Preface

The “Modern Engineering: Science and Education” (MESE) conference was initially organized by the Mechanical Engineering Department of Saint Petersburg State Polytechnic University in June 2011 in St. Petersburg (Russia). It was envisioned as a forum in which to bring together scientists, university professors, graduate students, and mechanical engineers, presenting new science, technology, and engineering ideas and achievements.

The idea of holding such a forum proved to be highly relevant. Moreover, both location and timing of the conference were quite appealing. Late June is a wonderful and romantic season in St. Petersburg—one of the most beautiful cities, located on the Neva river banks, and surrounded by charming greenbelts. The conference attracted many participants, working in various fields of engineering: design, mechanics, materials, etc. The success of the conference inspired the organizers to turn the conference into an annual event.

The third conference, MESE 2013, attracted 150 presentations and covered topics ranging from mechanics of machines, materials engineering, structural strength, and tribological behavior to transport technologies, machinery quality and innovations, in addition to dynamics of machines, walking mechanisms, and computational methods. All presenters contributed greatly to the success of the conference. However, for the purposes of this book only 16 reports, authored by research groups representing various universities and institutes, were selected for inclusion.

I am particularly grateful to the authors for their contributions and all the participating experts for their valuable advice. Furthermore, I would like to thank the staff and management of the University for their cooperation and support, and especially, all members of the program committee and the organizing committee for their work in preparing and organizing the conference.
Last, but not least, I would like to thank Springer for its professional assistance and particularly Mr. Pierpaolo Riva who supported this publication.

Saint Petersburg

Alexander Evgrafov

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Chapter 6
Designing a Power Converter with an Adaptive Control System for Ultrasonic Processing Units

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Abstract We describe the features of circuit design construction and design of power converters included in ultrasonic process plants. We discuss the results of simulation of an equivalent circuit of the power converter. We then develop information flow diagrams of adaptive control system of the power converter.

Keywords Ultrasound technology • The power converter • Data flows • Data flow diagrams

Introduction

In machinery we find widely used sonication and purification of different parts [1]. Methods of acoustic control in nondestructive testing of engineering products are also widespread. In this case, efficiency increase of ultrasonic processing units (UPU) is an insistent task. There are different ways to increase the efficiency of UPU: using modern methods of constructing the power converters (automatic tuning of generator frequency, control of permissible oscillation amplitude of the piezoelectric transducer (PETs), etc.), improvement in performance of the piezoelectric transducer itself (a rise in sensitivity, efficiency factor and reduction of
mechanical losses etc.). This article presents a method of constructing the power converter (PC), that includes the adaptive parameter control system of output signals in order to maximize the efficiency of the UPU.

In technological processes, associated with the handling of solids by ultrasound, and at cleaning with high amplitude fluctuations, the main technological parameter is the oscillation amplitude. In [2] it is shown that for ultrasonic transducer (UT) the curve of oscillation amplitude dependence on the input power has a linear (with capacity not exceeding 0.9 kW) and a non-linear plot. With an amplitude increase of input voltage the amplitude of the oscillations or acoustic power increases to a certain limit, the value of which is determined by the fatigue strength of structural elements UT. In the nonlinear regime with increasing of voltage amplitude at the input the mechanical or electrical losses in the UT will also increase. This leads to a decrease in sensitivity, performance and the efficiency factor. In this case, the allowable vibration amplitude UT accepts the value at which decrease in sensitivity or efficiency factor does not exceed a predetermined value [2].

It is known [3] that the piezoelectric and magnetostrictive transducers are resonant systems. Maximum power from the PC is given to the load when the generator frequencies of PC are equal to resonance frequency of the piezoelectric transducer, when reactive load components (PETs) are compensated and there is only resistance. This factor determines the need of tuning the PC generator frequency to the changing load frequency during the use of UPU.

The Structure of the UPU Power Converter

Based on the requirements for setting PC, it is necessary to ensure the following requirements for an ultrasonic generator (UG):

1. Amplitude of the PETs input voltage should be stable and adjustable.
2. Frequency of this voltage ($f$) should be equal to the resonance frequency of the tool attached to the PETs, i.e. it is necessary to adjust $f$ during the operation.
3. A PC Control system should provide a rapid response to PET's output parameters changes.

A PC functional scheme (presented in Fig. 6.1) is proposed for ensuring these requirements. This scheme forms the harmonic output signal during the operating of transistor generator in mode key [4], it makes possible to achieve high efficiency. Moreover, the adaptive PC control system maintains stable amplitude of output voltage (control block CB-1) and required resonant frequency (control block CB-2). Changing the nominal values of the power high-pass filter HPF elements provides an opportunity further to stabilize the generator output voltage (in a given range) when load changes.

Power Source (Fig. 6.2) is used to provide a generator rectified and smoothed voltage network. This is a single-phase diode bridge with a low-pass filter (LPF). Its output is connected with down-type DC converter (DCC) [5]. It consists of a

![Fig. 6.1 PC functional scheme (PS power source, G generator, HPF high-pass filter, S sensor, CB control block)](image)

![Fig. 6.2 Scheme for PC modeling nodes](image)

series-connected transistor, the choke and the diode, providing energy recovery inductor to the load. This scheme provides:

- Regulation of the supply voltage in the range 0-0.9 Um.
- Reduction of low-frequency output ripple through the use of DCC in the control unit CB-1 pulse width modulation (PWM)—controller.
- Protection against overcurrent and overvoltage.
- Maintenance of the input voltage generator accuracy due to the formation of high-frequency switching transistor DCC.
- PC soft start.
Modern development of microelectronics provides a large selection of tools for measuring the PETs oscillation amplitude. Optical measurement methods [7] and a variety of microelectronic mechanical devices based on MEMS—Technology (Micro-Electro-Mechanical Systems) [8] are widely used. For the following task it is convenient to use MEMS-accelerometer, which permits conversion of oscillation amplitude value to digital output signal. For example, sensor ADXL350 (firm Analog Devices) has a high resolution (13 bits), a wide measurement range and a variety of interfaces. As digital processing of measured parameters is assumed, we choose high-speed interface SPI (Serial Peripheral Interface), which forms synchronous serial data stream. The selected sensor is mounted on PETs body (sensor A, Fig. 6.1).

To maximize the efficiency of using PETs as a part of process unit, current is generally controlled, which measurement can be performed, for example with the use of a transformer current sensor. Another method of controlling a resonant mode is associated with the phase detector that performs selecting the phase relation of PETs voltage and current passing through it [9]. This method is useful for low power radiation or as an additional control to maintain (for example, current control). To control the PETs current resonant value it is necessary to have a transducer amplitude-frequency response characteristic (AFC). Determining methodology is given in [2]. AFC allows specifying the source data for the control system.

Considered list of monitored parameters and requirements for the implementation of monitoring shows a need for an adaptive control system. We define problems for the adaptive system:

- Maintenance of a given output voltage amplitude through generator’s power level adjustment (PWM—control). At the same control characteristics can be selected depending on the mode of use of UPU.
- Allowable PETs oscillation amplitude control through tuning the voltage generator power.
- PETs resonant mode control through adjustment of the oscillator frequency.

Digital processing of the control system is based on the digital matrix—programmable logic integrated circuits (FPGA). Advantages of using this technique is its high matrix performance, convenient implementation of the control algorithm in the form of stream processing, a large number of library functions presented in the form of IP-cores. The big advantage is the ability to use FPGA reconfiguration hardware implementation unlimited number of times. In addition, the development can be done on hardware description languages (Verilog, VHDL), that increases development productivity and allows one to perform functional and timing simulation project.

Modern FPGA incorporates means for effective implementation of the model calculation data flow—Digital Signal Processors (DSP), which enables one to develop and implement high-performance control loops PC [10].
Problems of PC lower level digital control, for example, the control process of the power switches at resonant frequency tuning, information obtaining by SPI—interface (sensor vibration amplitude) in real time requires the performance of the FPGA and an order of less than several microseconds.

To ensure the formation of a predetermined load setting mode UPU (including uploading the local network), the microprocessor can be used to network ports.

**Determination of the Control System Information Flows**

To develop a PC control system it is necessary to analyze the input information flows which are generated at the system’s output. Such an analysis is conveniently performed using data flow diagrams (Data Flow Diagrams—DFD), which can be used to develop a specification of requirements in system design. Classical diagram DFD is used for structural analysis and design of information systems. There are several widely used notations DFD [11] with different syntax. Diagrams describe the sources and data flow, represent processes and memory for storing results of processing data streams in the process. These diagrams cannot be directly used in the analysis of information flows control systems (CS) power converters for the following reasons:

- Processes of stream processing must be strictly determined.
- Each process usually runs on a certain condition, therefore, necessary to process input signals to determine the shaping condition logic.

Consider the work of CS at the example of simplified diagram (Fig. 6.4), making it possible to analyze the data flow from external sources, flows processing, logical calculations and destination of calculation results. The diagram is based on data processing units, so called capsules. The capsule consists of two components: the logic condition and processing of data flow. Logic condition is a logical function of the equation, which solution starts the process. The process converts the input data flow to output, generating control signals for other capsules. Wherein, the process algorithm is involved into the capsule (encapsulated). Each capsule can be a hierarchy of nested processes capsules [12].

Sources of input data flow (external entities) CS considered are listed below:

- ADC—analog-to-digital converter in the path of the current control mode resonant probe.
- RR—converter’s oscillation amplitude reference register.
- S—control PET sensor of allowable oscillation amplitude. Address stream processing results:
- G—PC generator.
- DCC—DC converter.
- clk—external event to synchronize all processes.
- str—external event to initialize the PC works.

![Fig. 6.4 Graph of time dependence](image)

Analyzing the diagram we can see, that control system receives three independent data flow and two events. As a result, two control signals are generated at the output:

- F—generator frequency setting signal for the resonance of PETs.
- A—signal providing a predetermined value generator power through the RR (and thus the acoustic power), the amplitude of the oscillation is controlled riding probe.

Since the digital part is implemented on FPGA CS, the resulting chart with parallel processing of data streams easily implemented in the project, which requires algorithms processes (P1–P10) each capsule described in terms of HDL (e.g., Verilog).

To check the results of the mathematical modeling experiment there was provided an experiment on a physical model of PC. Layout of its capacity of about 500 W power transistors assembled JRF840, with a control system implemented on FPGA family Cyclone III (firm Altera).

A generator oscillatory circuit has the following parameters: L1 = 200 mH, C1 = 230 nF, C2 = 0. Frequency F = 1/2t where t—half-harmonic of the output voltage (t = 20 ms, F = 25 kHz). Tests were conducted at a supply voltage generator Ud = 20 and 30 V. Source impedance Ro = 1.56 Ohm. Table 6.1 shows the results of experiments.
Table 6.1 The results of the simulation and test layout

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<th>U_0</th>
<th>I_0</th>
<th>I_m</th>
<th>P_m</th>
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This table uses the following symbols and signals:
- Ud, Id-voltage and current power supply generator.
- Il—oscillating circuit current, which is equal to the current of the power transistor.
- Unm—amplitude of the voltage across the load.
- P.av—load power (average value).

Conclusion

Analysis of the data shows a good convergence of the simulated results and the experimental results (the difference does not exceed 25%). Large deviations of certain values can be attributed to random error.

We have developed a scheme for a power converter with improved UPU Stability generator output voltage and the precision of its adjustment, and the control process admissible oscillation amplitude of the tool. The structure of the adaptive system allows an increase in the efficiency of a process plant.

This work was supported by the Russian Foundation for Basic Research (project NK14-07-00422/14).

References