Developing the Method and Devices for Controlling the Working Process in Multifunctional Ultrasonic Apparatus

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***Abstract*—In the present article published the results of researches of find the way for solution the problem of matching between electronic generator and resonant piezoelectric ultrasonic oscillatory system, that carry out the ultrasonic influence upon various technological mediums with variable physicochemical characteristics. Results of the researches is development of novel method of optimal electric matching and its practical realization.**

I. Introduction

APPLICATIONS of High-Intensity Ultrasonic oscillations (HIU) is sufficiently effective way for realization, intensification and stimulation of various physicochemical processes in the industry technologies, scientific researches and medicine.

For the implementation of HIU to various mediums and materials using the special devices – ultrasonic technologies apparatus (USTA), which carry out conversion the energy of power grid to the energy of ultrasonic oscillations, theirs transformation and input to processing medium. Structures of USTA, depending on its purpose, may be different, but every apparatus includes electronic generator (EG), that converts energy of power grid to a ultrasonic frequency electric oscillations, and ultrasonic oscillatory system (UOS), that converts energy of electric oscillations to elastic ones, their transformations and input into processing medium (material) [1].

Till recently the ultrasonic technological apparatus develop on the extensive way – required level of ultrasound effect occurs by "simple scaling" of ultrasonic systems. As a result – its efficiency was not more than 10-15%, the devices had been strictly specialized, required the permanent regulation and adjustment. The level of automation was sufficiently small (or lacking) and maintain required conditions of ultrasound influence carried out by manual adjustment.

Certainly, that devices by now do not satisfy the up-to-date requirements. Therefore at present time continuously carrying out the works aim at USTA development and upgrading. Development occurs by the following ways: enhancement of the energy converting efficiency, broadening the functional purpose, increasing the degree of automation, reducing the size-mass ration and depreciation.

Most essential results have been took by application in electronic generations a MOSFET, that works at switching mode, using the microprocessors in automation systems and piezoelectric transducers in UOS. The total result is providing the energy conversion efficiency 95% and more in electronic generators and up to 80% in UOS. Microprocessor based controlling systems provides optimal mode of ultrasonic influence on various mediums and materials and fully automatize the process of USTA controlling [2].

Now sufficiently neatly discover novel development way of ultrasonic technique – compact multipurpose USTA, that have possibility to carry out various technological operations (liquid mediums processing, ultrasonic cleaning, sizing, welding and so on) [3]. Customer demand on multifunctional USTA causes by development of small-scale enterprises and general tendency on electronic technique market.

Recent years have been worked up a few series of multifunctional USTA (or ultrasound processors). However, generally, in that devices was copied the designs of specialized USTA and differ only by broad set of changeable working tools and a few perfected algorithms of automation systems.

Such approach leaves out of account that the maximum effectiveness of EG and UOS functioning occurs only if that units are matched with each other and with processing medium. The multifunctional USTA work at variable matching conditions during deviation of major parameters of processing mediums,

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oscillatory systems and electronic generators.

The problem of acoustic matching between UOS and processing medium solves by EG automatic frequency control (AFC) in compliance with every possible deviations of UOS natural frequency.

However at that the problem of electrical matching between EG and UOS do not solve. Electronic generator, that based on transistor switched mode output stages sufficiently sensitive for matching conditions – their efficiency essentially reduces but electromagnetic noise level grows even if the matching conditions change slightly. Moreover working to unmatched load may be cause for EG damage.

The electrical matching (EM) provides by using special matching devices (MD), that are electric circuits made up on basis of reactance components (capacitors, inductors), which inserting between EG output and piezoelectric transducer of UOS. The reactance components rejects the harmonics of output square-form voltage and reduction the complex load impedance to full active value at reference frequency (1st harmonic). At that the parameters of reactance components ought to chance during deviation parameters of processing mediums and UOS – only then may be provides the optimal mode of EM. However now do absent the practical constructions of MD with changeable due to work. Therefore makers of multifunctional USTA compel to use uncontrollable during work matching devices (UMD) using a few settlement by compromise: or purposely decrease effectiveness of EM in all modes of USTA work, provides more or less uniform parameters characteristics for all functional applications, or provide the best matching only in one mode, ignore the decrease effectiveness in another modes. As a result in the both suites the efficiency and output power are significantly less the same values for specialized USTA. However, except the non-optimal matching, other obstacles for advancement the effectiveness of multifunctional USTA are absent, because of the mere fact that EG and UOS may be effectively work in broadband of loads, frequencies, temperatures and so on.

Therefore now is actual problem of development a new method for control the working process of multifunctional USTA that provides automatic establish the optimal matching mode (OMM) after turn-on the generator and automatic maintain the OMM due to USTA working.

Cardinal problem during working out of new method have been caused by necessity to take into account the number of features of EG, UOS and MD, that considered further.

II. Peculiar properties of ultrasound oscillatory system as an electrical load

The equivalent circuit of piezoelectric UOS as an electrical load at frequencies near the major mechanical resonant frequency (MRF) shown in Fig.1

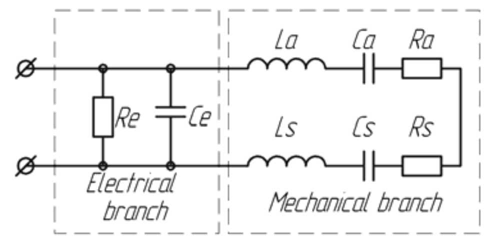

Fig. 1. Equivalent circuit of piezoelectric ultrasound oscillation frequency

Ce и Re – fully electric values that are self-capacitance and dielectric loss of piezoelectric transducer (PT) correspondingly and also known as “electrical branch”. Elements La, Ca, Ra, Ls, Cs, Rs – are electric analogs of mechanical values and form “mechanical branch”.

Inductance La – is analog of oscillatory mass of UOS, Ca – its equivalent flexibility, Ra – damping on internal friction. Ls, Cs, Rs – concern to processing medium, where Ls – is co-oscillatory mass, Cs - equivalent flexibility of medium, Rs – resistance that includes power wastes to acoustic emission, viscous friction and maintaining the cavitation mode.

UOS is characterized be following values: mechanical resonant frequency (denote as *f*), quality factor *Q*, resistive impedance of “mechanical branch” (*Rm*), self-capacitance of PT (*Ce*).

Distinctive feature of UOS is consist in that its input electric impedance are changeable with various the parameters of processing mediums (wave impedance, viscosity, cavitation process and so on) during technological process as well as rechange the working tool, deviation the temperature of PT and other factors.

The experimental researches discover that resistive impedance varies in 300-3000 Ohms band, MRF – in ±20% band and self-capacitance in 1,5-2 times band.

III. Peculiar properties of the matching devices using between switching mode electronic generators and piezoelectric transducers

As have been noted above, the matching devices occurs two major functions: rejects the harmonics of output square-form voltage and reduction the complex load impedance to full active value at reference frequency (1st harmonic).

Harmonics rejection provides sinusoidal current forms through UOS and output transistors of EG and excludes addition dissipations at high harmonics (without rejections efficiency reduces down to 40%-50% [1]).

Reducing the impedance of load to active values (impedance correction) provides work of output transistors when they switch on zero current (SZC-mode).

SZC-mode provides minimal energy losses on internal resistance of output transistors, minimal noise level and minimal level of danger voltage surges caused of stray wiring capacitance and inductance, that may damage transistors.

When UOS works at MRF impedance of its "mechanical branch" is fully resistive and providing SZC-mode reduces only to compensation of "electric branch" capacitance.

On Fig.2 shown two most distributed schemes of MD for USTA.

In the schemes UOS replaced with parallel connected resistive impedance of "mechanical branch" Rm and capacitance of "electric branch" Ce.

For provides the temperature stability, occurs the required parameters of MD and properly work of AFC using additional capacitor (Cadd) that connected parallel lead of UOS.

In the scheme, that shown on Fig.2a (hereinafter – *first type* device) rejecting and impedance correction provides by same pair of reactive components L1-C2, that establish single-mess filter.

SZC-mode is realizing when

$$L1 = (R_M^2 C_2)/(1 + 4\pi^2 f^2 R_M^2 C_2^2),$$

where f is mechanical resonant frequency of UOS. At that, first type MD provides voltage transfer constant

$$K_H = \sqrt{1 + 4\pi^2 f^2 R_M^2 C_2^2} > 1,$$

that is serious advantage when using high-resistance UOS.

In the scheme, that shown on Fig.2b (hereinafter – *second type* device) rejection carries out by electric filter L1-C1, while impedance correction – by inductor L2, that connected of parallel lead of UOS.

Elements L1-C1 consist the series-tuned circuit, while L2-C2 – the parallel-tuned circuit.

SZC-mode provides when $f = f_1 = f_2$, where $f_1 = 1/(2\pi\sqrt{L1 \cdot C1})$, $f_2 = 1/(2\pi\sqrt{L2 \cdot C2})$ - resonant frequencies of series and parallel tuned circuits correspondingly. Voltage transfer constant equal than one.

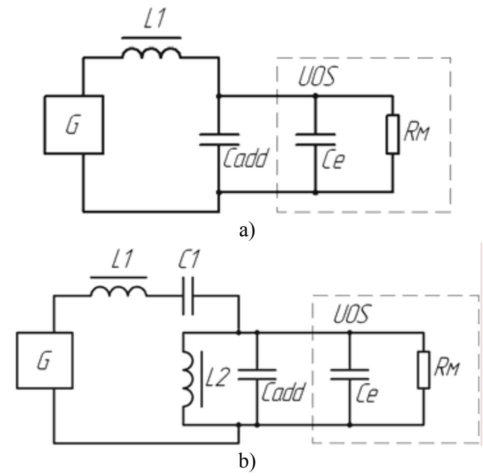

Fig. 2. The most distributed types of electrical matching devices for USTA

Based on analyzed peculiar properties of UOS and matching devices has been made a resolve to develop the controlling method applied to USTA that including second-type MD, because parameters of its reactance component are independent from resistive impedance of UOS "mechanical branch" (the most fallibility value). This firstly sufficiently narrow the reactance components tuning ranges, but secondary – simplify the procedure of automatic establishing th OMM after turn-ob the USTA.

IV. Development the Control Method and Systems for Its Practical Realisation

The automatic control impossibly without the measurement information acquisition and working-out the control action accordingly with controlling algorithms and optimality criterion.

Structure of automatic control system (ACS) for USTA submitted on Fig.3. ACS includes nine measurement signals.

Signals U1 and U2, that give from voltage divisor D1 and D2 carry the information about amplitude and phase of voltage at nodes A and B correspondingly. Signals I1 – I3 carry the information about amplitude and phase of current at branches I-III correspondingly. Output signal Im from the differential amplifier AD make by subtraction from signal I3 a normalized by regulable amplifier RA. Signal Im carries out information about current through "mechanical branch".

Signal VR carries out information about output stages (OS) supply voltage, signal FS – about output frequency and signal TR – about temperature of piezoelectric transducer.

ACS used five keying signals. Signal VS – control the output stages supply voltage, FS – output frequency, KS – gain of regulated amplifier. Signals L1 and L2 control the inductance of inductors Ind1 and Ind2 through execution units EU1 and EU2. Control unit (CU) realized some working modes. After the turing on CU occurs the initialization during one provides the measure of self-capacitance of PT and search the MRF of UOS. That values required for establish OMM.

For measure the initial self-capacitance CU carries out following actions.

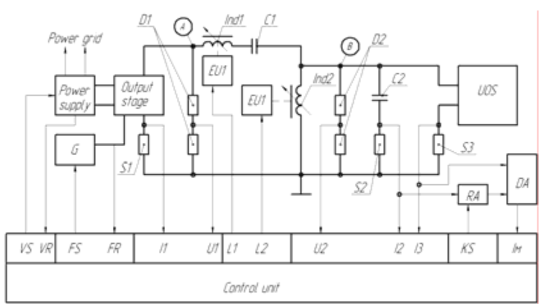

Fig. 3. Structure of automatic control system for ultrasound technological apparatus

At first CU sets by signal FS the output frequency thus that about 5-8 kHz higher than nominal values of MRF. At that the absolute value of "mechanical branch" impendence more greater than capacitive resistance of "electrical branch", that in this case determinates the input current of UOS.

Calculating the necessary values of inductance of Ind1 and Ind2 use equations $L_1 = 1/(4\pi^2 f^2 C_1)$ and $L_2 = 1/(4\pi^2 f^2 C_2)$ CU sets the values by L1 and L2 signals. Use signal KS CU sets minimal values of RA gain.

Set by signal VS the supply voltage value as 15% of maximal, CU provides difference by amplitudes values of node voltages A and B (signals U1 and U2) not more than 10% by correcting the inductance of Ind2.

After that starting the process of capacitance measure. CU fluently increases the gain of RA (by signal KS) while amplitude of signal Im greater than 1/50 of signal I3 amplitude, that observes when $C_2 K = C_E$, where K is a gain of RA. Self-capacitance is calculated from its equation. After that CU measures the initial temperature and passing to MRF search.

CU turns off the supply voltage of output stages (by signal VS), sets the minimal output frequency (by signal FS), after that carries out fades-in the supply voltages by signal VS up to 30% of maximum value. Fluently increasing the frequency CU checking the phase difference between signals Im and U2 and setting the inductance of Ind1 and Ind2 from equations

$$L_1 = 1/(4\pi^2 f^2 C_1) \text{ and}$$

$$L_2 = 1/(4\pi^2 f^2 (C_2 + C_{\text{Э}})).$$

Zero phase difference between signals U2 and Im indicates that output frequency of generator equals with MRF of oscillatory system. If its condition required the CU switching to main working mode (MWM).

If due to on every initialization step the amplitude values of currents and voltages exceed than overload capacity at least in one branch the CU carries out immediate emergency switching down for prevent the generator damage.

In the main working mode CU provides the optimization of acoustic matching (between UOS and processing medium), electric matching (between electronic generator and UOS) and maintains the output power value in compliance with required level. For that the CU establishes five control loops (CL).

First CL carries out the automatic frequency control, continuously measuring and minimizing the phase difference between signals Im and U1 by changing the output frequency (using signal FS). First CL maintains the acoustic matching. If work of first CL faults, control unit repeats the initialization mode.

Second CL maintains the required value of output power, continuously measuring the product of amplitude values of signals U2 and Im and regulating the output stages supply voltage by signal VS.

Third CL provides work of output transistors in SZC-mode, continuously measuring and minimizing the phase difference between signals I1 and U1 by changing the inductance of Ind1 (using signal L1).

Forth CL regulates the inductance of Ind2. Working algorithm of this CL depends of value of "mechanical branch" resistance. If that value relatively small, the CL continuously measuring and minimizing the phase difference between signals I1 and U2 by changing the inductance of Ind2 (using signal L2). If of "mechanical branch" resistance sufficiently high (1500 Ohms and more) the forth CL increases the voltage transfer constant of MD by decreasing the value Ind2 inductance while the power value fall short the required value or inductance value greater than minimal acceptable value.

Fifth CL continuously measuring the temperature of PT (by signal TR), calculating the current value of self-capacitance and correcting the gain of RA correspondingly the equation $K = C_E / C_2$ that provides more accuracy work of other CLs.

If due to work the amplitude values of currents and voltages exceed than overload capacity at least in one branch the CU carries out immediate emergency switching down for prevent the generator damage.

For the researches the principal advantages of the noverl method have been made the prototype of the USTA.

Structure of the regulated inductors (chokes) shown on Fig.4.

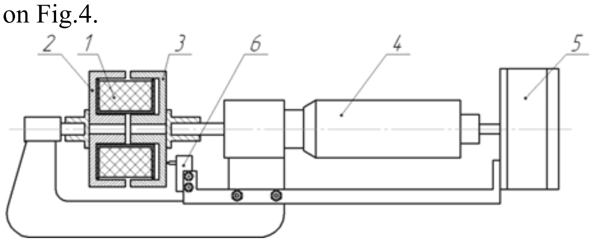

Fig. 4. Structure of regulated inductors

This construction includes properly inductor and gap regulating system. Inductor includes the winding 1 that placed between two cup-shaped half-core set with regulated air-gap. The gap is regulated by screw mechanism 4 and stepping motor 5. End switch indicates the initial position.

The stepping motor is controlled by single-chip microcontroller that consist the ROM with lookup table of pair values "steps from initial position – inductance". The inductors has a following properties: inductance range 3 – 14 mH, maximal current 5A, regulating speed 2 mH/s, discontinuity – less than 10 mcH.

As long as the controlling method requires many calculation operations and flexible logic of work all functions have been realized software, using the three microcontrollers - central and two microcontrollers of inductors. Central microcontroller realizes all logics in initialization mode (microcontrollers of inductors only set required inductance values at the command from central microcontroller).

In the MWM the main microcontroller realize the functionality of first, second, fifth a particularly forth CLs. Microcontroller of Ind1 – functionality of third CL while microcontroller of Ind2 – forth CL.

Operation testing of USTA prototype allows to discover, that developed method provides identical high effectiveness of various mediums ultrasonic processing using rechangeable tools and UOS. At that the effectiveness maintain 97% (while same processes carry out with turned off the automation matching system, the output power reduces about 15%, but in some modes – down to 60%, while efficiency reduces down to 85%).

CONCLUSION

The carried out analysis have to discover the ways for increasing the effectiveness of USTA through automatic optimization of electric matching between electronic generators and UOS. Offered and developed method and its practical implementation allows to provide the efficiency of electronic generator up to 97% during any changes of processing mediums and UOS parameters.

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