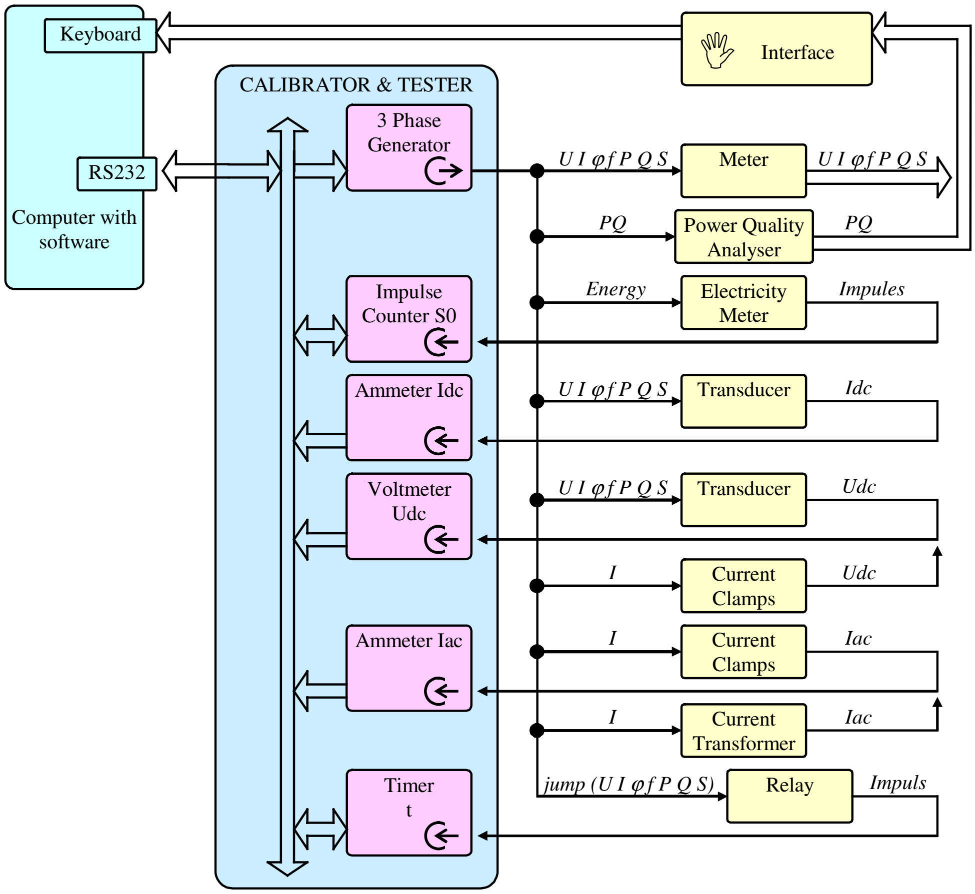
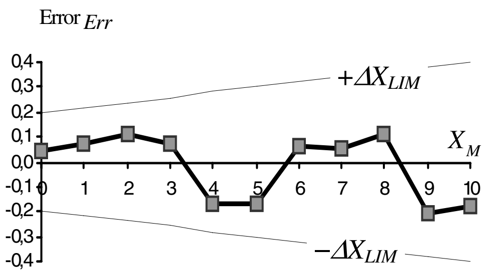
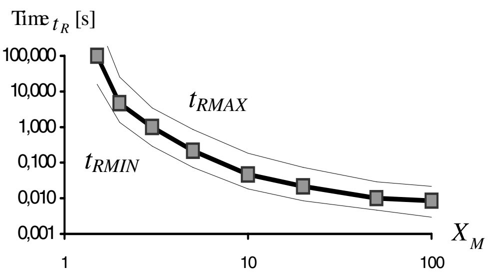


Fig. 4.14. Block diagram of the three phase automatic calibration system



(a)



(b)

Fig. 4.15. Characteristics of the equipment under the test:
(a) error curves, (b) response time curves

- time curves (see Fig. 4.15(b)) of protection relays, e.g. overcurrent relays, in a fully automatic way,
- error curves of the analogue or digital meters and power quality analysers in a semi automatic way.

The error *Err* and response time t_R characteristics can be presented as a graph or a table. Efficient testing and performance analysis require well-defined reference values ΔX_{LIM} in Fig. 4.15(a) and t_{RMIN}, t_{RMAX} in Fig. 4.15(b). The C300 calibration system can automatically create the reference values on the basis of customer requirements. Specialized software will compare the actual measurement result with the reference values and check for any deviations from the reference values. The results are correct for the following requirements:

$$-X_{LIM}(X_M) < Err(X_M) < +X_{LIM}(X_M), \tag{4.30}$$

$$t_{R\ MIN}(X_M) < t_R(X_M) < t_{R\ MAX}(X_M). \tag{4.31}$$

4.8. Conclusions

The first calibrators were designed with structures similar to manually controlled systems. In the next calibrators, for stabilizing the amplitude of voltages or currents in multifunction and power wide range calibrators are used closed single or multi loop structures and PI controllers. For stabilizing phase angles in power calibrators there are used closed structures with an additive correction of errors. Static and dynamic analyses are required to achieved good calibrator parameters: high accuracy and short settling times. In most of the modern calibrators there are used PWM DAC, and autocalibration and digitally adjustment methods are implemented to achieved high accuracy. The automation of calibration procedures is particularly important for checking three phase electrical devices, e.g. energy meters or protection relays. For this purpose there is presented the idea of the three phase automatic calibration system, which is implemented in the compact three phase power calibrator model C300, dedicated to calibrate extremely wide range electrical devices.

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