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NEW INSTRUMENTS TO MEASURE PARAMETERS OF INFRA-LOW FREQUENCY VOLTAGE SIGNALS

The paper presents the design, the principles of operation and the technical specification of two types of infra-low frequency voltage instruments: the integrating converter instrument and the microprocessor instrument. Both instruments are designed for the following frequency range: 0.01 - 10 Hz. The integrating converter instrument measures the mean modulus value and the rms value of voltage. The microprocessor instrument measures the mean modulus value, the rms value, the shape coefficient and the frequency of the measured signal at the same time. The measurement takes from one to four periods of the measured signal.

Keywords: infra-low frequency, rms value, mean modulus value

1. INTRODUCTION

The measurements of electrical quantities such as infra-low frequency voltage are needed in many fields of science and technology. Voltages with a frequency range of 0.01 - 10 Hz are used for measuring the properties of dielectrics [1, 2, 3] as well as magnetic materials [4]. Signals with a frequency of a few Hertz are encountered in medicine and geology.

Commercially available instruments cannot be applied in such a low range of frequencies. Due to the dynamic properties of these instruments, the moving element follows instantaneous torque changes. Such a movement causes the indicator to oscillate around the value corresponding to the mean torque value. The oscillations make it difficult to take the measurement and lower the quality of the measurement. A change in design parameters of an instrument, for example, an increase in its moment of inertia, affects other metrological properties of the instrument. The length of a transient state and consequently the time to take the measurement may increase significantly. Therefore, the design changes are not acceptable in practice.

A number of infra-low frequency instrument designs have been proposed. The instruments considered are designed to measure one quantity only, for example, mean value of sinusoidal voltage. Such instruments are complex and are not versatile [5, 6].

A measurement system for the reconstruction of a 10 Hz signal has been developed in Instituto Elettrotechnico Nazionale "Galileo Ferraris" in Turin. The system is based on sampling with an integrating analog to digital converter. The samples collected are used to compute the frequency and the Fourier series coefficients for the sampled signal approximation. Next the rms value is computed. It has been shown in [8] that the results of the integrating sampling method are of the highest accuracy. However, the method is very time consuming. The length of a measurement is one of the main problems in the infra-low frequency domain. The time needed is usually a multiple of the voltage period (e.g., if the frequency is equal to 0.01 Hz, the measurements can take as long as few minutes).

We present two instruments developed in the Institute of Theoretical Electrotechnics, Metrology and Material Science at the Technical University of Łódź. The instruments can be used to measure parameters of voltage signals with the frequencies in the range from 0.01 to 10 Hz. Time needed for a measurement is a multiple of the signal period. The instruments have simple design and are easy to use. The first instrument contains an integrating converter with switchable integration direction and is designed to measure the rms value and the mean value of the voltage modulus. We present also the model simulation results for this instrument. The second instrument is a microprocessor meter based on the signal sampling method. This instrument is designed to measure the rms value, the mean value of the modulus, the shape coefficient and the frequency of the measured signal at the same time.

The paper describes the results of the research on infra-low frequency voltage measurements that have been conducted by one of the authors [9, 10, 11] for a few years.

2. THE INTEGRATING CONVERTER INSTRUMENT

2.1. Principle of operation

The measurements conducted with the instrument are based on the frequency method of converting voltage into a series of impulses whose number is proportional to the mean value of the voltage modulus. An integrating converter with switchable direction of integration is the principal element of the instrument. The block diagram illustrating the principles of the converter's operation is shown in Fig. 1.

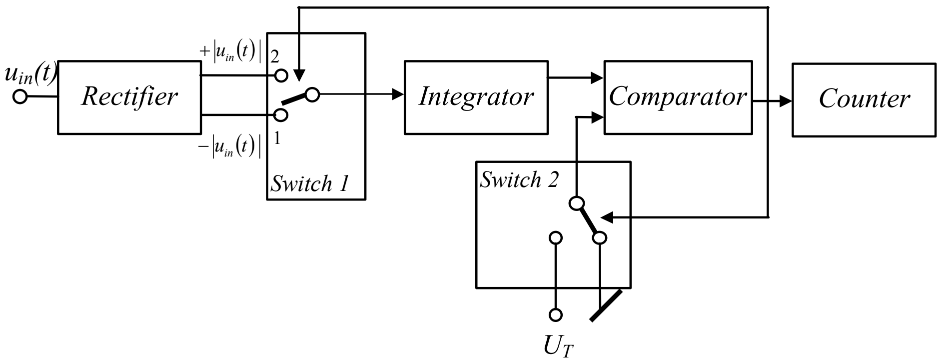

Fig. 1. The block diagram of the integrating converter.

The operation of the converter starts when the measured signal reaches value zero. The input voltage $u_{in}(t)$ is directed to an integrating unit input through a rectifier with two symmetrical outputs and switch 1. Switch 1 is switched with the pulses at the comparator output. These pulses are generated whenever the integrating unit output voltage becomes equal to one of the comparator reference voltages, either U_T or voltage equal to zero. The reference voltages are directed to the comparator input by switch 2. The switch is controlled by the comparator output pulses. A counter keeps track of the number of pulses. The length of the converter's operation cycle is equal to the period of the measured voltage. The number of pulses denoted by N is equal to:

$$N = \frac{1}{RCU_T}\int_0^T |u_{in}(t)|dt\,, \qquad (1)$$

where: U_T - comparator reference voltage, $R\ C$ - time constant of integrator, T - period of the measured voltage, $u_{in}(t)$ - input voltage.

If the value U_T of the comparator reference voltage is proportional to period T of the measured voltage, and the input voltage is the measured quantity, then the number of pulses is proportional to the mean value of the measured voltage modulus. But, if the converter input voltage is proportional to the mean value of the measured voltage, the number of pulses is proportional to the square of the measured voltage rms value. The block diagram of the instrument is shown in Fig. 2.

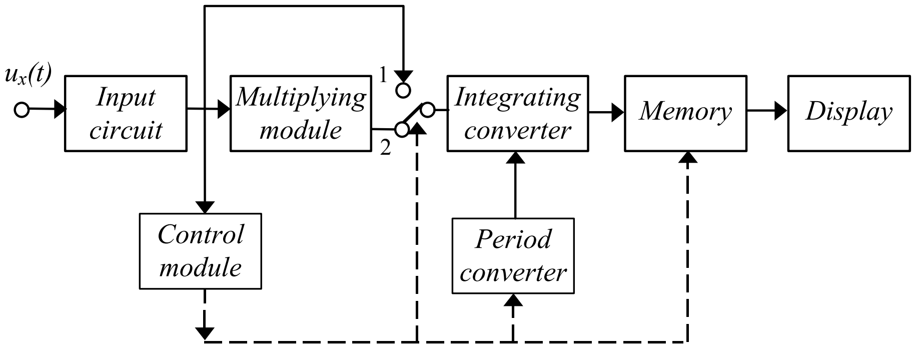

Fig. 2. The block diagram of the instrument with the integrating converter.

The input circuit block converts the measured voltage value from the range of 0 - 1000 V into a value smaller or equal to 5V, i.e. a value acceptable for other blocks. For a mean value measurement the output signal of this block is directed to the integrating converter. For an rms value measurement the signal is directed to the multiplying module. In addition, the converter receives also a signal proportional to the measured voltage period which is formed in the period converter. The control module oversees the operation of the entire measurement system.

The measurement process consists of two cycles. The length of each cycle is equal to the measured voltage period determined by the control module. During the first cycle, the period converter generates a voltage U_T proportional to the length of the period:

$$U_T = c_T T, \qquad (2)$$

where: U_T - reference voltage of the integrating converter comparator, T - period of the voltage, c_T - converting constant.

In the second measurement cycle the integrating converter processes the measured voltage. If the mean value of the voltage modulus is the subject of the measurement, the voltage signal is directed to the input of the integrating converter after passing through the input circuit block. The multiplying module is omitted (switch in position "*1*"). If the rms value is the subject of the measurement, the instantaneous values of the measured voltage are first squared by the multiplying module (switch in position "*2*") and then processed by the integrating converter. The number of pulses at the end of the second measurement cycle in each of these two cases is given by Eqs. (3) and (4), respectively.

N_{mv} - number of pulses for a measurement of the mean value

$$N_{mv} = \frac{1}{RCU_T}\int_0^T |u_x(t)|dt = c_1 \frac{1}{T}\int_0^T |u_x(t)|dt = c_1 U_{mv} \,. \tag{3}$$

N_{rms} - number of pulses for a measurement of the rms value

$$N_{rms} = \frac{1}{RCU_T}\int_0^T [u_x(t)]^2 dt = c_2 \frac{1}{T}\int_0^T [u_x(t)]^2 dt = c_2 U_{rms}^2 \,, \tag{4}$$

where: RC - time constant of integrator, c_1, c_2 - constants, U_{mv} - mean value of voltage modulus, U_{rms} - rms value of voltage.

These numbers are stored in memory. For the rms value measurement, the square root of N_{rms} is read from memory and displayed after undergoing a code conversion. For the mean value of voltage modulus measurement, the mean value is converted from a binary representation into a decimal representation and displayed.

The operation of the multiplying module is based on the conversion of the measured voltage into a series of rectangular pulses whose amplitude and length in time are proportional to the instantaneous values of the voltage.

The period converter contains an integrating converter with switchable integration direction [3]. The converter converts the standard voltage U_s into a number of pulses N_T registered by the counter. The time needed for the conversion is equal to the measured voltage period. The number of pulses is proportional to the voltage period as given by Eq. (5):

$$N_T = \frac{1}{U_s RC}\int_0^T U_s dt = c'_T T \,, \tag{5}$$

where: c'_T -constant, U_s - standard voltage.

The binary representation of the pulse number N_T is passed to the digital-analogue converter's input. The direct voltage obtained at the converter's output is proportional to N_T according to formula (6).

$$U_T = q\, N_T = c_T\, T, \tag{6}$$

where: q - output voltage quantum of D/A converter.

Voltage U_T is the comparator reference voltage. The application of the same integrator in both the period converter and the integrating converter, reduces the stability requirements for the *R* and *C* elements used in the integrator feedback loop.

2.2. Metrological properties

The instrument is designed to measure the mean value of the modulus and the rms value of voltages with a frequency from 0.01 Hz to 10 Hz in three different sub-ranges. The proper sub-range is selected automatically. The frequency range is divided into three sub-ranges so that the maximum acceptable value of the discretization error equal to 0.25% is not exceeded. The time constant of the integrator is equal to:

- *0.0125* s for the frequency range 0.01 - 0.1 Hz,
- *0.00125 s* for the frequency range 0.1 - 1 Hz,
- *0.000125 s* for the frequency range 1 - 10 Hz.

The total length of the measurement is equal to one, two or four measured voltage periods depending on the variability of the voltage frequency. For a constant frequency the measurement cycle lasts one period. The period conversion cycle is skipped after the frequency range determination. If the signal frequency changes during the measurement process, the measurement length increases to as many as four periods. This increase is related to the selection of the proper frequency sub-range (repetition of the frequency measurement cycle for the converter's time constant determination). Note that the total measurement length includes a so called waiting time, i.e., the time between switching the measured voltage on and the moment when the voltage reaches value zero. The measurement cycles are initiated at the end of the waiting time.

The instrument design and the coefficients of the amplifiers used in the design are selected in such a way that the basic voltage amplitude range is 5 V with the discretization error equal to 1%. The input circuits allow measurement of voltages in the range 0 - 1000 V divided into five sub-ranges. The instrument can measure parameters of AC voltage and periodic voltage with a peak coefficient below 2. The last limitation is due to the danger of over-controlling. Moreover, only a signal that reaches value 0 only once within each period can be measured, since the period length is determined by three consecutive moments when the measured signal reaches the value zero.

The estimated measurement error of the instrument, based on the analysis of the comparative measurements, is of the order of 1%.

2.3. Computer model examination results

A model of the instrument has been created in Matlab (version 5.3). The model does not include the input circuits block, the memory and the reading block. The following elements have been added: excitation block, computational module, memory and visualization module. Moreover, in order to simplify the model, separate models were created for the mean modulus value measurement and for the rms value measurement. The integration step is equal to $T/10^6$ for the former type of measurement and $T/10^7$ for the latter type, where T is the measured voltage period. Such a selection of the integration step results in comparable precision obtained in both models and does not increase the length of the simulation significantly.

The model has been examined for input voltages with the following shapes: sinusoidal, triangular and trapezoidal, the following values of an amplitude: (0.25, 0.5, 1.0, 2.5, 5.0) V, and three frequency ranges: 0.01 - 0.1 Hz, 0.1 - 1 Hz and 1 - 10 Hz.

The rms and the mean modulus values obtained through the simulations were compared with the values computed according to the formal definitions of these two quantities. The differences between the simulation values and the computed values were the bases for the evaluation of the model quality and the accuracy of the measurement method. The relative errors did not exceed ±1% for a majority of the measurements. Larger errors were observed for the rms measurements in the initial frequency range and were caused by an integration step being too large. A change in the integration step decreases the error but increases the duration of the simulation to several hours.

Fig. 3 and 4 present examples of the simulation results obtained for sinusoidal, triangular and trapezoidal voltages with a constant amplitude equal to 5 V and a variable frequency.

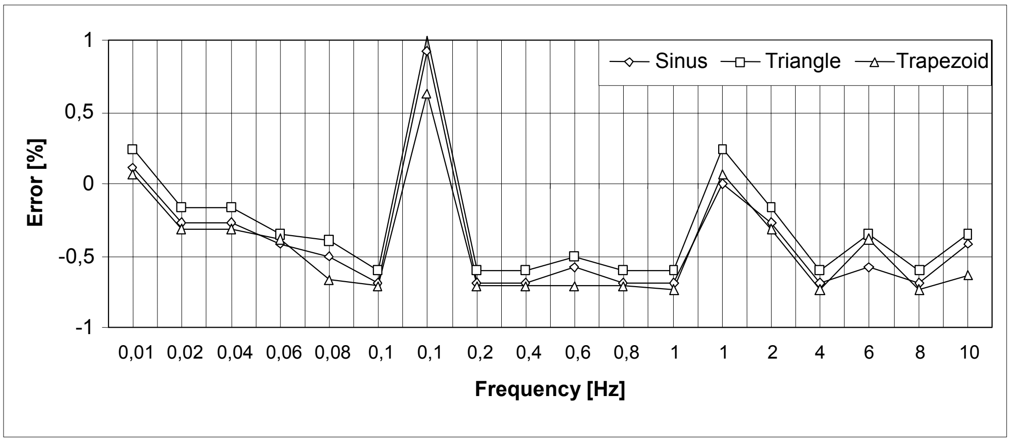

Fig.3. The relative simulation error dependence on the frequency for the mean value model with different voltage shapes and constant amplitude.

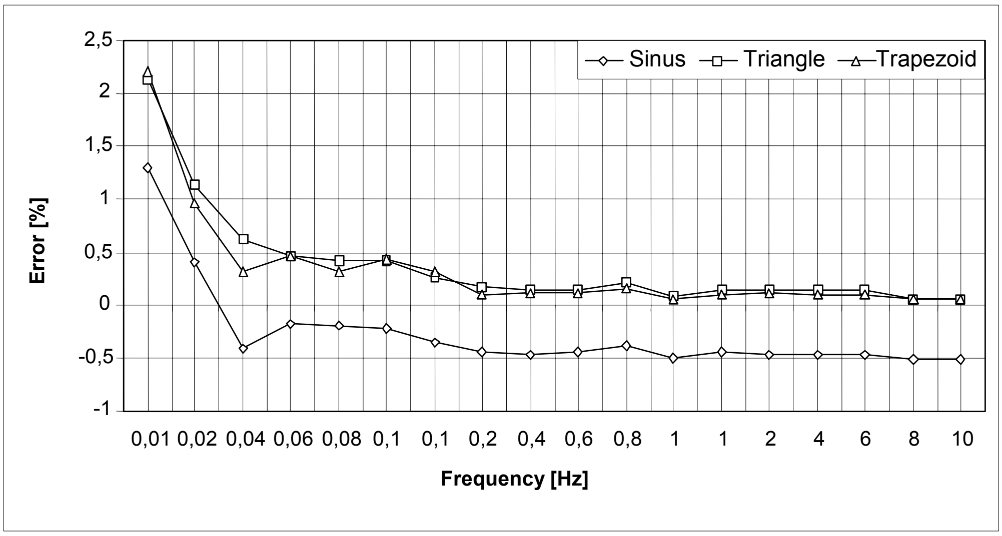

Fig. 4. The relative simulation error dependence on frequency for the rms value model with different voltage shapes and constant amplitude.

The frequency values of 0,1 Hz and 1 Hz as well as the error values are shown twice in both Figures for different instrument frequency sub-ranges.

The results of the model examination have confirmed that the frequency changes in a given range and the shape of the measured signal do not affect the value of the error. On the other hand, the relative error depends on the amplitude of the processed voltage. The error increases with a decrease in the amplitude. Such an increase takes place due to an increase in the voltage discretization error caused by a decrease in the number of pulses. The latter is a direct result of the amplitude decreases.

The results of the investigation emphasize the influence of the precision of the reference voltage U_T determination on the processing error. A digital error occurring due to the 12-bit digital-analogue converter and the value of the voltage quantum equal to 1.22 mV, plays an important role in the reference voltage determination. A 10-fold decrease in the error has been observed when a voltage whose values were computed based on the measured voltage period, and not the voltage generated by the period converter, was set as the input of the integration converter. A decrease in the digital error due to an increase in the number of digital-analogue converter bits is limited by the time needed for switching and the response time of the converter. The switching duration and the response time become comparable to the length of integration between switching. Therefore, the integration converter should not be used for the reference voltage determination. The voltage should be determined in a different way, for example, with a standard frequency impulse generator and a digital to analog converter.

The model diagram and the complete description of the simulation results can be found in [12]. The results of the examination of the real instrument as well as of its model confirm the efficacy of the frequency conversion method in the given frequency range. The results have shown also the limitations of this method related to the measurement precision.

3. THE MICROPROCESSOR INSTRUMENT

3.1 Design and operation

The rms and the mean value of the voltage signal can also be measured with the microprocessor instrument. The principles of the instrument operation are as follows. The measured signal transient values are first sampled, then converted into digital form, and next used for computations based on the definitions of the measured quantities (7).

$$U_{rms} = \sqrt{\tfrac{1}{N}\sum_{i=1}^{N}|u_i|^2}\,, \qquad U_{mv} = \tfrac{1}{N}\sum_{i=1}^{N}|u_i|\,, \qquad k = \frac{U_{rms}}{U_{mv}}\,, \tag{7}$$

where: U_{rms} - rms value voltage estimator, U_{mv} - mean voltage modulus value estimator, u_i - consecutive sample values, N - number of collected samples, k - wave-shape coefficient.

The sampling frequency is adjusted based on the frequency of the measured voltage in such a way that the number of samples within one period is equal to $N = 1000 \pm 70$.

The frequency of the measured voltage is determined by counting the number of standard frequency impulses in a time interval of length equal to one period of the measured voltage. In the second measurement cycle, when the frequency changes do not exceed ±7%, the frequency determination is based on the number of samples u_i.

The frequency of the signal is determined by identifying three consecutive moments when the measured signal reaches the value zero. The identification is performed by the zero detector.

The functional diagram of the instrument is presented in Fig.5. The instrument consists of six modules: an input module, a converter module, a display module, a microprocessor module, a printer module and a power source module.

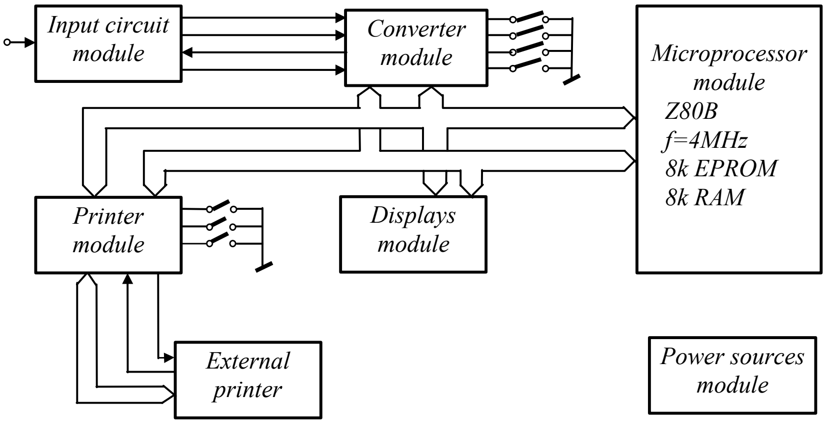

Fig. 5. The block diagram of the microprocessor instrument.

The input module consists of a voltage divider, a low-pass filter, a period detector and a voltage range excess detector. The converter module contains a sample-and-store circuit and a digital-analogue converter. The display module consists of blocks of two eight-segment displays. The first display shows the signal frequency, the second one displays the mean modulus value, the rms value or the wave-form coefficient, depending on the option selected (by pressing the button on the instrument front panel).

The microprocessor module consists of Z80B microprocessor and memory systems. The printer module enables the use of an external printer. The printer is controlled in order to obtain printouts of the measured parameters with a given frequency, i.e., after every measurement or once per ten or a hundred measurements. The printouts are also generated in response to the signal frequency variations exceeding ± 7% during sampling, as well as in response to the signal exceeding a given voltage range.

The technical specification of the constructed instrument model:

Voltage ranges:	100 mV, 1 V, 10 V, 100 V.
Frequency range:	0.01-10 Hz.
Measurement time:	1.5T or 3.5T depending on the signal frequency variations.
Relative measurement errors:	U_{rms}, U_{mv} and k - ± 0.5% and f - ± 0.15%.

4. CONCLUSIONS

The measurements of mean modulus and rms values obtained with the digital conversion method are characterized by higher precision than the measurements based on the frequency conversion.

In order to increase the precision of the integrating converter instrument, a method for determining the period of the measured signal has to be modified. The precision of the microprocessor instrument can be increased either by the application of converter blocks and a microprocessor with better parameters, or by modifying the sampling method and the algorithm for the determination of the measured signal properties.

The measurement length is the comparable for all presented methods. The time needed to complete a measurement is longer for a signal with highly variable frequency, especially for a frequency towards the end of the considered frequency range.

Both presented instruments have simple designs, are easy to use and due to a small size are portable.

REFERENCES

1. Cichy A., Szadkowski B.: *Meter of phase shift of infra-low frequency sinusoidal signals*. Zeszyty Naukowe Politechniki Śląskiej, Elektryka, z. 144, 1995, pp. 5-10, (in Polish).
2. Cichy A., Szadkowski B.: *On certain errors in phase-shift measurements in infra-low frequency range*. Zeszyty Naukowe Politechniki Śląskiej, Elektryka, z. 162, 1998, pp. 23-35, (in Polish).
3. Vitner P.: *Examination of power cables using infra- low frequency sinewave voltage.* Elektro nr 12, Praha, 1999. Oprac. Bobrowski W., Wiadomosci elektrotechniczne, nr 8, 2000, pp. 442, (in Czech).
4. Gozdur R.: *Design and metrological analysis of the measurement system for determination of quasi-static magnetic hysteresis loops.* Rozprawa doktorska, Łódź 2004, (in Polish).
5. Schoenwetter H. K.; *An rms voltmeter/calibrator for very low frequencies*, IEEE, Transactions on Instrumentation and Measurement, vol. IM-27, no 3, 1978, pp. 259-268.
6. Field B.;*A fast response low-frequency voltmeter*, IEEE Transactions on Instrumentation and Measurement, no 4, 1978, pp. 368-372.
7. Pogliano U.: *Precision Measurement of AC Voltage below 20 Hz AT IEN.* IEEE Transactions on Instrumentation and Measurement, vol. 46, no.2, 1997, pp. 369-372.
8. Kampik M., Laiz H., Klonz M.: *Comparison of three Methods to Measure AC Voltage at Low Frequencies.* IEEE Transactions on Instrumentation and Measurement, vol. 49, no. 2, 2000, pp. 429-433.
9. Kalus-Jęcek B.: *The instrument to measure the mean modulus value and the rms value of infra-low frequency voltage signals*. Pomiary Automatyka Kontrola, nr 11, 1990, pp. 234-235, (in Polish).
10. Kalus-Jęcek B., Kowalski J., Średniak B.: *The microprocessor instrument to measure parameters of infra-low frequency voltage signals*. Pomiary Automatyka Kontrola, nr 3, 1992, pp. 53-54, (in Polish).
11. Kalus-Jęcek B., Graczyk A.: *The instrument to measure parameters of infra-low frequency voltage signals.* Zeszyty Naukowe Politechniki Łódzkiej, Elektryka, z. 98, 2001, pp. 319-328, (in Polish).
12. Graczyk A.: *Modelling and simulation of analog to digital converter of rms and mean modulus values of infra-low voltage signals.* Praca dyplomowa, Łódź 2000, (in Polish).

NOWE MIERNIKI PARAMETRÓW SYGNAŁÓW NAPIĘCIOWYCH O INFRANISKICH CZĘSTOTLIWOŚCIACH

Streszczenie

W artykule przedstawiono budowę, zasadę działania oraz dane techniczne dwóch typów mierników parametrów sygnałów napięciowych o częstotliwościach z zakresu (0.01-10) Hz: miernika z przetwornikiem całkującym oraz miernika mikroprocesorowego. Miernikiem z przetwornikiem całkującym można mierzyć wartość średnią z modułu i wartość skuteczną napięć z zakresu (0 - 1000) V z dokładnością ± 1% w czasie od jednego do czterech okresów sygnału badanego. Miernikiem mikroprocesorowym można mierzyć jednocześnie: wartość średnią z modułu, wartość skuteczną i współczynnik kształtu z dokładnością ± 0.5% oraz częstotliwość napięcia badanego z dokładnością ± 0.15%. Czas pomiaru miernikiem mikroprocesorowym wynosi od 1.5 do 3.5 okresów sygnału badanego.