# Thermal Wattmeter with Direct Power Conversion

L. Grno

*Abstract*-**A thermal wattmeter with a-novel method of direct power to voltage conversion is described. The conversion is based on power substitution by a three-terminal thermoconverter (TTTC). The TTTC is principally a thermally isolated heater with dynamically controlled impedance enabling simultaneous application of mutually independent current and voltage. The power dissipated in the heater is directly converted into output voltage or current in dual self-balancing thermal bridge circuit.**

## I. INTRODUCTION

EXTENDED exploitation of high-speed switching components in industrial electronics like power converters and inverter power sources has evoked an increasing demand for a broad frequency range of power measurements. High-frequency noise in a power system may significantly affect classical measuring equipment. we have developed a novel method of direct broad-band power measurement based on ac-dc substitution by a three-terminal thermoconverter (TTTC). The TTTC is principally a thermally isolated heater with dynamically controlled impedance. The impedance control enables simultaneous application of mutually independent current through and voltage across the heater. A simple realization of TTTC based on an operational amplifier-controlled FET with its drain-source channel as the heater is principally shown in Fig. 1.

The TTTC has three terminals: the voltage terminal VT, the current terminal CT, and the common terminal GND. An operational amplifier having the FET in a negative feedback loop keeps zero potential difference between the current terminal and the GND terminal and this way ensures the voltage across the source-drain channel of the controlled FET to be equal to the voltage applied across the VT and GND terminal

$$U_{sd} = U_{vt\text{-}gnd} \tag{1}$$

and the current through the sourcedrain channel of the controlled FET to be equal to the current forced into the CT terminal

$$I_{sd} = I_{ct}\ . \tag{2}$$

The dissipated power $P_{sd} = U_{sd} I_{sd}$ heating the FET is fully determined by the external voltage and current sources; that is, 'the electrical parameters of the transistor do not explicitly affect the dissipated power.

The structure shown in Fig. 2 consists of two controlled FET's Qa and Qb and temperature sensor TS on a thermally isolated common substrate. Thermal symmetry of Qa and

Manuscript received July 1, 1994; revised October 15, 1994.

The author is with the Slovak Institute of Metrology, 842 55 Bratislava, Slovakia.

IEEE Log Number 9408693.

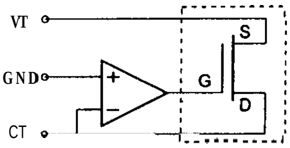


Fig. 1. Principal TTTC circuit.

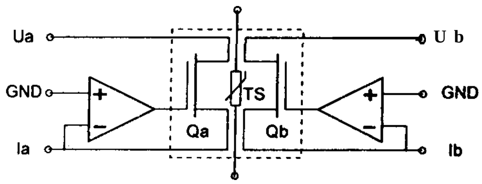


Fig. 2. Principal diagram of dual TTTC.

Qb, referred to the temperature sensor TS, enables mutual substitution of dissipated power originating in two independent sources. If the temperature of the substrate is kept constant by controlling the power dissipated in Qb, then, supposing constant environmental temperature, we obtain

$$\Delta P_a = -\Delta P_b \tag{3}$$

Controlling the power by means of control of the voltage Ub at constant current Ib or by control of the current Ib at constant voltage *Ub* and using the controlled quantity as output quantity we have a power-to-voltage converter or a power-to-current converter, respectively.

The complete self-balancing thermal bridge circuit, the basic unit of the TTTC-based powermeter, is shown in Fig. 3. The dc voltage and current $U_{ofs}$ and $I_{ofs}$ produce dc offset ensuring the correct working point for the multiplying FET at all possible combinations of the four-quadrant input signal Uac and Iac values. The thermally symmetrical supports S1 and S2 create a thermal bridge suppressing influence of environmental temperature fluctuations. The support S2 is heated by an auxiliary power source creating a reference temperature for the thermal bridge. Zero temperature difference between S1 and S2 means equality of power dissipated on S1 and S2; thus constant auxiliary power on S1 keeps constant sum of dissipated power on S2.

The basic balance equation of the circuit according to Fig. 3 is

$$\frac{1}{T}\int_0^T (U_{ofs} + U_{ac})(I_{ofs} + I_{ac})\,dt + U_{out}I_{dc} = \text{const} \tag{4}$$

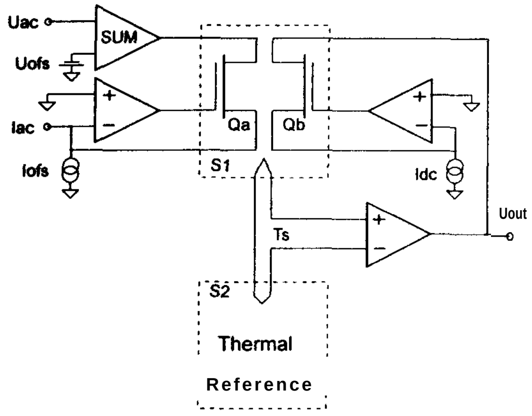


**Fig.** 3. Automatic self-balancing thermal bridge.

which for zero mean values of $U_{ac}$ and $I_{ac}$ signals for increments of $U_{out}$ yields

$$\Delta U_{out} = -\frac{1}{I_{dc}T}\int_0^T U_{ac}I_{ac}\,dt. \qquad (5)$$

## II. Measurement Uncertainty Sources

For precise power measurement, the following major TTTC measurement uncertainty sources have to be considered:

1) thermal asymmetry of heater transistors referred to the temperature sensor;
2) power dissipation in thermal isolation section;
3) power dissipation due to transistor control.

The thermoelectric effects which are the most important sources of ac/dc differences in classic thermoconverters affect the measurement by different temperature distribution along the heater for ac and dc signals. Due to the negligible size of the drain-source channel of the FET (a few micrometers) creating the heater of the TTTC and its location on thermally isolated support the thermal gradients causing ac/dc difference are expected to be negligible.

The sources 1) and 2) can be easily determined by external evaluation and then corrected. The power dissipated in the FET due to its control is directly determined by electrical parameters of the FET. The value is nonlinearly dependent on values and the relation of applied voltage and current signals so it cannot be directly eliminated but it can be minimized and kept on a negligible level by an appropriate transistor construction and its working point selection.

## III. Sensors

We have implemented very simple experimental monolithic TTTC power sensors based on Si MOSFET to verify the principle and the electronics. The sensors consisting of thermally isolated chips with standard MOSFET transistors achieved thermal resistance approximately 1400 K/W.

A GaAs MESFET sensor based on especially designed transistors and novel circuit topology is being developed in cooperation with the Institute of Electrical Engineering of the Slovak Academy of Science [3]. The thermal resistance of the latest version of these MESFET sensors has exceeded 5200 K/W, that is, the working point approximately 100 K above the environmental temperature can be excited by less than 20 mW of dissipated power. The on-chip integrated Shotky diode as temperature sensor with sensitivity 2 mV/K yields responsivity over IO V/W. The value of transconductance of the implemented MESFET's is approximately 4 mA/V and its open resistance is 150 Ω.

## IV. Experimental Results

**We have** tested the linearity (only voltage input varied) and quadraticity (voltage and current inputs varied simultaneously) **of the Si MOSFET** TTTC by comparison with DATRON 4808 calibrator at 1 kHz. The deviations from linear and quadratic regression function did not exceed 50 ppm.

Si MOSFET TTTC wired as a square-law converter by driving the current input with a low-inductance resistor from the voltage input was used to measure the output voltage of a FLUKE 5700A calibrator at constant voltage settings and varied frequencies. The measured deviations from the best fitting linear regression function in the frequency range from 100 Hz to 500 kHz did not exceed 70 ppm.

A commercial three-phase power analyzed based on Si MOSFET TTTC equipped with broad-band electronically compensated glass-metal current transformers and differential voltage inputs having. 0.1% maximum measurement error specification has been evaluated in PTB, Braunschweig. The evaluation results at 220 V, 5 A, 53 Hz, and cos(ϕ) values from 0.25 to 1.00 both inductive and capacitive, showed error values from 0.0026% to 0.060%.

## V. Conclusion

The basic evaluations show the thermal power converter to be capable of providing exactly defined power measurement up to the megahertz range. The broad frequency range and the transparency of the power conversion predestine the TTTC for precise power measurements not only of harmonic signals but also of distorted current and voltage waveforms. Extensive applications of the TTTC as an accurate multiplier are expected.

Further work is aimed at the improvement of accuracy and reliability of the sensors for broadband power standards and development of commercially available all-purpose precision multipliers for power and energy meters,' synchronous rectifiers, phase sensitive detectors, etc.

## Acknowledgment

The author thanks R. Bergeest and M. Kahman, PTB Braunschweig, for valuable help and encouraging discussions, and T. Lalinsky and M. Porges, IEE of the Slovak Academy of Science, for development of the GaAs MESFET samples.

## References

[1] L. Gmo and J. Groch, "Precise direct measurements of phantom power by three-terminal thermoconverter." in CPEM'92 Dig., Paris, France, June 1992, p. 80.
[2] L. Grno et al., "Leistungsmesskonverter," German Patent 4 117 133.
[3] J. Kuzmik et al., "DC performance of short-channel ion-implanted GaAs MESFET's," *Solid-State Electron., vol. 33, no. 10,* pp. 1990.