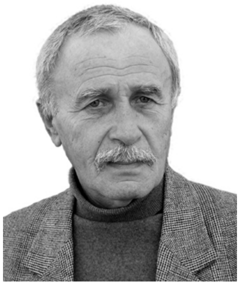

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STATUS AND TRENDS IN DEVELOPMENT OF AC MEASURING THERMOELECTRIC CONVERTERS

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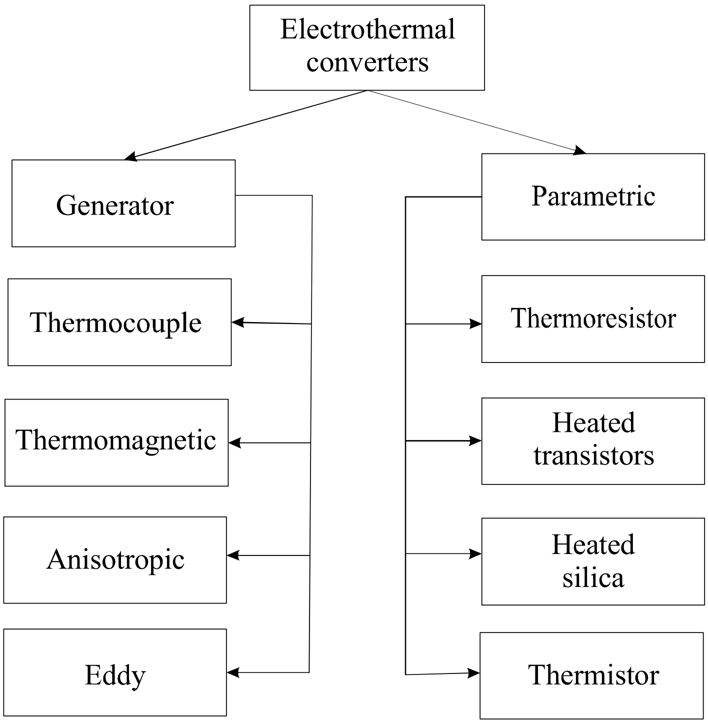
• *Based on comparative analysis of measuring thermal converters made by different techniques, their advantages and shortcomings are briefly characterized, promising lines of theoretical and experimental studies aimed at creating new devices to suit present day requirements, are substantiated.*

Introduction

The only true measure of electric signal power is its effective value. Only this value precisely reflects signal power and, respectively, opens up the possibility of direct and rigorous comparison of thermal action of DC and AC currents regardless of their form by electrothermal method [1].

Table 1

Classification of electrothermal AC converters



The prototype for electrothermal device was thermal cross used to study thermal action of current, created by Peltier in 1834. In 1884 N. A. Gesehus proposed to use a similar thermal cross as a device for measuring current strength in electric circuit. The Gesehus device consisted of two thermopiles with their junctions mounted into reservoirs of air differential thermometer. As electric current was passed through thermopile, thermometer recorded temperature change proportional to current strength [3].

Classification given in Table 1 covers known devices that for conversion may employ different physical effects, such as temperature dependence of thermistor resitance, frequency change due to silica heating, etc. Common to all kinds of converters is conversion of measured signal into thermal energy that is released in the heater. The most widespread heated noncontact converters of generator type based on thermocouples will be considered in more detail below.

The relevance of research is due to drastically increased requirements to accuracy of measurement of AC electric values in wider frequency range and the fact that metrological centres of many countries pursue active search for new technical solutions and develop high-precision measuring instruments and means for their measurement assurance.

The purpose of this review – based on comparative analysis of measuring thermal converters made by different techniques to briefly characterize their advantages and shortcomings, substantiate promising lines of theoretical and experimental studies aimed at creating new devices to suit present-day requirements.

Classification and comparative analysis of measuring thermal converters

The basic component of thermoelectric comparison method is measuring thermal converter in which the energy of measured current is converted into thermal energy, released in resistive heater, and subsequent conversion of thermal into electric energy by means of thermoelement (thermocouple). The heater serves as the input circuit of thermal converter, the thermocouple – as the output circuit. Relation between current supplied to the heater and EMF developed by thermoelement E_T is approximately described by expression

$$E_T = KI_H^2, \tag{1}$$

where K is coefficient depending on the heater and thermoelement material, thermal converter design and its operating conditions.

From expression (1) follows the main property of measuring thermal converters – independence of EMF at its input on current direction in the input circuit, which allows using measuring thermal converters to measure the effective values of alternating current, power and other values [2].

With a knowledge of relationships between the variable values of currents supplied to thermal converter and thermocouple thermoEMF, it is possible to measure alternating currents by means of direct current equipment. High accuracy of thermoelectric method is based on the results of all-round study of physical effects and thermal processes occurring in thermal converters and their influence on conversion accuracy. Thus, the accuracy of measurement of AC values is largely dependent on the quality of thermoelectric converters.

In the course of their development, thermocouple measuring converters constantly improved, their designs were changed to improve the accuracy and reliability of measurements. Table 2 gives classification of thermal converters in which different methods are used to realize relation between the input and output circuits.

Generalized model of thermocouple measuring converter and its equivalent electric circuit are given in Fig. 1 *a, b.*

This converter realizes the simplest conversion of measured value signal power P to power of converter output signal

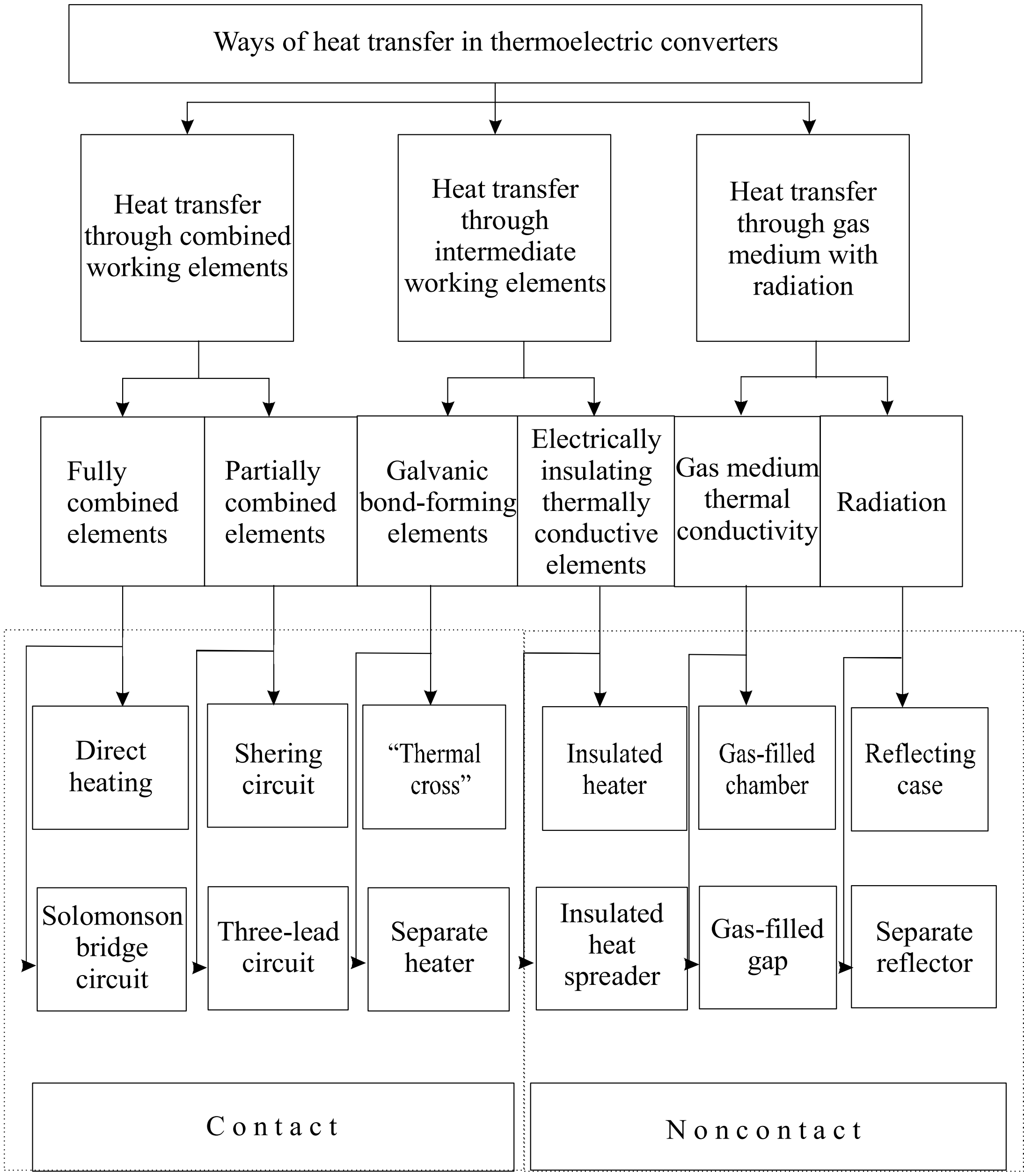
$$P = K_0 P_{out}, \tag{2}$$

where K_0 is coefficient characterizing conversion efficiency [5].

Consider the models of directly heated thermal converters (Fig. 2).

Table 2

Classification according to the way of heat transfer between the input and output circuits



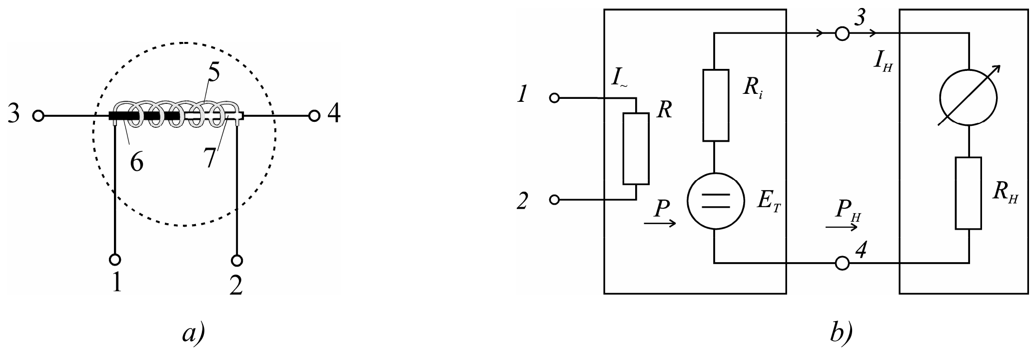


Fig. 1. Model of generator thermoelectric converter (a) and its equivalent circuit with attached measuring instrument (b). 1, 2 – input circuit; 3, 4 – output circuit; 5 – heater; 6, 7 – thermocouple legs.

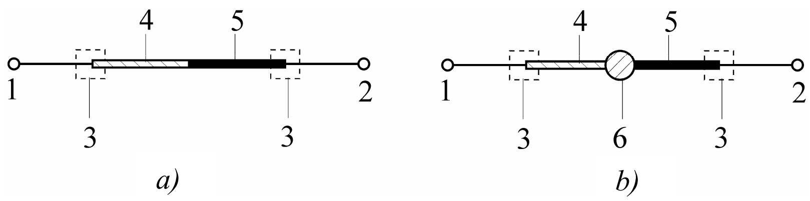


Fig. 2. Models of directly heated thermoelectric converters:
a) with additional heater; b) 1, 2 – electric leads; 3 – thermostat;
4, 5 – thermocouple legs; 6 – additional heater.

Directly heated converter the model of which is shown in Fig. 2*a*, has no separate input and output circuits. The thermocouple consisting of legs 4 and 5 serves simultaneously as the input and output circuits. Alternating current measured in such thermal converter flows through thermocouple, heating its legs and junction. Constant EMF component generated by thermocouple is removed from its cold ends (T_a) to direct current measuring instrument.

Such thermal converters offer the advantage of maximum design simplicity and minimum number of working elements. It is really possible to minimize thermal losses and, hence, to achieve high sensitivity and maximum speed of response.

The disadvantage lies in the impossibility of their direct current calibration as a result of distorting action of the Peltier and Thomson effect, low accuracy of conversion, limited frequency range.

The model explaining the operating principle of directly heated thermal converter by means of bridge circuit is shown in Fig. 3.

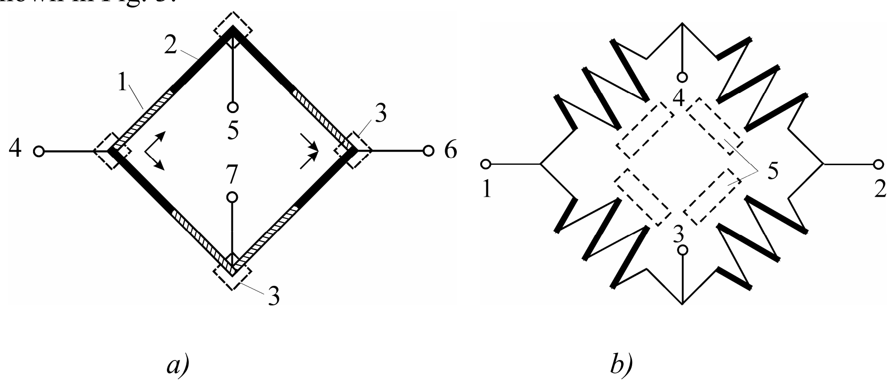


Fig. 3. Models of thermal converters with the use of bridge circuit:
a) single-element, b) multi-element.
1, 2 – thermocouple legs; 3 – thermostats (T_0); 4, 6 – contacts for
measured current supply; 5, 7 – thermoEMF leads.

As can be seen from Fig. 3, the bridge circuit of thermal converter consists of four properly connected thermocouples, through which the measured current flows. Each of the thermocouples is, in fact, the above considered directly heated thermal converter. The output thermoEMF of the four parallel-in-series connected thermocouples is brought out to direct current measuring instrument.

Fig. 3 shows a model of multi-element converter made with the use of the bridge circuit with designations: 1, 2 – input; 3, 4 – output, 5 – thermostats.

Directly heated converters based on the bridge circuit principle can be manufactured for any number of thermocouples multiple of four, in which case each arm of the bridge includes *n* thermocouples, allowing increase in the figure of merit *A* [4].

Increase in the figure of merit is important for the manufacture of precise and reliable portable thermal instruments.

The advantages of directly heated thermal converters with the bridge circuit include high sensitivity and speed of response.

The shortcomings include large common portion of AC and DC circuit restricting frequency application range, impossibility of DC calibration and manufacturing complexity, as a consequence – low conversion accuracy.

Fig. 4 shows a model of thermal converter with partially combined elements.

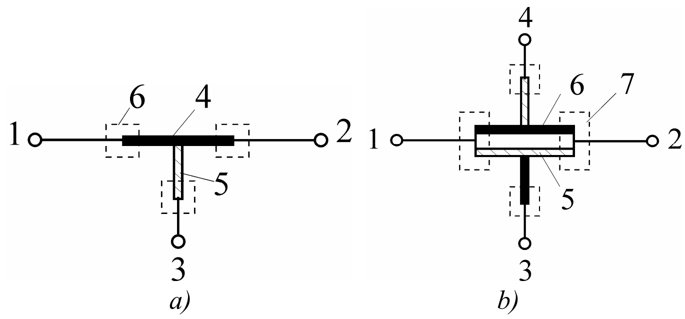


Fig. 4. Model of directly heated thermal converter with partially combined elements (a).
Thermal converter with partially combined elements based on the Shering bridge circuit (b).
In Fig. 4: 1, 2 – input circuit; 2, 3 – output circuit;
4,5 – thermocouple legs; 6 – thermostat.

In thermal converter the model of which is shown in Fig. 4, the measured alternating current flows across one of the legs of thermocouple 1, however, it does not pass from one material to another, as it is the case in the above considered thermal converters. It is possible to partially solve the problem of independent optimization of input and output circuits of thermal converter, which is impossible in directly heated converters, wherein the heater and thermocouples are fully combined.

Thermal converters of three-lead circuit are used in transformer converters where a heater is powered from separate secondary winding of measuring transformer and calibrated by alternating current of reduced frequency [9, 16].

If we make mirror image of thermal converter elements (Fig. 4*a*) and interchange material of thermocouple legs, we obtain a thermal converter based on the Shering bridge circuit, Fig. 4*b* with designations: 1, 2 – input; 3, 4 – output; 5, 6 thermocouple legs – heaters; 7 – thermostats.

Such thermal converter consists of two directly heated series-connected thermocouples. One of the legs of each thermocouple consists of two parallel-connected legs (is bifurcated). If a rectangle formed by bifurcation of both thermocouples is symmetric in the impedance, thermal current will not get into measuring circuit, and measured current – into thermoEMF meter.

The shortcomings of such thermal converters include relatively large common portion of AC and DC circuit, restricted frequency range and complexity of manufacturing well balanced bridge circuits, restricted choice of materials. Materials for legs of current-heated thermocouples should be chosen with close thermotechnical and temperature coefficients.

Further expansion of working frequency range and increase in the accuracy of AC signals conversion is achieved in thermal converters in which common portion of combined elements is reduced to point contact. The simplest thermal converter of this type is "thermal cross" (Fig. 5), formed by connection of two thermoelectrodes in the geometrical midpoint. The input circuit is formed by conductor segments from the point of connection to contacts 1, 2, and the output circuit – by segments from the point of connection to contacts 3, 4. Like in directly heated thermal converter, the heater consists of segments of two materials, and operating current passes from one material to another, which does not allow this thermal converter to be used on direct current. Another shortcoming of thermal converter of "thermal cross" type is impossibility of separate optimization of input and output circuit parameters. Thus, in the development of thermal converters for large currents, when forming the heaters, half of the thermocouple wire must be of large section, which will result in thermal inertia growth and heat removal from the hot junction, hence, the sensitivity will be reduced [12]. For reasons indicated above, thermal converters of "thermal cross" type are of limited application.

a) *b)*

*Fig. 5. Model of thermal converter of "thermal cross" type (a)
and contact thermal converter with a separate heater (b).
In 5a: 1, 2 – heater circuit; 3, 4 – thermocouple circuit;
5 – thermostat; 6,7 – thermocouple legs.*

Relatively high parameters and characteristics are peculiar to contact thermal converters with a heater in the form of a linear section of conductor made of resistive material. In the geometric midpoint the heater is connected (for instance, by welding) to thermocouple junction, Fig. 5, with designations: 1 – heater; 2, 3 – thermocouple legs; 4 – thermostat.

In this converter the heater properties can be optimized in conformity with temperature and frequency requirements regardless of thermocouple legs material properties. In the constructions of contact thermal converters the accuracy of conversion is greatly improved and the frequency range is considerably expanded.

A limitation of such thermal converters is the presence of galvanic contact between the input and output circuits, which results in the error increase at high frequencies. Thermal converters in which electric contact between the heater and thermocouple is absent, and thermal contact is realized through electric insulator of material with a good thermal conductivity are called noncontact [14].

In the noncontact thermal converter, in heat spreader in the form of insulation drop, considerable improvement of metrological and operational characteristics is achieved. It is primarily predetermined by galvanic decoupling of the input and output thermal converter circuits. The value of resistance of insulation heat spreader is provided more than 100 MOhm, which essentially reduces the possibility of alternating current penetration to thermocouple circuit and, hence, measuring instrument.

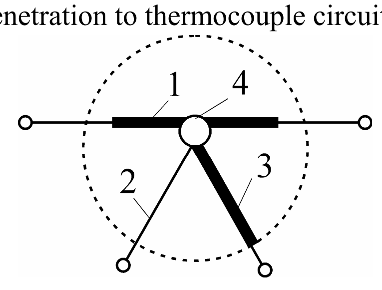


*Fig. 6. Model of noncontact thermal converter with one thermocouple:
1 – heater; 2,3 – thermocouple legs; 4 – insulation "drop".*

Besides, heater and thermocouple materials can be independently optimized in conformity with thermal and electric requirements to provide optimal conversion conditions. Owing to this, in the noncontact converters considerably lower conversion errors were achieved in the range of alternating current frequencies.

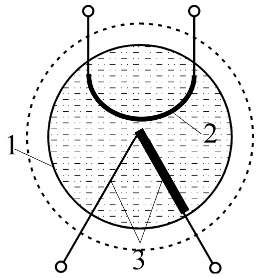


Fig. 7. Model of converter with a heat spreader in the form of a capsule filled with gas.
1 – capsule, 2 – heater, 3 – thermocouple.

Reduction of asymmetry error without considerable degradation of frequency characteristic of thermal converter is achieved in devices (Fig. 8, *b*) with increased area of thermal contact between the heater and thermocouple formed by heat spreader in the form of a capsule filled with high thermal conductivity gas, such as hydrogen.

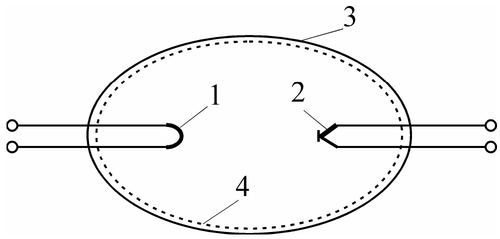


Fig. 8. Model of converter with ellipsoid-shaped case.
1 – heater; 2 –thermocouple; 3 – case; 4 - reflecting coating.

Further improvement of frequency characteristics, as well as increase in breakdown voltage value, is achieved in thermal converter with radiation heat transfer. Design of such thermal converter is shown in Fig. 8. The converter is mounted into a case shaped as ellipsoid of revolution, the internal surface of which is coated with reflecting film. Close to one of ellipsoid foci is a heater, and to the other – a thermocouple with a receiving pad. For reduction of convective losses the case is evacuated. In such devices the heater and thermocouple can be located at relatively large distances enabling considerable reduction of the value of coupling capacitance and the influence of high-frequency currents on thermocouple output circuit.

Experience of development and use of noncontact converters contributed to creation of devices with extended functional opportunities and increased accuracy of alternating current conversion. Such measuring converters, similar to well-known classification of measuring means [4], can be tentatively divided into converters of measured values and converters of measured and auxiliary values.

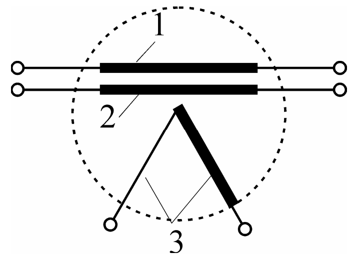


Fig. 9. Model of converter-adder.
1, 2 – heater; 3 – thermocouple.

Classification of thermal converters according to the number of converted values is given in Table 3.

Fig. 9 shows a model of converter-adder. Converter-adder consists of two electrically insulated heaters having thermal contact with a thermocouple or a thermopile.

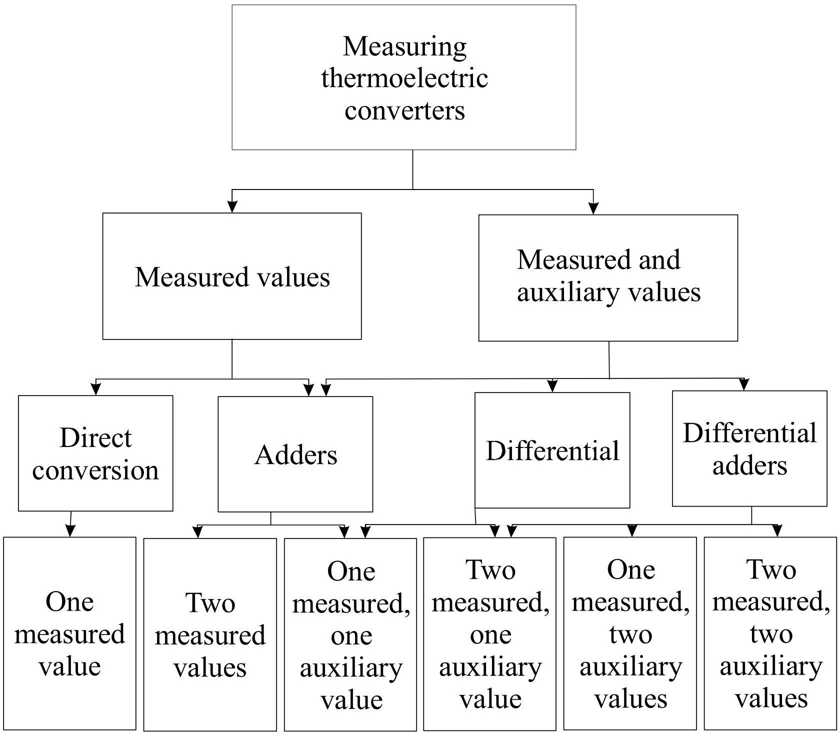
This converter realizes conversion of the type:

$$E_T = k\left(I_{H1}^2 + I_{H2}^2\right), \tag{3}$$

where I_{H1} and I_{H2} are currents in heaters 1 and 2, respectively (Fig. 2).

Table 3

Classification of thermal converters according to the number of converted input values



Currents I_{H1} and I_{H2} can be induced by supply to converter inputs of two independent measured signals or one measured and one auxiliary signal. In the former case output thermoEMF E_T is a function of the sum of two measured values, in the second case it is possible to realize original conversion method that came to be known as equal temperatures method [6]. In this case, with a change in measured value, the auxiliary value is changed such that the total power of both converted values remains constant and the operating temperature of thermocouple junction does not vary. The temperature that is kept constant is chosen optimal for given thermal converter, that is, when maximum value E_T, satisfactory accuracy of conversion and stability are provided simultaneously. In case of using equal temperatures method, the influence of temperature dependences of heater and thermocouple material parameters on the accuracy of conversion and nonlinearity of thermal loss is reduced [7].

Low operating and metrological parameters of converters with metal thermocouples complicate their use in the development of up-to-date electric measuring instruments that call for application of various structural methods of precision improvement [8, 9].

In a differential converter two identical heaters are in thermal contact with the junctions of differential thermocouple.

Such a converter realizes conversion of the type:

$$E_T = k(I_{H1}^2 - I_{H2}^2) \ . \qquad (4)$$

Heater currents I_{H1} and I_{H2} can be induced both by signals of two measured values of alternating current and one value of alternating current and one auxiliary value of direct current.

Fig.10 shows models of differential converters.

The above brief classification represents the basic types of models of thermoelectric converters that serve the basis for creation and improvement of present-day alternating current converters according to new technological principles.

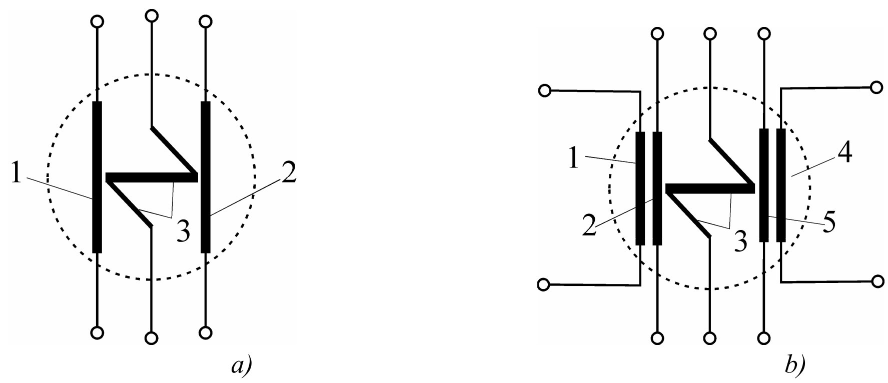


Fig. 10. Model of differential converter (a) and differential adder (b).
1, 2, 4, 5 – heaters; 3 – differential thermocouple.

Today there are three main lines in their development:
- cryogenic converters based on the Josephson effect [10, 11];
- converters based on semiconductor optimized materials [12–15];
- thin-film converters [16, 17].

Cryogenic converters based on the Josephson effect are highly sensitive and primarily used to investigate minimum values of alternating current. However, the high cost and complexity of such systems restrict their wide application.

Film converters based on microelectronic technology are distinguished for high reproducibility of parameters, identity and precision of direct current conversion. Their disadvantages include restricted frequency range of conversion and high resistance of film thermopile, involving high noise level [18].

Development of semiconductor thermoelectric materials optimized according to requirements of measuring technique and metrology, has created backgrounds for basically new approaches to design and manufacture of thermoelectric converters:

– achievement of sensitivity 100 V/W created conditions for expansion of the range of measured alternating currents toward low rated values to 0.1 mA;

– reduction of operating temperature of the heater by a factor of 10–15 (as compared to converters based on metal thermocouples) increased the overload capacity and reduced the influence of the Thomson effect on the accuracy of direct current conversion;

– high sensitivity of semiconductor thermocouples made it possible to do away with evacuation of the working volume of converters with sensitivity to 10 V/W and diversify considerably the choice of structural materials, for example, for expansion of operating frequency range to 500 MHz;

– abandonment of evacuation and filling the working volume of one thermocouple-converters with gas mixture enabled deviation from conversion square-law characteristic 0.01–0.005%;

– use of semiconductor thermocouples allows improving the performance of converters by a factor of 10 and more.

Conclusions

Alongside with a search and use of new physical effects for creation of high-sensitive primary measuring converters (for example, based on the Josephson effect) and up-to-date technologies of their manufacturing, it remains relevant and promising to study in detail:

– thermal conditions and temperature operating conditions of semiconductor thermal converters;

– influence of configuration and material properties of fuel elements and thermoelement shape on thermal processes;

– peculiarities of heat exchange in gas-filled device constructions.

It opens up additional opportunities for the elaboration of new designs of semiconductor thermal converters:

– differential, with highly identical characteristics, increased output signal, reduced frequency error and increased reliability;
– small-size, with increased speed of response and expanded frequency range;
– shielded, with large functional opportunities for operation in electromagnetic fields;
– high-sensitive converters for low values of rated currents.

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