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Precision active power measuring channel

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Abstract

The article is devoted to increasing the reliability, noise protection and improving the metrological characteristics of active power measuring converters. Much attention is paid to the problem of developing effective methods for constructing structural diagrams of active power measuring converters. This is explained by the growing requirements for the basic metrological characteristics of active power measuring converters as elements of information – measuring systems.

The main attention in the work is paid to the development of ways to correct the influence of destabilizing factors in working conditions. The undoubted advantage of the work is a thorough analysis of the instrumental errors of the measuring channel, the original means of correction of the phase error and the error due to the limited suppression coefficients of in-phase interference.

The obtained simulation results in the Electronics Workbench environment made it possible to determine the most effective way to protect against interference.

Keywords: active power measuring converters; error correction; protection against normal and general interference; multipliers; wide-pulse modulation.

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Introduction

The study aims to create an inexpensive, reliable, and noise-proof measuring channel with improved metrological characteristics for active power measurement. Many consumers have already realized their interest in settlements with the energy supplier not with any conditional norms, contractual values, or obsolete and inaccurate devices, but based on modern and high-precision metering. The first step towards saving energy and reducing financial losses is accurate energy accounting. The main method of reducing instrumental losses is to improve metering devices. Measurement of power, which is an important energy characteristic, occupies a significant place in modern measuring technology, is one of the main types of measurements in many fields of science and technology.

The main unit of the electronic electricity meter, which determines the error of the latter and the stability of the characteristics over time and when changing the parameters of the environment, is a measuring power converter (MPC).

In most cases, three-phase active power measuring converters with an accuracy class of 0.2–0.5 are required to convert the power of large generators and a class of 1.0–1.5 to convert the power of smaller generators, motors, and power transmitted via power lines. The input signals of the MPCs (voltages or currents of the monitored network) have a shape close to sinusoidal.

Modern electronic electricity meters use MPCs in which the informative parameter of the input signals is the voltage, and the output signal – frequency. This uniformity is because the construction of most household electricity meters includes analog-digital circuits of MPCs in integrated design [1, 2]. The output signal, as a rule, arrives at the mechanical reading device with the stepper motor or on the microcontroller, for the further processing and issue of the information on tariff zones, etc.

There are also analog MPC circuits in the integrated version. But their accuracy does not exceed 1.0, and the accuracy of the electricity meter, built using these schemes, does not exceed 2.0. While the power industry is moving to the use of electricity metering devices with a high accuracy class, usually 1.0.

Analysis of the number of electricity losses showed that a significant part of them is due to shortcomings in the operation of electricity meters or the low accuracy class of the latter. Therefore, the main trend in the development of MPCs is to increase their accuracy in operating conditions [3–6].

Statement of the research problem

Analysis of errors in existing means and methods of active power conversion shows that a significant contribution to the decrease in accuracy is made by frequency deviation and significant content of odd harmonics [7], due to increasing use of inverter power supplies and insufficient efficiency of error correction methods. The frequency component is considered additional, not basic [8].

In general, two groups of methods are used today to measure electric power. The first group is based on the use of synchronous detection. In this case, the quadrature components of the input voltages in one way or another with the involvement of hardware and software are converted into a signal proportional to the active power. The advantages are the possibility of using an analog-to-digital converter (ADC) of the integrating type and a small amount of software, as the average values are multiplied. The disadvantages include the difficulty of providing precise control signals for synchronous detectors coherent with the mains voltage, as well as the inability to work with non-sinusoidal periodic signals. According to the classification given in [9], MPCs of this group are called medium-power converters.

The basis for the construction of the MPC of the second group are multipliers of instantaneous values of the input signals, which allows measuring the active power of non-sinusoidal periodic input signals, so the MPCs of this group are called active power converters. Instantaneous multipliers can be analog (in 4-square mode calibration error 0.1...0.2%), pulse, or digital. Digital instantaneous multipliers in this case are based on ADC instantaneous values with direct conversion and microcontroller or the basis of $\delta-\Sigma$ ADC. In the first case, to ensure the dynamic error of the ADC at 0.02% in the frequency band up to 350 Hz (seventh harmonic), it is necessary to have an ADC with an aperture of fewer than 0.1 μs and a speed of several μs, which complicates practical implementation due to the fact the maximum ADC speed of a single-chip PIC microcontroller is 10 kHz. In the case of $\delta-\Sigma$ ADC – problematic, in the volumes of the PIC-microcontroller there is a need for precise measurement of small-time intervals ($\leqslant$ 100 μsec).

The operating frequency range (Table 1) shows the values of the main error depending on the sampling frequency. The main error (φ = 0) shows the error for the network frequency (50 or 60 Hz). The error of the 3rd harmonic shows the main error for the network frequency (150 or 180 Hz). The 5th harmonic error shows the main error for the network frequency (250 or 300 Hz). The error of the 7th harmonic shows the main error for the network frequency (350 or 420 Hz). For any number of current and voltage measurements over a full period, a rough estimate of the error can be made using this table [10]. It is advisable to consider the use of pulse multipliers based on PWM with negative feedback on the informative parameter (which are known to have high accuracy (0.01%) in a wide dynamic range even when working in 4-square mode) to build precision measuring power converters on an operational amplifier and an iterative integrating converter. In this case, the study of the computer model of such multipliers in the operating frequency range when changing the angle of phase shift φ within $\pm$ 60° shows an increase in the errors presented in Table 1 by about an order of magnitude.

Table 1

Frequency error from the PWM frequency

Measuring the number of points in a period	PWM frequency			Error			
	Single-phase 50 Hz	Two-phase 50 Hz	Three-phase 50 Hz	Basic (the first harmonic)	The third harmonic	The fifth harmonic	Seventh harmonic
20	1000	2400	3000	-4.89%	-36.4%	-95.2%	-174%
30	1500	3600	4500	-2.19%	-16.9%	-47.8%	-87.42%
40	2000	4800	6000	-1.23%	-9.7%	-28.8%	-52.67%
50	2500	6000	7500	-0.78%	-6.2%	-18.3%	-33.47%
60	3000	7200	9000	-0.55%	-4.3%	-13.4%	-22.28%
70	3500	8400	1)	-0.40%	-3.2%	-9.5%	-17.34%
80	4000	9600		-0.30%	-2.4%	-7.3%	-13.35%
90	4500	1)		-0.24%	-1.9%	-6%	-10.97%
100	5000			-0.20%	-1.6%	-4.7%	-9.28%
110	5500			-0.16%	-1.3%	-3.9%	-7.13%
120	6000			-0.13%	-1.1%	-3.2%	-5.85%
130	6500			-0.11%	-0.9%	-2.7%	-4.94%
140	7000			-0.10%	-0.8%	-2.4%	-4.39%
160	8000			-0.08%	-0.6%	-1.9%	-3.43%
180	9000			-0.06%	-0.5%	-1.5%	-2.74%
200	10000			-0.05%	-0.4%	-1.2%	-2.2%

Main part

To solve this problem, a block diagram of the active power measuring channel is developed (Fig. 1), the feature of which is the use of analog pulse multiplier with pulse-width modulation (PWM), which has a negative feedback on the informative parameter and iterative integrating converters with connecting devices (IIC) as a high-speed averaging device, the use of measuring amplifiers with differential current inputs (MADCI) with a high coefficient of suppression of in-phase interference in the operating frequency range.

Direct use as primary sensors of phase voltages and currents of resistive dividers and shunts together with measuring amplifiers with differential current inputs with increased noise suppression of general appearance and providing galvanic isolation using galvanically isolated power supply with harmonic power supply power amplifier class AB [11], and digital optocouplers OP_1,..., OP_4 for isolation of both digital and analog signals, use as a measuring converter of an alternating voltage of an active rectifier with separate circuits of negative feedback on direct and alternating currents and with iterative integrating converter with dynamic storage devices as a fast averaging device.

UIS circuit (see Fig. 2): input signals phase voltage U_f and phase current I_f or their linear analogs, depending on the method of accounting for three-phase power (three-element or two-element circuit), are converted in the switching unit and conversion of UIS input signals into proportional voltages U_u and U_I respectively. Precision resistors (R_1R_2, R_4R_5) and low-voltage (75 mV) shunts R_s together with $MADCI_{1,2}$ with the improved coefficient of suppression of a common-mode signal, due to the introduction of an automatic system of compensations are used as primary converters of primary voltages and currents. based on PWM.

Resistors (R_1R_2, R_4R_5) also perform a protective function and are taken at a value of 100 K, which is enough to protect against overloads at the input up to 2 kV. These resistors together with the input capacitors (not shown in the diagram) of measuring amplifiers (which can be increased to 10 pF) form filters from high-frequency electromagnetic fields (EMI), while the phase error is introduced by them at the frequency 50 ±5 Hz will be less than 0,1°. Resistors R_3, R_6 are so-called “attracting” resistors [12].

In the “operation” mode, which consists of two main and two additional cycles, the movable contact of the relay P_1 is in position “1” while the voltage U_s is applied to the input of the measuring amplifier $MADCI_2$. In this case, the circuit voltage U_f is applied to the input of the measuring amplifier $MADCI_1$.

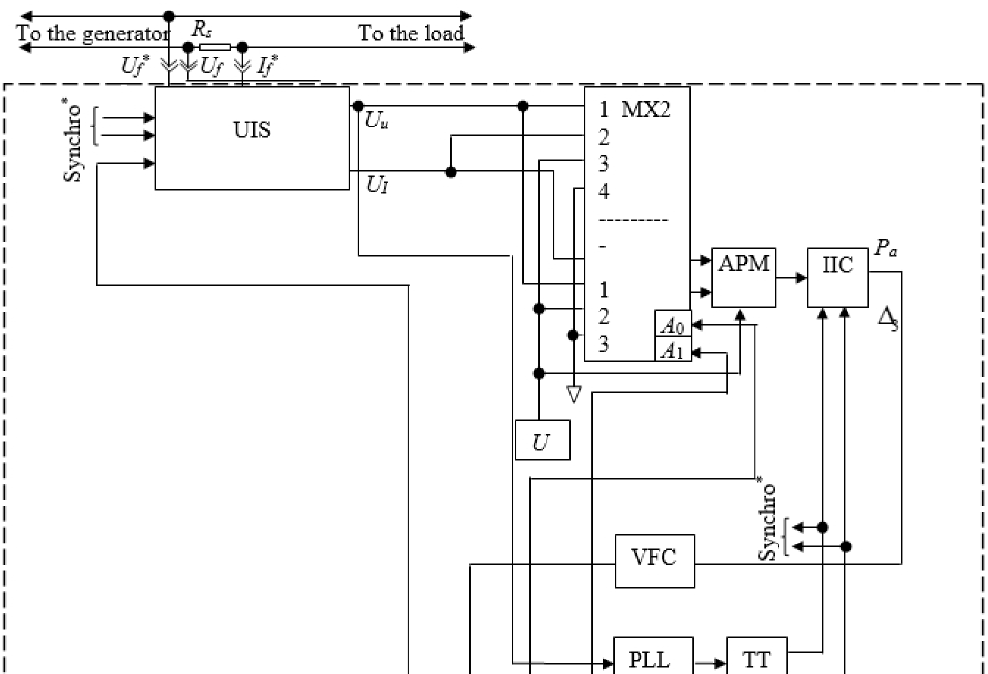

Fig. 1. Block diagram of the measuring channel of active power: UIS – switching unit of input signals; PLL – phase-locked loop; APM – analog pulse multiplier with PWM, which has a negative feedback on the information parameter; IIC – interactive integrating converter; VFC – measuring voltage-frequency converter; MX – analog multiplexer; TT – T-trigger; μs – Microcontroller family 8051; GIPS – galvanized power supply; OP_1,..., OP_4 – digital optocouplers

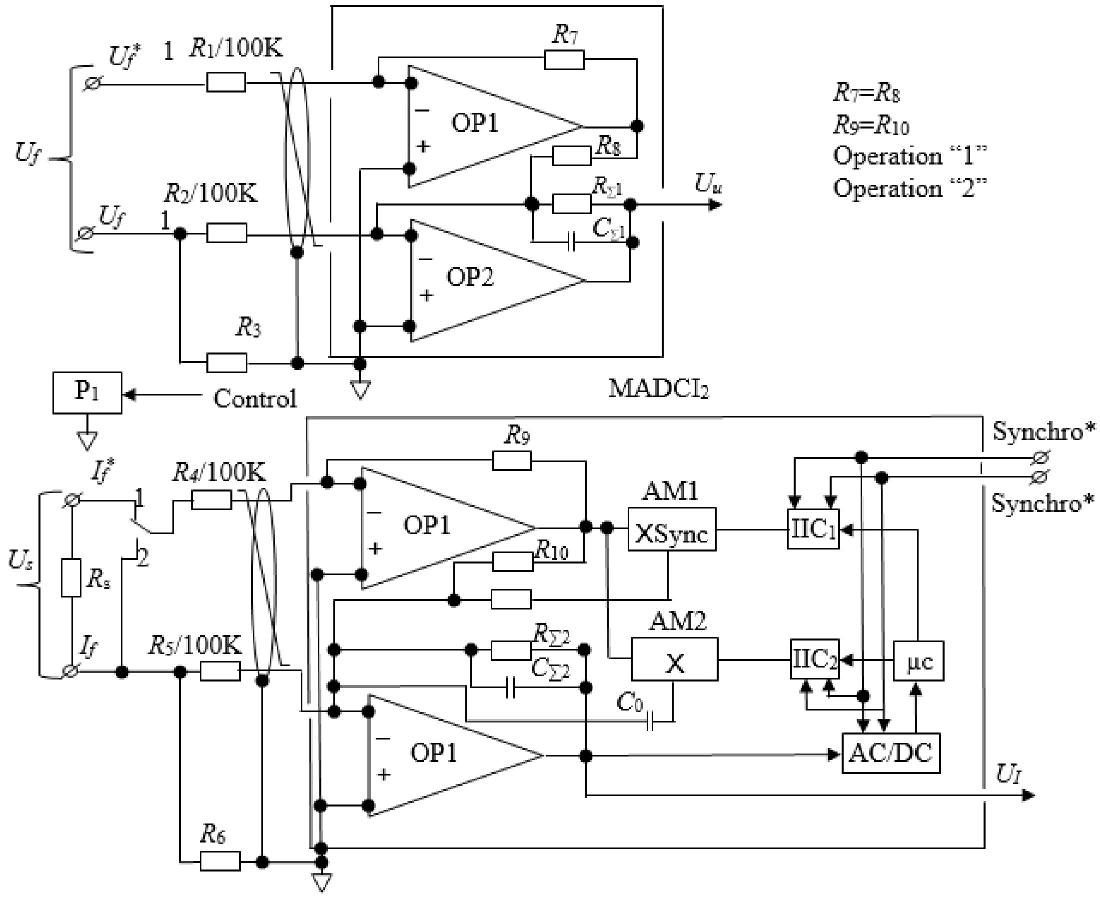

Fig. 2. Block diagram of the switching unit of the input channels of the UIS and the operation of MADCI: AC/DC means the development of a full-wave rectified time waveform

To increase the noise immunity, the MADCI_1 and MADCI_2 signals pass through identical low-pass filters formed by the $R_{\Sigma 1}C_{\Sigma 1}$ and $R_{\Sigma 2}C_{\Sigma 2}$ circuits. At the output of the UIS, voltage U_u and U_I are formed in proportion to the mains voltage and current, respectively:

$$U_u = U_f k_{\text{MADCI}_1};$$

$$U_I = I_f R_s k_{\text{MADCI}_2},$$

where U_f is the voltage for the 3-element circuit or U_s for the 2-element circuit; I_f – phase current; k_{MADCI_1} and k_{MADCI_2} – the value of the transmission factor of the measuring amplifiers MADCI_1 and MADCI_2, respectively.

Since in a two-element circuit, the common-mode voltage can reach several hundred volts, and the in-phase suppression coefficient is determined by the accuracy of fitting the ratio of β-link resistors. Thus, if the ratio of the pairs of resistors differs by 0.1% in the voltage channel, the signal-to-noise ratio will be more than 66 dB, and in the current channel about 0 dB. This means that additional compensation of the in-phase interference effect is required in the current channel, and such compensation is performed in the “U_{com} calibration” mode. In the mode “U_{com} calibration”, the movable contact of the relay P_1 is in position 2. At the same time at the input, MADCI_2 gets in-phase voltage.

The process of “U_{com} calibration” occurs at the position of the switch K1 in position “2”, while the signal “unbalance” U_{out} at the output OP2 is compensated by adjusting the active (R0) and reactive (C0) currents of analog multipliers AM1 and AM2, respectively. The control voltages AM1 and AM2 are formed by PWM modulation of the microcontroller μc according to the program of extreme balancing. The high linearity of the components of the measuring channel makes it possible to implement additive-multiplicative correction of the systematic components of the errors of the entire measuring channel at two points.

In the “operation” mode in the first main clock, the switch of the UIS unit and the MX multiplexer are moved to position “1”, the output voltage of the IIC is converted into a code and stored in memory μc under the name N_1, the output voltage of the IIC will be equal to:

$$U_{\text{IIC}(1)} = R_s I_f U_f k_{\text{MADCI}_1} k_{\text{MADCI}_2} k_{\text{APM}} k_{\text{IIC}} \cos(\varphi + \Delta\varphi) + \Delta_1,$$

where k_{APM} – the transfer factor of the analog multiplier; k_{IIC}– the transfer factor of the iterative integrating converter; φ – phase shift between phase current and voltage; Δφ – the final systematic component of the phase error; Δ_1 – additive systematic component of error.

In the second main clock, the MX multiplexer is moved to position “2”, the output voltage of the IIC is converted into code and stored in memory μc under the name N_2, the output voltage of the IIC will be equal to:

$$U_{\text{IIC}(2)} = R_s I_f U_f k_{\text{MADCI}_1} k_{\text{MADCI}_2} k_{\text{APM}} k_{\text{IIC}} \cos(\varphi - \Delta\varphi) + \Delta_1.$$

In the first auxiliary clock, the MX multiplexer is moved to position “3”, the output voltage of the IIP is converted into code and stored in memory μc under the name N_3, the output voltage of the IIC will be equal to:

$$U_{\text{IIC}(3)} = U_o^2 k_{\text{APM}} k_{\text{IIC}} + \Delta_1.$$

In the second auxiliary clock, the MX multiplexer is moved to position “4”, the output voltage of the IIP is converted into a code and stored in memory μc under the name N_4, the output voltage of the IIC will be equal to:

$$U_{\text{IIC}(4)} = \Delta_1.$$

Then the final result is calculated by the formula:

$$N_p = \left(\frac{\frac{1}{2}(N_1 + N_2) - N_4}{N_3 - N_4} \right) \left(U_\text{o}^* \right)^2 = $$

$$= R_s I_f U_f k_{\text{MADCI}_1} k_{\text{MADCI}_2} \cos(\varphi),$$

where U_0^* – the value of the sample voltage stored in memory μc.

Conclusion

As can be seen from the calculation of the formula, the adjusted result of the measurement does not depend on the additive and multiplicative errors of the measuring channel. In this case, since the error correction was performed at the mains frequency, their frequency component will also be removed, and the accuracy of measurements will be determined by the accuracy class of the shunt R_S and the accuracy class of the DC reference source U_0. On the modern element base, the total error of the measuring amplifiers will correspond to the accuracy class of 0.1, taking into account the frequency component. The results of the study were confirmed by modeling the proposed correction algorithm in the software environment Electronics Workbench with real characteristics of electronic components for general use by computer simulation. In addition, the use of IIC with dynamic storage devices in the analog multiplier as a high-speed averaging device can significantly increase the frequency of PWM, which will reduce methodological errors. It was proved by simulation that the methodological errors (Table 1) at a given PWM frequency of 50 kHz decreases by 2 orders of magnitude.

Прецизійний вимірювальний канал активної потужності

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Анотація

Статтю присвячено підвищенню надійності, завадозахищеності та покращенню метрологічних характеристик вимірювальних перетворювачів активної потужності.

Першим кроком у напрямку забезпечення економії енергоресурсів і зниження фінансових втрат є точний енергооблік. Основним блоком електронного лічильника електроенергії, який визначає похибку останнього і стабільність характеристик у часі та при зміні параметрів зовнішнього середовища, є вимірювальний перетворювач потужності (ВПП). Вимірювання потужності, яка є важливою енергетичною характеристикою, посідає значне місце в сучасній вимірювальній техніці, є одним з основних видів вимірювань у багатьох галузях науки і техніки. Аналіз обсягів втрат електроенергії показав, що значна їх частина зумовлена недоліками в роботі пристроїв обліку електроенергії або низьким класом точності останніх. Тому основною тенденцією в галузі розробки ВПП є підвищення їх точності в робочих умовах експлуатації.

Проблемі розробки ефективних методів побудови структурних схем вимірювальних перетворювачів активної потужності приділяється велика увага. Це пояснюється зростанням вимог до основних метрологічних характеристик вимірювальних перетворювачів активної потужності як елементів інформаційно-вимірювальних систем.

Основна увага приділяється розробці способів корекції впливу дестабілізуючих факторів у робочих умовах експлуатації. Безсумнівною перевагою роботи є ретельний аналіз інструментальних похибок вимірювального каналу, оригінальні засоби корекції фазової похибки та похибки, зумовленої обмеженістю коефіцієнтів придушення синфазних завад.

Проведено глибокий теоретичний аналіз пріоритетних методів, які могли б застосуватися для визначення активної потужності. Одержані результати моделювання в середовищі Electronics Workbench дали змогу визначити найбільш ефективний спосіб захисту від завад.

Ключові слова: вимірювальні перетворювачі активної потужності; корекція похибок; захист від завад нормального та загального виду; перемножувачі; широтно-імпульсна модуляція.

Прецизионный измерительный канал активной мощности

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Аннотация

Статья посвящена повышению надежности, помехозащищенности и улучшению метрологических характеристик измерительных преобразователей активной мощности. Проблеме разработки эффективных методов построения структурных схем измерительных преобразователей активной мощности уделяется большое внимание. Это объясняется ростом требований к основным метрологическим характеристикам измерительных преобразователей активной мощности, как элементов информационно-измерительных систем.

Основное внимание уделяется разработке способов коррекции влияния дестабилизирующих факторов в рабочих условиях эксплуатации. Несомненным преимуществом работы является тщательный анализ инструментальных погрешностей измерительного канала, оригинальные средства коррекции фазовой ошибки и погрешности, обусловленной ограниченностью коэффициентов подавления синфазных помех.

Полученные результаты моделирования в среде Electronics Workbench позволили определить наиболее эффективный способ защиты от помех. Статья посвящена повышению надежности, помехозащищенности и улучшению метрологических характеристик измерительных преобразователей активной мощности.

Ключевые слова: измерительные преобразователи активной мощности; коррекция ошибок; защита от помех нормального и общего вида; умножители; широтно-импульсная модуляция.

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