# Embedded Microprocessor System for Monitoring and Control of Resonant Inverters

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*Abstract* - **Analyses of some aspects of the processes in induction heating has been done in order to define the necessary parameters of the object (resonant inverter), which have to be measured and controlled in real time.**

**A variant of architecture of embedded microcontroller system for monitoring and control of a class of resonant converters is suggested.**

**The blocks generating the frequency of the two-phase sequence of control signals and forming the duration of the pause when switching the transistors in resonant converter implement the Direct Digital Synthesis approach and a programmable logic device. They allow essential extending the range of control frequencies and increasing the resolution.**

*Keywords* - **embedded microprocessor system, monitoring, resonant inverter, direct digital synthesis, programmable logic devices.**

## I. Introduction

The resonant and quasi-resonant inverters have been wildly spread in induction heating of various materials for surface hardening, surface melting, sticking, casting etc. The proper operation of the system inductor-detail depends on both the parameters and modes of operation of the passive and active components of the inverter and the equivalent parameters of the whole system. During the technological process together with changing the heating temperature these parameters also change in some range. In order to measure the characterizing parameters of the operational modes and to control and/or regulate to achieve optimal operation, it is necessary to know the nature of their change [1].

A variety of architectural and schematic solutions for control of such systems based on various components – analogue and digital – have been published. In order to increase the quality of the control and operational capacities becomes more necessary using intelligent control systems based on microcontrollers, digital signal processors, programmable gate arrays, or combination. [2,3,5,6]. Preconditions for that are the rapid progress in the last decade both of the digital, microprocessor and programmable components and also improving the technologies and the means, which the companies provide to facilitate and to decrease the time for development, testing, debugging and programming of such systems [7].

Implementing intelligent digital systems to control converter devices results in many advantages as:

- More flexible systems, where it is possible to add a wide variety of features and characteristics;
- Implementing some features by software results in decreasing the size, consumption and cost of the system;
- Storing, processing and monitoring of various data about operation of the object and the whole system;
- Low energy consumption by the control system;
- Enhanced opportunities for automated control and diagnostics of the whole system, increasing in such a way the reliability and improving the quality and operational features of the system.

*Aim of the report*: Development of universal variant architecture of an embedded microprocessor system (EMS) intended for monitoring and control. The system has to be adaptable to operate in a wide frequency range and with high resolution and will be applied to control the signal parameters of a class of resonant inverters (RI).

*Main problems of the report:*

- Brief analysis of some aspects of the induction heating technological process in order to define the parameters which have to be measured, monitored, controlled and regulated;
- Defining the most common features and operation modes of the EMS;
- Synthesizing the architecture of the EMS using the DDS approach and programmable logic devices to form the control signals of the system.

## II. Analyses of Some Aspects of the Induction Heating Technological Process in Connection with Its Control

The bridge and half-bridge resonant inverters are most common power sources (converters) in induction heating of materials with small mass. A classical circuit of a bridge resonant inverter using transistors as switching devices is shown in Fig. 1.

***Y1, Y2, Y3, Y4*** – Control signals, applied to the transistor gates

***CS1, CS2, CS3, CS4, CS5*** – Current Sensors, submitting data about the currents trough the transistors and the current of the resonant circuit

***VS1*** Resonant circuit Voltage Sensor

$Z_T$ Complex impedance of the heated material

***I*** Inductor, implementing the galvanic isolation and the link of $Z_T$ with the parallel resonant circuit of RI.

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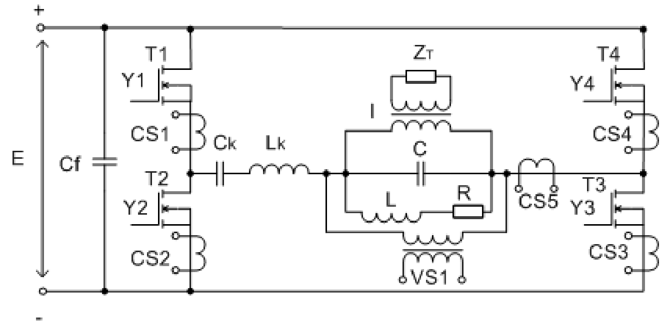


Fig. 1. Classical circuit of a transistor RI

***E*** Source voltage

***T1, T2, T3, T4*** – Transistors, operating in switch mode, switching the resonant circuit *L,R,C* to the power source *E*.

The necessary active power for heating the material to the previously defined temperature according to the purpose of the induction heating (hardening, soldering, melting, etc.) is a multi-factor value and depends on the following variables:

$$P_M = k_1 (G.\Delta T.C)/\Delta t\,, \tag{1}$$

where:

- $\boldsymbol{P_M}$ Detached into the material heat power
- ***G*** Mass of the processed material
- $\boldsymbol{\Delta T}$ The difference between the initial and final temperature of the material
- ***C*** Special thermal capacity of the material
- $\boldsymbol{\Delta t}$ The time necessary to reach the final temperature
- $\boldsymbol{k_1}$ Dimensions equalizing coefficient

The power $P_И$, generated by the RI and detached into the inductor, can be defined taking into account the active losses and the power $P_M$, detached into the heated material. Using the efficiency of the inductor $\eta$:

$$\eta = F_1(\Delta T, S, \Delta t)\,, \tag{2}$$

we can write:

$$P_И = P_M/\eta\,, \tag{3}$$

where *S* is the whole surface of the heated material.

With the increasing of the temperature *T* of the heated material during the technological process its properties vary and hence the active and reactive components of its impedance [1,4] are:

$$Z_T = R_T + j\varpi L_T = F_2(\Delta T) \tag{4}$$

Usually the change of the active and the inductive components passes through three basic phases when heating metals.

It is clear from the study that the active component of the load $R_T$ increases nearly linear with the temperature increasing; hence the equivalent power factor of the resonant circuit during the three phases tends to decreasing and the frequency band of the circuit expands.

In metal heating it is interesting the change of the inductive component of the load $L_T$. It is clear from the study that during the first and the third phase $L_T$, although with different values, keeps the characteristics of the inductive load nearly constant with the temperature change. During the second phase when the temperature of the object reaches the Cury point the relative permeability $\mu_r$ rapidly becomes 1, hence the load inductivity $L_T$ rapidly decreases and the equivalent inductivity of the circuit rapidly increases:

$$Le = L - L_T' \tag{5}$$

As:

$$Qe = \rho/\mathrm{Re} = \sqrt{Le/C}/\mathrm{Re}\,, \tag{6}$$

the Q-factor of the resonant circuit at Cury point rapidly increases.

As the capacitance *C* in the resonant circuit is a constant when increasing the temperature, the equivalent inductance $L_e$ at the Cury point quickly increases, and the equivalent resonant frequency increases too:

$$\varpi_e = \sqrt{Le.C} \tag{7}$$

The conclusion from the above reasonings is the need of measuring and regulating the control frequency for the RI operation in order to keep the resonant or quasi-resonant mode of operation.

It is necessary to measure the currents through the transistors and the voltage of the resonant circuit to receive information about the power in the resonant circuit.

To control the operation of the RI it is necessary to generate two-phase control signals supplied to Y1 and Y3 with one phase and to Y2 and Y4 with an inverse phase. At that the frequency of the control pulses $f_Y$ have to be regulated in a wide range with maximum resolution for more easy regulating of the power.

Fig. 2 shows the relation of the two control signals.

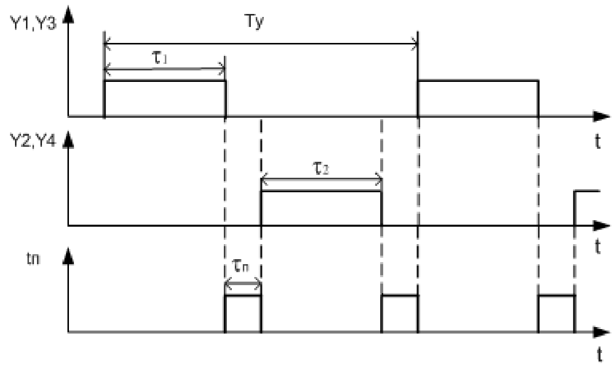


Fig. 2. Control signals, supplying the gates of the switching transistors

where:

$$f_Y = 1/T_Y \tag{8}$$

$$\tau_П = [T_Y - (T_1 + T_2)]/2 \tag{9}$$

As the duration of the control impulse usually is $\tau_1 = \tau_2 = \tau$, the equation becomes:

$$\tau_П = T_Y/2 - \tau \tag{9'}$$

The value of $\tau_П$ can be defined, taking into account two considerations. The first one is that two consecutively connected transistors have not to be turned on, because otherwise the power source *E* will be sort circuited. From the datasheets of the switching transistors it is clear that the following equation is true:

$$t_{on} \leq t_{off} \qquad (10)$$

where $t_{on}$ is the turn-on time of the transistor, and $t_{off}$ – its turn-off time. These two times depend on the frequency features and the operation mode of the transistor.

To take into account the first consideration it is necessary to realize the following equation:

$$\tau_{\Pi}^{\min} > 2.k_2(t_{off} - t_{on}), \qquad (11)$$

where $k_2$ is a safety coefficient, which can vary in the following range $1{,}1 \leq k_1 \leq 1{,}5$.

The second fact to consider with when defining the duration of the pause is that with its increasing the detached power in the inductor will decrease, so the power regulation coefficient $k_P$ will be:

$$k_P = \tau/(T_y/2) = 2/T_y(T_y/2 - \tau_{\Pi}) = 1 - 2\tau_{\Pi}/T_y \qquad (12)$$

The range of variation of $k_P$ will be:

$$0 \leq k_P \leq 1 - 4k_P(t_{off} - t_{on})/T_y \qquad (13)$$

Eq. (12) shows, that except automated regulation of the control frequency, the duration of the pause $\tau_{\Pi}$ has to be controlled too in order to regulate the power in the inductor of the RI.

As a conclusion with a reference to the first problem it is necessary to measure the currents of the transistors and the resonant circuit, the voltage of the resonant circuit, the resonant frequency of the circuit in every moment of the technological process and the temperature of the heated material. In order to control the RI and to allow the possibility to regulate the detached into the heated material active power it is necessary to regulate the controlled frequency $f_Y$ and the pause duration $\tau_{\Pi}$.

## III. Architecture of an Embedded Microprocessor System for Monitoring and Control

*Features and operational modes of the embedded system*

In order to perform its purpose for a class of resonant inverters in a wide frequency range and a possibility to regulate the power, the embedded microprocessor system for monitoring and control must be able to operate in two basic modes and to have some definite features:

Main operation modes of the system:

- Programming and debugging the software of the control unit MCU. A development system with JTAG interface, PC and proper programming and debug software can be used.
- Setting the mode of regulation, the variation range and the values of the parameters of RI and the technological process.
- Implementing a frequency grid to find the optimal mode of operation of RI, using the DDS block in FPGA. It forms a frequency sequence with a definite step of variation in a previously defined range. The active power detached into the object has been measured automatically by measuring the currents and the voltages in the RI. The optimal power value has been defined using selected sorting approach.
- Operational mode of the control system including three sub-modes:
  - Working mode with automated assertion of the regulation law without statistics and with local monitoring;
  - Working mode with automated assertion of the regulation law with accumulating and processing of statistical data from the object and the technological process;
  - Emergency sub-mode. The system will be put in it manually or automatically when the differential defense turns out and the generation of control signals for the RI will has been stopped.

Main features of the system:

- Setting the ranges of the control frequency, duty cycle, time and temperature parameters of the technological process using keypad. A choice a of regulation law for the technological process.
- Automatic generation of two-channel control frequency sequence galvanically isolated from the object. The two frequencies must be dephased at $180^0$ with a changeable duty cycle depending on the power regulation law.
- Using the frequency grid approach at the start mode of the RI and a proper optimization method to define the maximum active power detached in the RI.
- Indicating on LCD or the monitor the operation frequency, the pause, currents, voltages, active power, the processed material temperature, time intervals, etc. Indicating on LEDs the operational mode, emergency sub-mode and the status of the power source.
- Accumulating, processing and displaying statistical information from RI and the technological process.

*Architecture of embedded microprocessor system*

Description of the system blocks:

***JTAG*** - Standard interface of the development system for programming and debugging the monitor program in MCU and tracing the connections between the blocks in the FPGA

***PC*** Personal Computer for accumulating, statistical processing and monitoring of the measured values from RI and system operation control.

***LCD, LEDs &KeyPad*** – Keypad, display and indicators for setting the operation modes and initial values and indicating the measured values and operation modes

***DC/DC ISO*** – Normalization and galvanic isolation block of the incoming data about the current and voltage from the RI

***ISO DR*** - Isolating Driver forming the control signals with necessary power for the switching components in RI.

***CG*** Clock Generator – generates the switching frequency of the memory components in FPGA and MCU

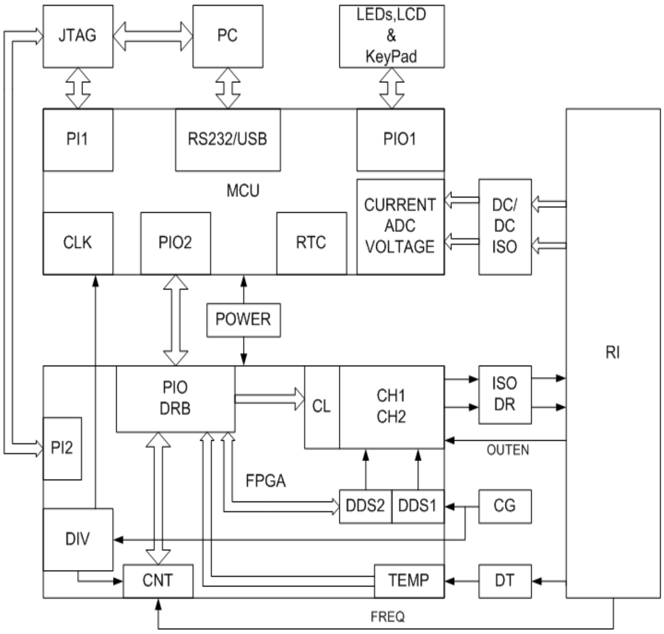


Fig. 3. Architecture of the system for monitoring and control

***DT*** Digital Thermometer, measuring the temperature of the heated material

***TEMP*** – Temperature digital value processing block.

***POWER*** – Power source for MCU and FPGA

***OUTEN*** - Signal enabling/disabling the control signals for the RI. It is formed by the differential defense of RI.

***MCU*** Microcontroller – initializes the FPGA, processes the information received from the RI, implements programming and debugging of the system and interfaces with KeyPad, LCD, LEDs, PC.

***PI1, PI2*** – Interfaces for programming and debugging of the monitor program in MCU and programming the FPGA

***RS232/USB*** – Interface for connection with PC

***PIO1*** Parallel Input-Output interface with the KeyPad, LCD and LEDs

***ADC*** Multi-channel ADC receiving the digital code of the currents and voltages in RI.

***CLK*** Clock input for the MCU

***PIO2*** Parallel Input-Output interface with the FPGA

***RTC*** Real Time Clock

***FPGA*** Field Programmable Gate Array, implementing the DDS control signals oscillator for channel 1 (CH1) and channel 2 (CH2)

***PIO DRB –*** Input-output driver buffer, used by the DDS oscillator, for measuring the temperature of the heated material and/or generated frequency.

***CL*** Digital logic, setting the pause duration at switching the consecutively connected switching devices (transistors).

***CH1, CH2*** – Channel 1 and channel 2 forming control signals for RI

***DDS1, DDS2 –*** Digital blocks forming square waves

***DIV*** Frequency divider blocks for synchronizing the MCU and CNT

***CNT*** Counter block measuring the frequency of RI

***RI*** Resonant Inverter for induction heating

In the suggested in the present article architecture of the system for monitoring and control the following blocks have been implemented in Altera FPGA EP1C6T144C8 using the integrated development environment Quartus – DDS1, DDS2, CH1, CH2, and CH3. Their functional circuits as a result of the development have been given in [8].

## IV. CONCLUSION

The contributions in the present report are as follows:

- A brief analysis of the induction heating technological process and the operation of the RI as a power source has been done. The parameters to be measured, monitored, controlled and regulated have been defined.
- The main features and operational modes have been defined. The architecture of an embedded microprocessor system has been synthesized.
- Architectures of the blocks built in FPGA have been synthesized. DDS approach for generating a frequency grid with a high resolution has been used.

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