A new type of high power ultrasonic generator for welding and cutting processes

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The paper presents a new type of high power ultrasonic generator for welding and cutting processes developed by the Tele & Radio Research Institute. The new generator can provide up to 5 kW of electrical power to an ultrasonic transducer in the frequency range of 16 kHz up to 60 kHz with regulation step down to 0.1 Hz. The device utilizes an innovative microcontroller with built-in high resolution timing blocks that enable direct synthesis of control signals for the generator's resonant converter, without the need of an external DDS unit or programmable device. This new approach to designing ultrasonic generators can benefit in greater flexibility and reliability of the device. New algorithms with cycle-by-cycle parameter control, and precise regulation of output frequency and power delivery, have been developed. Various parameters of ultrasonic stack, such as impedance and resonant frequency, are measured by the generator in real-time, and can be used for ultrasonic stack wear monitoring and fault detection.

Keywords: ultrasonic, ultrasonic welding, ultrasonic cutting, ultrasonic generator

1. Introduction

Ultrasonic welding is the process of bonding elements using ultrasonic acoustic vibrations delivered locally to bonded elements held together under pressure. It is most commonly used for joining plastic elements, but it can also be used to join thin metal foils and non-woven fabrics. Joining and cutting of elements can be accomplished in a single process. Ultrasonic technology utilizing similar devices as ultrasonic welding can also be used to process liquids, i.e. mixing paints, or purifying waste water. Ultrasonic welding has great advantages over other joining techniques. Firstly, it is a very fast process. A single joint can be created in under 1 second. It also does not require additional substances like glue. The joint is formed by locally melting bonded materials. This results in reduced costs, and increased throughput of the technology. Due to these advantages, ultrasonic welding and cutting is becoming more and more popular in industry [1]. Typical ultrasonic welding machines have output power of up to 6 kW, and operate at frequency ranges of 20 kHz to 70 kHz. To efficiently realize new, more complicated, technologies, a new type of ultrasonic welding generator with output power of at least 5 kW, and precise control of output parameters is required. Such technologies include large area welding (sonotrode area above 100 cm^2), metal foils welding, copper cable bonding, and ultrasonic processing of liquids. The aim of the paper is to present a novel design of an ultrasonic welding generator.

2. Ultrasonic welding machine

Example of an ultrasonic welding machine is presented in Figure 1.

Fig. 1. Ultrasonic welding machine.

The welding machine consists of a machine frame with an acoustically sealed welding chamber, an anvil, an ultrasonic stack, and an ultrasonic generator. Welding process takes place inside the welding chamber, which is protected against accidental access by a moving curtain. Elements to be welded are placed inside the welding chamber, positioned on the anvil either manually, or by means of an automatic feeder. After activating a welding cycle, the curtain is lowered to close the chamber. Sealing the chamber is also important to decrease the ultrasonic noise level outside the machine. Only after successful lowering of the curtain, the ultrasonic stack is lowered onto the elements to be welded using a pneumatic actuator. The actuator applies a predefined amount of pressure on the stack. It is important to carefully choose the applied pressure in order to provide enough compression force on the to-be welded elements. Insufficient force may lead to element separation during welding, thus causing a weak weld. Excessive force, on the other hand, leads to mechanical amplitude decrease on the sonotrode, and insufficient power delivery to the weld [2, 3].

Ultrasonic stack is an electro-mechanical resonator that is responsible for creating ultrasonic vibrations and delivering them to the to-be welded elements. Figure 2 presents the picture of an exemplary ultrasonic stack. Figure 3 depicts a mechanical model of the stack. It consists of three major elements: ultrasonic transducer, booster and sonotrode. Ultrasonic transducer is an element that transforms the electrical signal that is delivered to it into mechanical vibrations. The transducer is composed of piezoceramic discs in a sandwich type configuration. More information about ultrasonic transducers can be found in [4, 5]. Booster is an element that acts as a mechanical guide and mechanical transformer. It is most commonly used to increase (boost) the amplitude of mechanical vibrations received from the transducer. It is also used as a mounting point for the ultrasonic stack (an auxiliary mounting point is located on the transducer itself). In some designs, the booster can be eliminated completely. The sonotrode (often called "horn") is responsible for delivering ultrasonic vibrations to the chosen elements. It is the most important element of the ultrasonic stack, and it has to be custom-designed and manufactured for each particular technology.

Fig. 2. Ultrasonic stack.

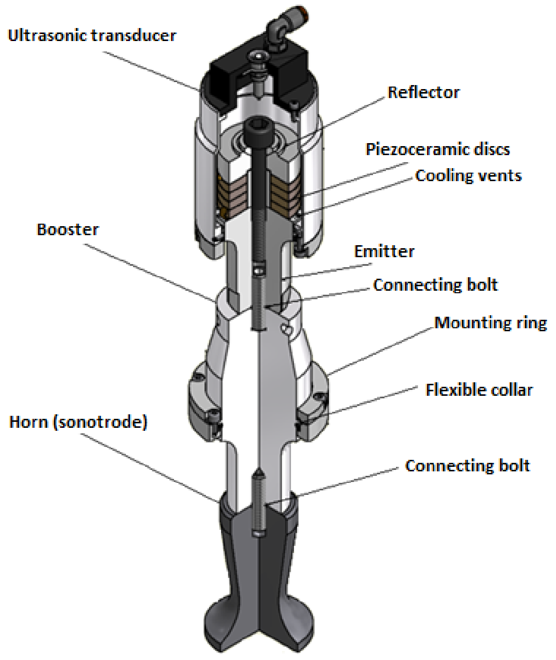

Fig. 3. Ultrasonic stack assembly parts.

From the electrical point of view, the ultrasonic stack can be represented as equivalent RLC circuit (commonly known from literature as Butterworth van-Dyke model) shown in Figure 4 [4, 5]. This model allows for complex electrical simulation of generator - ultrasonic stack system. C_S, L_S and R_S elements represent the mechanical properties of the stack, while C_{0S} represents parallel capacitance of the piezoceramic disks. Ultrasonic stack is typically supplied with a sinusoidal waveform with a voltage of 1 to 2 kV RMS, and frequency selected from 20 kHz to 70 kHz (20 kHz systems are the most commonly used). The ultrasonic stack bandwidth is usually very narrow, which requires the generator to precisely monitor and tune itself to the resonance point of the stack. The accuracy of this tuning is often required to be better than 1 Hz at 20 kHz output frequency. The impedance curve of an ultrasonic stack can be seen in Figure 5. Measurements of impedance curve were conducted using the system described in [6]. Presented characteristics were gathered for the ultrasonic stack shown in Figure 2.

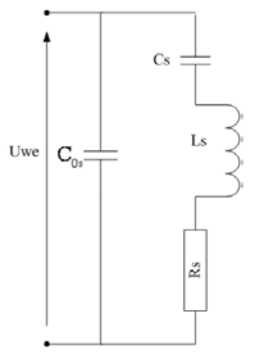

Fig. 4. Equivalent RLC circuit of the ultrasonic stack.

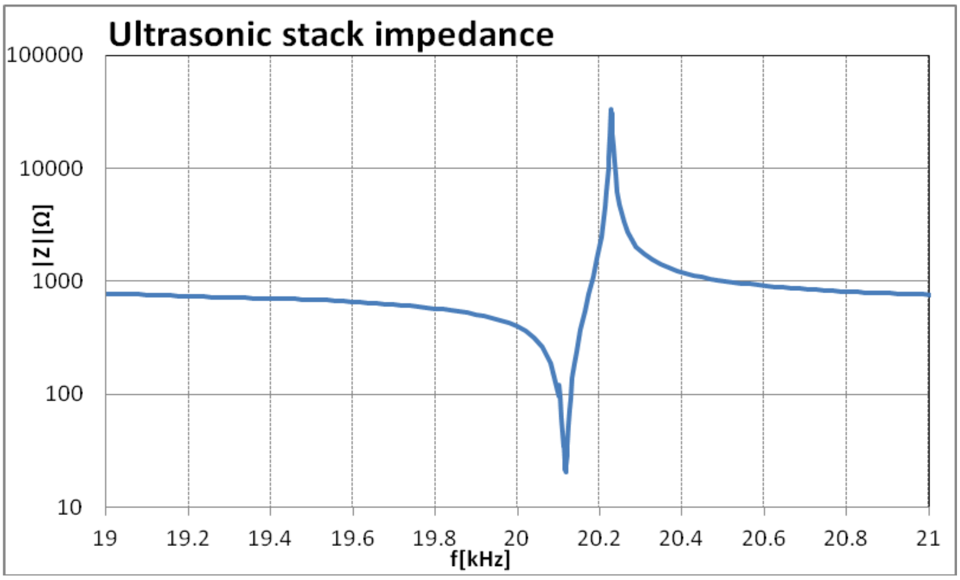

Fig. 5. Ultrasonic stack impedance curve.

3. New concept of ultrasonic generator design

The ultrasonic generator is responsible for creating the electrical signal powering the ultrasonic stack [7]. It has the greatest impact on the performance and reliability of the ultrasonic welding system. Temperature and load have a significant influence on the ultrasonic stack parameters. During the welding process, the generator is forced to constantly monitor stack parameters, and change output frequency and voltage accordingly. Digital measurements of output voltage and current, and digital signal processing algorithms can greatly increase the stability of generator control loop [8]. Cycle by cycle parameters monitoring can also protect both the generator and ultrasonic stack from overload and damage. Typical designs of ultrasonic generators have been described in [7, 8].

In order to achieve unprecedented performance and reliability of the generator, a new approach to generator design has been proposed. Figure 6 presents a block schematic of a new version of the device's power stage, including the control processor. The power stage is using a resonant converter design, described in [9], with a full bridge switching circuit composed of 4 silicon-carbide (SiC) MOSFET transistors.

SiC transistors have significant advantages over classical silicon MOSFET and IGBT transistors. Switching speed and $R_{DS(ON)}$ (Drain-Source resistance during conduction phase) of these transistors are similar to low voltage silicon MOSFETs, while operating voltage is as high as in IGBT transistors. More information about SiC transistor advantages can be found in [10, 11]. For example, transistors used in the generator design - SCT2080 have a turn-on time of only 70 ns, $R_{DS(ON)}$ = 80 mΩ, and operating voltage of 1200 V. Those features are especially important for the resonant converter. Using SiC transistors enabled an increase of the generator's output power, increase in efficiency, and allowed for smooth regulation of output voltage.

Primary LC tank, composed of Ls and Cs elements, is responsible for forming a sinusoidal waveform delivered to the transformer TR. Q factor of the LC tank is selected in such a way as to provide the ability to tune generator output frequency to the resonance frequency of the ultrasonic stack, and at the same time provide low distortion levels in the output signal. Transformer TR increases output voltage to nominal 1.8 kV RMS at full power. Output compensating coil, Lcomp, is added to provide apparent power compensation of ultrasonic transducer parallel capacitance C_{0S}. Selection of compensating coil value is done for particular types of ultrasonic transducer.

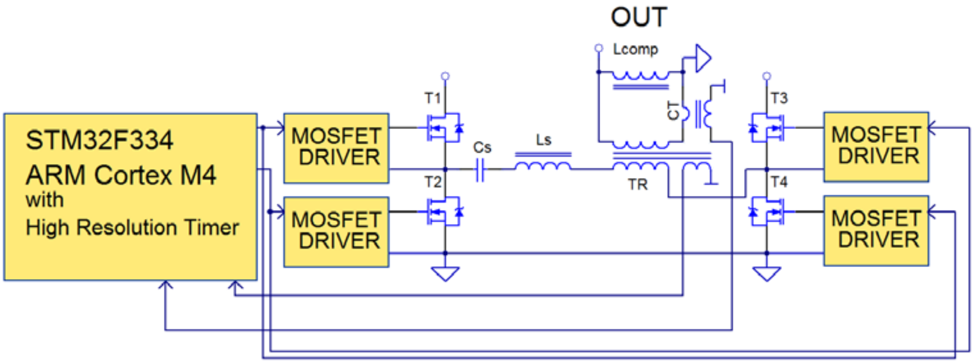

Fig. 6. Ultrasonic generator power stage.

4. Control signal generation method

In order to provide good frequency resolution of output signals, a new type of microcontroller has been used. STM32F334 is a low cost 32-bit ARM Cortex M4 microcontroller equipped with a single precision floating point unit, and an innovative High Resolution Timer (HRTIM). HRTIM peripheral uses Delayed Locked Loop (DLL) technique to generate multiple clocking signals of precisely controlled, shifted phase. From the user point of view, this mechanism acts as a timer clocked with an equivalent frequency of 4.608 GHz which results in time resolution of just 217 ps. This technique is very cost effective, because it does not require very high speed integrated circuits. Using this microcontroller with a built-in timing block simplifies the design, as well as increasing the reliability and flexibility of that design.

In the presented model, the High Resolution Timer block has been configured in such a way that it generates 4 separate control signals for MOSFET transistors, using 4 timing blocks chained together. Another timing block has been used to trigger an internal analog to digital converters (ADC) to provide coherent sampling of the output signal's voltage and current. Achieved output frequency resolution is 0.1 Hz at 20 kHz. The microcontroller carries out a 1st harmonic analysis using the Goertzel algorithm, to provide accurate data about the ultrasonic stack's condition. Complex impedance of the stack is calculated in real-time, as well as real power, and used as input data for the control loop realized in the software.

5. Modular design of the generator

The presented ultrasonic generator has been designed in a modular form. The generator consists of 5 separate modules:

- Main board with resonant converter and main power supply,
- Control panel,
- Input-Output card,
- SiC MOSFET drivers,
- Auxiliary power supplies 12 V & 24 V DC

Each module is replaceable, which allows for easy customization of the generator for particular purposes. Figure 7 presents the block schematic of the designed generator.

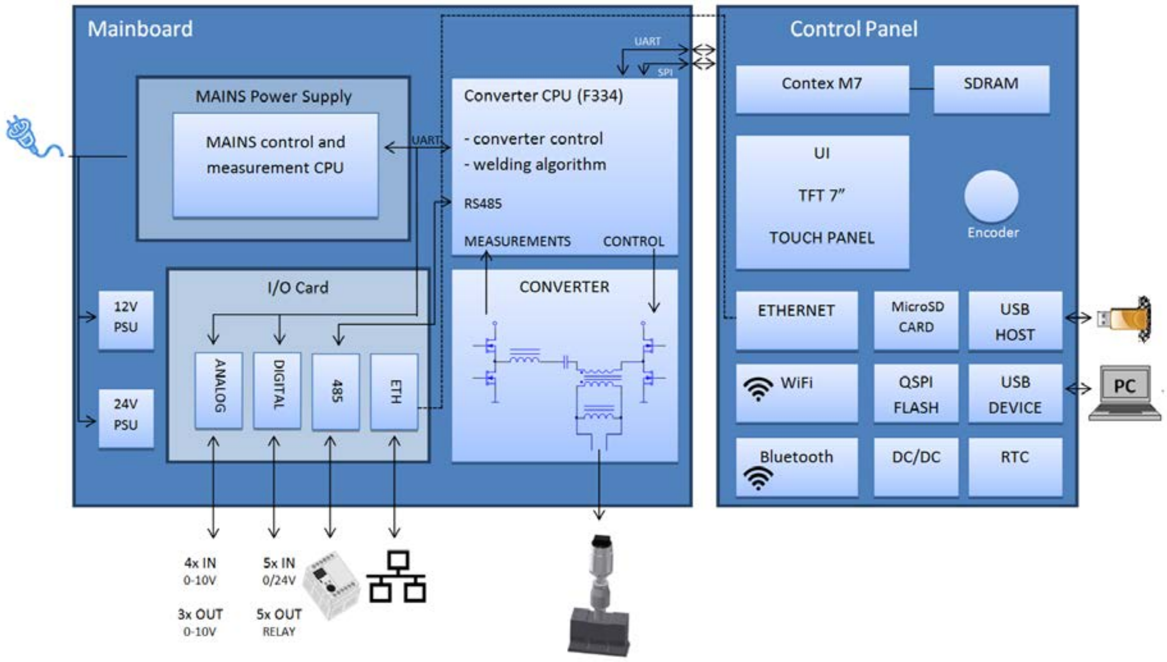

Fig. 7. Block schematic of the designed generator.

MAIN BOARD contains a resonant converter with control processor and SiC MOSFET transistors, mains power supply, and cooling system. The converter control processor has been described in a previous paragraph. Inductive elements of the resonant converter are custom designed and manufactured for the generator, and are based on an E65/32/27 ferrite core made of 3C90 material. Design of these elements plays a significant role in the efficiency and reliability of the device. Multiple versions of inductive elements were tested to select the optimum design. To provide power for the resonant converter, a single phase mains power supply has been designed. It includes a bridge rectifier with an electrolytic filtering capacitor, a triple stage EMC filter, and a separate control and measurement microcontroller. The microcontroller is responsible for switching the mains supply on and off, switching soft-start circuit, and measurements of mains voltage, current and power consumption. The microcontroller communicates with the converter control processor using a single wire, addressed, bidirectional UART bus. All other modules of the generator are connected to the main board.

CONTROL PANEL is responsible for managing the user interface, providing communication through various interfaces, managing settings, calculating statistics, visualizing and logging data, as well as the control parameters of the welding process. The panel contains an ARM Cortex M7 processor running at 200 MHz and equipped with 64 MB of DRAM memory, 16 MB of serial FLASH memory, and 8 GB of mass storage FLASH memory (internal MicroSD card). The panel is also equipped with a 7-inch color TFT display (800x480 pixels resolution) and touch panel. A modern user interface with a tablet-like touch menu was specially designed for the generator. It is intuitive and easy to use, even for non-professionals. Various internal data, like power curve or output voltage, and current waveforms, can be easily and clearly visualized. All internal data is logged and stored on the internal FLASH. Communication with external systems is possible through Ethernet 100BaseTX, WiFi b/g, Bluetooth 2.1 or a USB interface. It is also possible to attach USB pendrive memory to the control panel to copy settings, logged data, or to update firmware. The control panel can be detached from the generator case, and mounted in a different part of the welding machine. The connection between the control panel and the main board is achieved using an RS485 interface and a UTP cable. Figure 8 presents a photograph of the control panel during startup and various menu screens of the user interface.

Fig. 8. Control panel photo (top left), Main menu (top right), Welding curve menu (bottom left), Configuration menu (bottom right).

INPUT/OUTPUT CARD contains all interfaces designed to connect with the control system of the production line. It includes:

- Digital I/O (DB15F connector):
  - 4 isolated digital inputs 0/24 V DC,
  - 5 relay outputs 24 V AC/DC,
  - Auxiliary power supply output 24 V DC / 1.5 A.
- Analog I/O (DB9F connector):

  - 4 voltage inputs 0-10 V (2 of them can be reprogrammed to be 4-20 mA current loop receivers),
  - 3 linear voltage outputs 0-10 V,
  - auxiliary power supply output 12 V DC / 50 mA.
- Isolated RS485/RS422 interface, up to 500 kbps, RJ45 connector,
- Ethernet RJ45 connector.

Digital inputs can be used to trigger the welding process as well as receive information from external sensors such as end-stops. Relay outputs can signal generator state, and control external actuators, for instance the ultrasonic stack pneumatic actuator. Analog inputs can be used to monitor external parameters such as temperature of the transducer or weld depth. Analog outputs can be utilized to monitor output power, or frequency of the generator. Digital RS485 interface and Ethernet interface can be used to connect to PLC controller and transfer data and settings. The I/O card is exchangeable and can be customized for a particular system.

SiC MOSFET DRIVERS were specially designed to achieve the best possible switching speed of SiC transistors. They have full galvanic isolation of control signal and power. Output rise and fall times are below 10 ns, and maximum instantaneous output current is equal to 9 A. Additionally the drivers are designed to be particularly immune to EMC noise.

AUXILIARY POWER SUPPLIES deliver power for the electronic circuits of the generator. The 12 V DC is used by all internal circuits while 24 V DC is used by the I/O card to supply external actuators and valves. Each of the power supplies is protected from faults, has a built-in EMC filter, and is monitored by the main processor. Electrical efficiency of the auxiliary power supplies is above 89 %.

6. Design results and measurements

The designed generator was tested using artificial load specially designed to simulate an ultrasonic stack. More information about the artificial load and power measurements of ultrasonic generators can be found in [12]. Table 1 contains the measurement results of output power at different resistance of the load. During the test, the generator was set for a constant frequency of 20 kHz and maximum power. Tests showed the ability of the generator to deliver over 5 kW of power to the load in the continuous mode. Additional functional tests were performed using a real ultrasonic stack. The generator was able to correctly tune itself to the resonance frequency of the stack, and maintain it, during the welding process.

Tab. 1. Measurement results of generator output power.

R_{LOAD}	U_{OUT}	I_{OUT}	P_{OUT}
1760 Ω	1866 V_{RMS}	1.06 A_{RMS}	1978 W
880 Ω	1852 V_{RMS}	2.10 A_{RMS}	3898 W
660 Ω	1836 V_{RMS}	2.78 A_{RMS}	5107 W

The generator can be prepared to operate in one of the three frequency ranges:

- 16 - 25 kHz,
- 25 - 36 kHz,
- 35 - 60 kHz.

The device is supplied from single phase mains 230 V AC and the supply current is up to 25 A. It has a high electrical efficiency of over 96 % at full load. Figure 9 presents the front side of the generator case, with the control panel displaying main menu screen. Figure 10 presents a view of the inside of the generator, from the top after removing the top cover. Generator case is designed to prevent dust ingression. All cooling fans are equipped with dust filters and are monitored for their proper operation.

Fig. 9. Generator front panel displaying main menu.

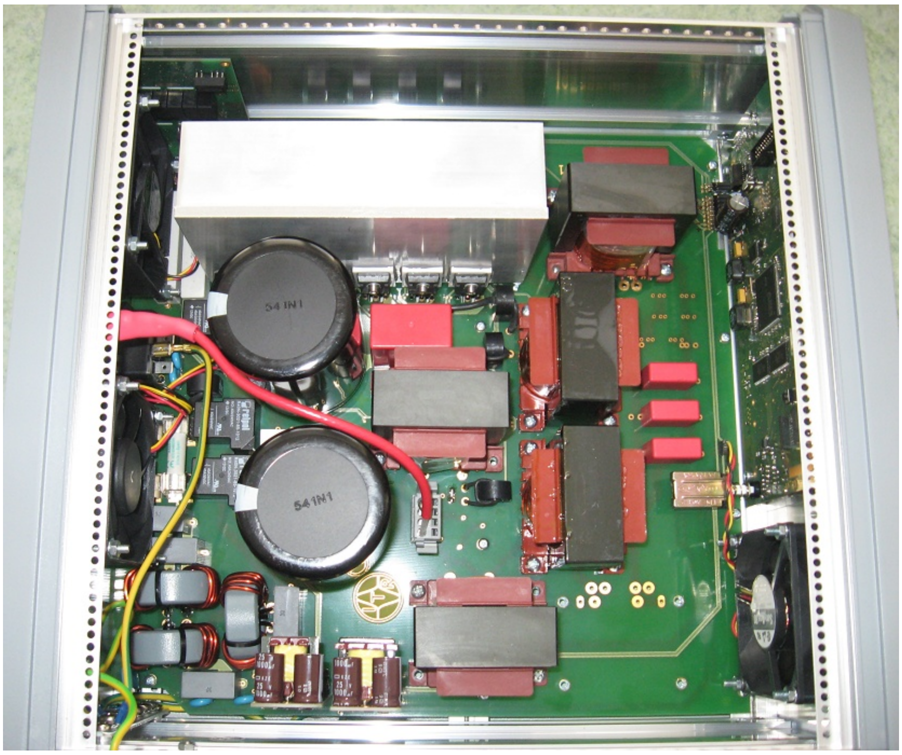

Fig. 10. View of the internals of the designed generator.

7. Conclusions

The designed device is suitable for modern welding and cutting systems, and can be used to realize a broad range of ultrasonic technologies. A modern user interface, with touch control, simplifies configuration and usage of the generator. Multiple communication interfaces provide easy access to settings, and stored data, as well as easy integration into existing welding systems. Ultrasonic stack diagnostic algorithms and generator self test mechanisms, greatly improve the reliability of the whole system. The generator can detect upcoming system failures and provide information about ultrasonic stack parameters.

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