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Pulse Form of Magnetron Anode Current Based Determination of Microwave Power Transferred to Reactor

Abstract. *An important task in designing microwave industrial plants is to determine actual power going into a process reactor. A part of magnetron power reflects from the microwave reactor into generator due to the processed material property changes. It results from dielectric property changes, due to changes of temperature, humidity, variation of boundary conditions in the reactor when moving the product. Moreover, the reflected wave significantly changes the magnetron regime of operation. The article shows that the power transferred to the processed product can be determined based on changes in the current pulse form when using a classic power supply (high-voltage transformer and a voltage doubling circuit) and power supply with invertor. Also it is possible to estimate the mutual influence magnetrons on each other in microwave installations with multi generator scheme. The difference in the operation of the classic power supply and inverted power supply leads to necessity for different power determining algorithms. Microwave power in the load determined experimentally coincides with the microwave power calculated by the developed method, which confirms the reasoning of the algorithm used*

Key words*:* magnetron, anode current, microwave power, matching with load, transformer power supply, inverter power supply

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Определение уровня микроволновой мощности, переданной в реактор, по форме анодного тока магнетрона

Аннотация. *Важной задачей при создании микроволновых (СВЧ) промышленных установок является определение фактической мощности, идущей в технологический реактор. При воздействии микроволновой энергии на материал в реакторе часть мощности отражается в генератор из-за изменений свойств обрабатываемого материала, а именно: из-за изменения диэлектрических свойств при изменении температуры, из-за уменьшения массы и влажности в процессе сушки, из-за изменения граничных условий в реакторе при перемещении обрабатываемого материала. Кроме того, отраженная волна существенно влияет на режим работы магнетрона. Целью данной статьи является определение микроволновой мощности, идущей в нагрузку, по форме анодного тока в низкочастотной цепи питания магнетрона. В статье показано, что по изменениям формы* *тока для трансформаторного (построенного с использованием высоковольтного трансформатора и схемы удвоения напряжения) и инверторного блоков питания можно определять мощность, переданную обрабатываемому продукту. По изменению тока магнетрона можно оценивать и взаимное влияние магнетронов друг на друга в установках, использующих многогенераторную схему построения системы возбуждения реактора. Отличия в работе трансформаторного и инверторного блоков питания приводят к необходимости создания разных алгоритмов определения мощности. Представленные данные экспериментальных исследований по верификации предлагаемого алгоритма показали приемлемое соответствие мощности, рассчитанной и экспериментально измеренной при разных значениях КСВ нагрузки.*

Ключевые слова: магнетрон, анодный ток, микроволновая мощность, согласование с нагрузкой, трансформаторный блок питания, инверторный блок питания

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Introduction. Nowadays commercial microwave plants are increasingly used in various fields: for thermal processing of food products [1], disinfection of medical wastes and instruments [2], obtaining new materials [3], etc. Alongside with technical term "microwave power" Russian authors often use "super-high frequency power" (SHF) as its synonym.

Microwave power application benefits include short-time heating response, absence of coolant and no need for temperature gradient. Special feature of microwave heating is also selectivity of affecting process material due to the difference in its dielectric properties. It induces the difference in depth of field penetration into different materials as well [4].

To achieve required power density in the process material design engineers often combine of mid-size power magnetrons (of about 1 kW) together with power supply units included in configuration of domestic microwave ovens. Lifetime of magnetrons produced in millions makes about 5000 hours charging €200…300 for 1 kW of electric power. Such approach allows to reduce the cost of microwave equipment and makes reliability excellence of the entire system.

Technological requirements to the modes of material processing are ensured by the right choice of operation frequency of generators, their number, and optimal design of microwave reactor. It is known that energy efficient operation regime is realized when it matches up with the transmission line and reactor in the chosen frequency range. At that, the voltage standing-wave ratio (VSWR) in the transmission line is equal to unity. However, during processing the product (or material) changes its dielectric properties, mass, moisture content, density and position which results in change of matching adjustment. Some amount of energy bounces off and enters the microwave generator that causes change of generator frequency and its output capacity. Considerable reflection might lead to generator failure or magnetron breakdown. This phenomenon is commonly referred to as generator pulling. In this case, processing mode control goes down, as the load power of the generator and frequency of its operation are unknown. As a result, it is impossible to forecast heating temperature and to estimate properly energy dose received by the product.

Use of coupler together with measuring equipment for determination of VSWR [5] increases the bottom-line price of microwave equipment as well as manufacturing complexity. During the development of equipment for producing high-level power the difficulty in operational evaluation of magnetron and load matching adjustment is caused by the magnetron mounting directly onto the reactor without any regular transmission [6]. In this case incoherent source power combining occurs directly in the microwave reactor and at the same time there might take place cross effect of magnetrons with similar operating frequency. It might give rise to the pulling effect even with good load matching adjustment. Operational tracking of magnetron cross effect is quite a complicated engineering task. The method developed provides one of options for its solution.

The purpose of this paper is to define evaluation criteria for the power transferred by the magnetron to the load based not on the VSWR but on the current pulse form in the magnetron supply line.

Magnetron anode current pulse form analysis. To determine the energy given up by the magnetron we make analysis of the magnetron power supply unit parameters and in particular the anode current waveform in relation to matching adjustment conditions. To obtain operating voltage of the magnetron included in household microwave ovens two types of power supply units are mostly used: inverter and transformer (with saturated high voltage transformer and voltage doubling circuit).

Experimentally measured anode voltage and anode current oscillograms are obtained by means of digital oscilloscope Agilent Technologies DSO3102A. The magnetron anode voltage is measured with the

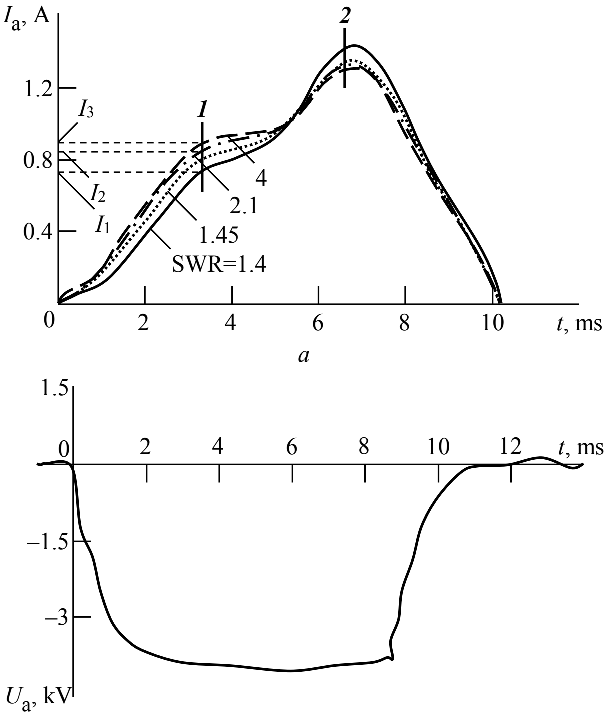

Fig. 1

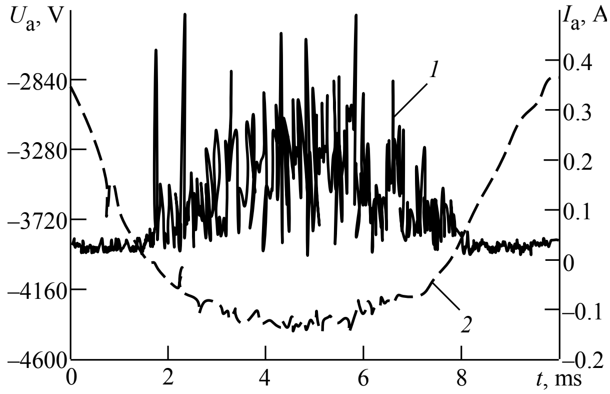

Fig. 2

use of oscilloscope and high voltage bleeder DNV-40, the anode current is measured with the use of Ohm resistor and power dissipation of 5 W. The measurements are made at the special laboratory bench [7].

The current oscillograms (at different VSWR level) and anode voltage for transformer power supply unit are provided in fig. 1, *a, b*. As it is shown in [7], the availability of current in local points (points 1 and 2 in anode current pulse form) is determined by nonlinear characteristics of saturated high voltage transformer [8] and magnetron itself.

As computer simulation (LTSpice) of nonlinear voltage doubling circuit with a saturated high voltage transformer shows, the current in local points 1 indicates a moment of core saturation [7]. When matching adjustment degrades, the current magnitude changes from I_1 to I_3. The authors relate occurrence of the local points 2 with VSWR degradation to physics of the process of sorting electrons passing inside the magnetron.

The power supply unit high voltage transformer operates in saturation mode and restricts power transmitted to the magnetron. Hence, the transformer restricts the magnetron current but according to measurement results, when matching adjustment is changing its average value remains constant. Current pulse form change is connected with the change in proportion of useful electrons and harmful electrons under non-optimal conditions of magnetron generation caused by the load changes ("sorting" process).

Inverter power supply has a high-voltage transformer and a voltage doubling circuit (similar to transformer power supply) with an output half-wave rectifier. The magnetron generation voltage is about 4000 V. To downsize the inverter power supply (high voltage transformer in particular) the transformer input frequency is increased up to 20…40 kHz instead of 50 Hz for a typical transformer unit. Controlling device of the inverter power supply assigns PWM modulation that specifies magnetron generation period from 4 to 14 ms. Control PWM signal modulated by the frequency of 20…40 kHz (depending on the power supply unit manufacturer) [9] arrives at the power transistor input and switches voltage to the high-voltage transformer input winding.

The inverter power supply benefits include magnetron power adjustability by change of duty ratio. With the decrease of PWM duty ratio, discharge of high-voltage power supply unit decreases. It results in the magnetron average current variations that in its turn results in the output power variations. Fig. 2 shows the magnetron current line 1 and voltage waveforms line 2 at maximum power output.

As is shown in [10], the magnetron average current (for each value of PWM duty ratio) increases with the increase of VSWR owing to the increase of the amount of harmful electrons in magnetron interaction distance. By means of measuring bench, current value was defined for each PWM level with unit VSWR. In contrast to transformer power supply where the magnetron current and hence its power is restricted by high-voltage transformer, in inverter power supply the value of current in the magnetron anode circuit is specified by the magnetron properties.

Processes taking place within magnetron interaction distance. To explain the increase of anode current when PWM level decreases we consider the processes taking place within magnetron interaction distance at the steady state condition of generation, when magnetron operates with the transformer power supply.

In the magnetron interaction distance under stationary operation condition, in the presence of high frequency electric field between adjacent resonators there are two types of electrons: useful electrons and harmful electrons. The useful electrons transfer part of their kinetic energy to decelerating high-frequency electric field and moving along cycloidal path arrive at the anode. As for the harmful electrons, in the process of interaction with high-frequency electric field they accelerate taking the energy from the field, arrive at the cathode and drop out of the process of interaction with high-frequency field. Such electrons cause the cathode excess heating and increase of the magnetron current. Loss electrons residence time in the interaction gap is significantly shorter in compare with recoil electrons. This phenomenon is called sorting of electrons. The recoil electrons transmit more energy to SHF field than loss electrons can take. This gives rise to high efficiency of the magnetron [11].

When matching up becomes worse, some part of SHF power bouncing off of the load reaches the interaction distance, changes the high-frequency field amplitude and phase at the magnetron coupled cavity gaps. This causes changes in the process of sorting and increase of the number of loss electrons that in its turn increases current in the second local points in the form of the magnetron current.

The conclusions presented above are valid when the magnetron operates with inverter power supply as well.

For quantitative assessment of operation processes, we made analysis of generation conditions for the device under test taking into consideration the size, supply voltage, the standing-wave ratio load level. Current waveform processing (local maximum relation analysis) and the magnetron generation power rating were performed by means of the developed microprocessor board integrated into the magnetron operating system [6]. Processing algorithm makes it possible to determine position of the magnetron current local points, as well as the average current over a period. When the magnetron generation power rating is performed, the time required for the cathode glow and the magnetron reaching the rated operating conditions, as well as possible changes in the cathode thermal emission is not taken into account.

The magnetron generation condition is defined as the ratio of the anode voltage value U_a and the permanent magnets density value B. For every magnetron design, the mode of generation is specified by the condition of SHF power generation [11]:

$$B \geq B_{crit};\, U_a \geq U_{a.\,crit},$$

where B_{crit} is critical density; $U_{a.crit}$ is critical anode voltage.

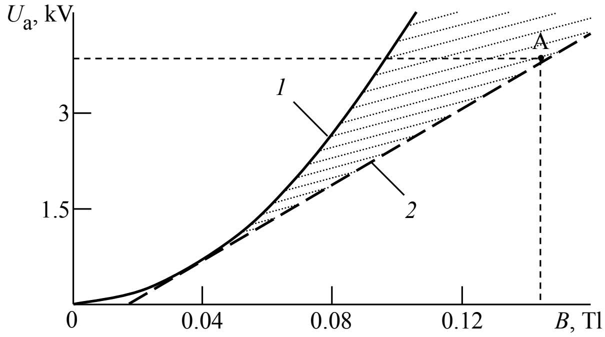

Fig. 3

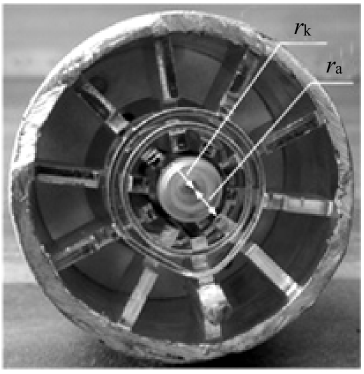

Fig. 4

The range of possible values of U_a and B (fig. 3) used in magnetrons is specified on the one side by critical-voltage parabola and on the other side by Hartley equation, that is a threshold line specifying the magnetron self-excitation condition [11]. In order to determine the magnetron mode of operation and the operating-point position we specify the resonator gap for the magnetron 2M214 [12] used in microwave commercial plants. The values $U_{a.crit}$ and B_{crit} are defined on account of the size of the magnetron anode and cathode assemblies, number of cavities and generation frequency. The size of the magnetron anode pack and the cathode is given in fig. 4.

The anode pack of the magnetron consists of ten cavities. The anode radius is $r_a = 2.5$ мм, the cathode radius is $r_k = 1.5$ мм.

The magnetron generation voltage (see fig. 1) equals to 3800 V and it is enough for the magnetron stable operation. To determine the permanent magnet density we used Hall sensor SS495A [13]. The sensor measures the density value and gives voltage proportional to its value. The measured density made 1.42T. These values of the magnetron voltage and field density specify the operating point of generation A.

In fig. 3, line 1 corresponds to critical-voltage parabola; line 2 corresponds to Hartley equation specifying condition for the magnetron self-excitation.

Fig. 3 indicates that the operating point A is located in the magnetron resonator gap.

Calculation of load power when operating with transformer power supply. We define the power transferred to the load when the magnetron is operating with transformer power supply. It is known [11] that with VSWR equal to one, the magnetron generated power makes:

$$P_{\text{load}} = U_{\text{a}} I_{\text{a}} \eta, \quad (1)$$

where U_{a} is anode voltage; I_{a} is the average anode current; η is the magnetron efficiency factor.

The magnetron efficiency rate with SWR equal to one is provided in documentation for each magnetron. For the magnetron used $\eta = 0.7$ [12].

As it is shown in [7], on change of VSWR the level of power bounced off of the load changes as well. This leads to the change of relation of local maximum of the magnetron current marked with digital symbols in fig. 1. We define power transferred (fig. 1). We define power transferred to the load by the change of the anode current waveform introducing a correction factor k_1 into (1):

$$P_{\text{load}} = U_{\text{a}} I_{\text{a}} \frac{I_1}{I_2} k_1, \quad (2)$$

where I_1 is current magnitude in point 1; I_2 is current magnitude in point 2; k_1 is a factor connecting the anode current waveform with power transferred to the load. It is defined by equality of experimentally measured power and corresponding waveform with VSWR equal to one.

Experimental and design power transferred by the magnetron to the load on change of VSWR are demonstrated in fig. 5. Current measurement on change of SWR was performed on measuring test bench [7] with calorimetric technique. In fig. 5, line *1* indicates load power defined experimentally; line *2* indicates power transferred to the load and calculated by (2).

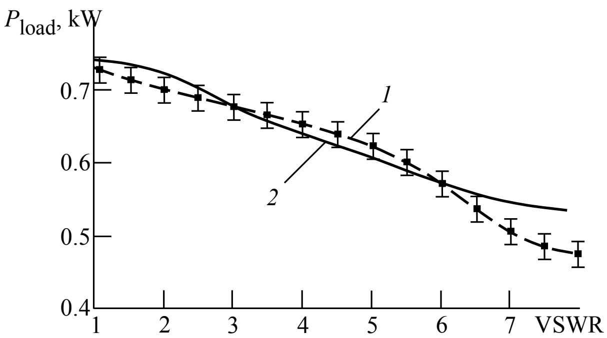

Fig. 5

Hence, design power transferred to the load corresponds to the level of power measured with calorimetric technique to a precision of $\leq 10\,\%$.

Calculation of load power when operating with inverter power supply. We define the change of power transferred to the load according to the magnetron average current magnitude when PWM is constant:

$$P_{\text{load}} = P_1 - (I_1 - I_{\text{a}}) k_2, \quad (3)$$

where P_1 is level of power corresponding to the set value of PWM; I_1 is the magnetron current magnitude, with SWR = 1; k_2 is a factor connecting the average value of the anode current with the load power. This factor is defined by comparison of experimental and design data in the point of VSWR = 1.

Change of the magnetron average current with the increase of VSWR is demonstrated in fig. 6 for three different levels of the output power.

In fig. 6, line *1* indicates load power defined experimentally, line *2* – indicates power transferred to the load and calculated by (3).

Power transferred to the load when operating with inverter power supply, determined by calculation corresponds to the level of power measured on a measuring test bench using calorimetric technique. The average error rate of the design value of load power at any level of the power supply unit installed capacity does not exceed 50 W.

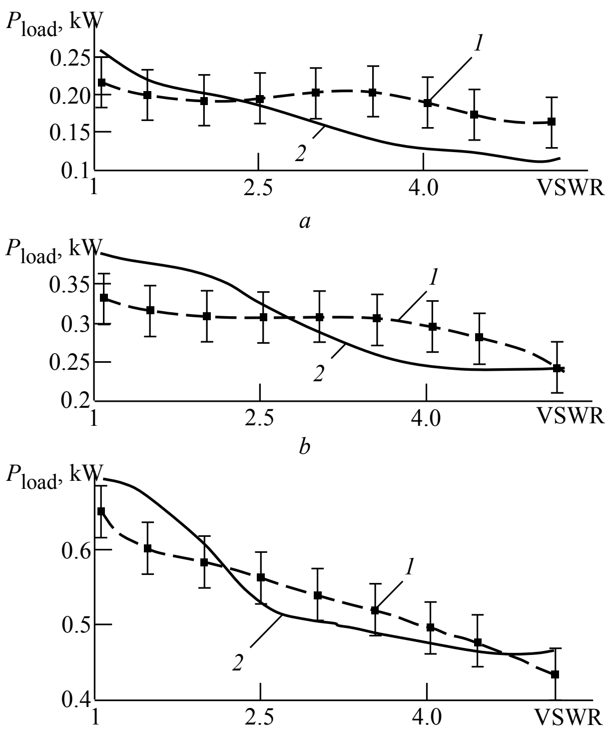

Fig. 6

The proposed analysis of the magnetron current waveform in multi-generator plants makes it possible not only to define power transferred to the load by each magnetron, but to assess the magnetrons' cross-effect as well [14].

Conclusions. Determination of microwave power transferred to the processed material makes it possible to control the material processing technological parameters. Forecasting of power going to microwave reactor according to the anode current waveform in the inverter and transformer power supply units makes it possible to automate the process control, to simplify maintenance operation and to reduce the bottom-line cost of microwave equipment.

The developed control algorithm is implemented in a control board specific for each particular generator. Preprocessed information on the magnetron mode of operation goes from this board to the central processor of the whole plant.

Use of adaptive control system [15] and a technique to specify power generated by each magnetron allows increase the plant energy efficiency in several ways:

– use of automatic matching system [16];

– magnetron shutdown with matching deterioration;

– change of power generated by magnetron (when operating with inverter power supply);

– magnetron switching on / shutdown with the change of processed material parameters leading to the change of matching (when operating with transformer power supply).

Besides, the analysis of the magnetron anode current pulse form allows ~~to~~ implements virtual sensors of product availability in reactor, movement (mixing) of the product in microwave reactor, boiling of water, microwave discharge inception, etc.

The use of the developed algorithm of anode current analysis and adaptive control system makes it possible to improve automation of entire system, to control more precisely the required radiant exposure of the processed product, to decrease the duration of debugging mode for new products and materials.

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