Simple Microcontroller Based Mains Power Analyzer Device

Petr Dostálek, Vladimír Vašek and Jan Dolinay

***Abstract*— Paper deals with design of simple microcontroller based power analyzer device for measurement of basic electrical quantities in mains network. Main part of the device is 8-bit general purpose microcontroller MC9S08GB60 by Freescale Semiconductor. It performs all tasks related to data acquisition, computation of desired values and communication with personal computer. Algorithms implemented in the device firmware allows measurements of true RMS values of voltage and current, real power and power factor independently on the shape of measured voltage and current waveforms. In advanced mode of operation it is also possible to send sampled waveforms to the personal computer for next analyses. Developed evaluation software is able to visualize all measured quantities in user friendly graphical user interface in form of graphs including long-term archiving function for further data analysis. Communication with supervision system is provided by standard RS232 communication interface.

***Keywords*— Apparent power, magnitude spectrum, power factor, power monitoring, MC9S08GB60, real power.

I. Introduction

ELECTRIC equipment connected to the electrical power system can be divided into two basic categories. Devices that have the apparent power equal to the real power, thus voltage and current are in the phase, belong to the first one. This requirement is satisfied only by appliances with pure resistive character, light bulbs and heating elements for instance. All others behave as a complex load consisting of a real and reactive part of power. The majority of the reactive part is represented by inductance of coil windings in transformers, inductors and motors, where alternating magnetic field is generated and it shifts the phase up to +90 degrees. On the other hand, devices with capacitive load characteristic occur less frequently. There is an electric part called capacitor, which has opposite function than coil – it shifts the phase up to -90 degrees. This reactive power causes great problems with power distributing because it overloads distribution nets and, in addition, electrometers do not record it, so the energy consumer will pay only the real part of the power that was transformed to light, heat, torque, etc. Due to this fact, wholesale customers must maintain the power factor in the range of 0.95 – 1.00. Energetic suppliers monitor this value and in most cases its violation is penalized by introducing extra pay. Due to this fact it is very important to monitor power factor in AC circuits and in case of need to correct it to acceptable range.

Special category forms nonlinear loads which are characteristic by non-sinusoidal current causing unwanted harmonic distortion of mains voltage. To this category can be included device such as for example switched mode power supplies, frequency converters, dimmers, electronics ballast for fluorescent lamps and other devices with rectifiers in the mains circuit. Higher harmonics components cause additional energy loses in the supply network, overheating of transformers and inductors and some sensitive devices can malfunction. To avoid these problems European standard EN 60555-2 was created. It defines maximum levels for harmonic currents injected by each category of electric load to the mains network.

There are defined four different classes:

- Class A – balanced three-phase equipment, household appliances excluding equipment identified as class D
- Class B – portable tools
- Class C – lighting equipment
- Class D – personal computers, monitors, radio and TV receivers with input power ≤ 600W [1], [9].

Paper proposes design of simple power analyzer device which can evaluate all basic electrical quantities in mains circuits – true RMS voltage, true RMS current, real power, apparent power, reactive power and finally power factor with ability to transfer them via serial communication interface to supervision system for further processing, visualization and data archiving. In advanced mode of operation it can work as data acquisition device sending voltage and current waveforms directly to the computer without evaluation of measured quantities. It enables to perform analyses such as magnitude spectrum of voltage and current, harmonics distortion and other analyses.

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II. Hardware overview

Power measurement device is based on Freescale MC9S08GB60 microcontroller (MCU). It is a member of low-cost, general purpose, high-performance Freescale 8-bit flash-based microcontrollers with Von-Neumann architecture. Central processor unit (CPU) with enhanced HCS08 core is fully upward compatible with Freescale 68HC05 family. Correct program function is monitored by integrated watchdog system and illegal operational code and address detection. Internal program loading and debugging is provided by on-chip debug module (DBG). Internal bus frequency can be 20 MHz at 2.08 V to 3 V supply or 8 MHz at 1.8 V to 3 V supply voltage range [2].

On the chip are integrated following peripherals:

- 3-channel and one 5-channel 16-bit timer/pulse width modulator modules (TPM)
- 2 serial communication interfaces (SCI)
- Serial peripheral interface (SPI)
- Inter-integrated circuit bus module (IIC)
- Internal clock generator module (ICG)
- 10-bit analog-to-digital converter with 8-channel analog multiplexer (ADC)
- 64 KiB FLASH memory with in-circuit programming capability
- 4 KiB RAM
- 56 general-purpose input / output pins (16 high-current pins)
- 8-pin keyboard interrupt module (KBI)
- Debug module (DBG) [1].

Central processing unit (CPU) features:

- 40 MHz operation at 3V
- 8-bit accumulator (A)
- 16-bit stack pointer (SP) with new stack manipulation instructions
- 16-bit index register (H:X) with index register instructions
- Memory to memory moves without using the accumulator
- Fast 8-bit by 8-bit multiply and 16-bit by 8-bit divide instructions [3]

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Power analyzer device design utilizes from these available peripherals serial peripheral interface (SCI) for communication with supervision system over RS232 interface, serial peripheral interface (SPI) for communication with external analog-to-digital converter and timer system (TPM1 and TPM2) for real-time operating system time base and triggering of analog-to-digital conversions with required time period.

SPI is four-wire synchronous serial interface which can work in master or slave operation mode. Master device, in our case microcontroller unit (MCU), initiates communication by selecting slave device using slave select signal which is active in logic low level. Then interface shifts data from the internal register to the MISO line (Master Out – Slave In) while on the SPSCK line is generated clock signal. At the same time master device receives data from the MISO (Master In – Slave Out) line. Slave select signal is pulled high logic level when communication with slave device is done. Operation options of the SPI interface are fully programmable so it is possible to program transmit bit rate, serial clock phase and polarity, MSB first or LSB first shifting and other possibilities. Transmitter and receiver double buffering eliminates possible character losses when high bit rates are used. Maximum clock frequency in master mode is bus frequency (f_{BUS}) divided by 2, in slave mode it is f_{BUS} divided by 4.

SCI is asynchronous serial interface which can be used to microcontroller connection to personal computers, workstations or other embedded systems equipped with RS232 port. Interface implements programmable modulo-based baud rate generator enabling to set all standard baud rates. Main features of SCI module are:

- Full duplex operation
- Standard NRZ format
- Hardware parity generation and checking
- Character length can be programmed to 8 or 9 bit.

Timers subsystem of MC9S08GB60 includes two independent 16 bit timer modules TPM1 and TPM2. TPM1 includes three channels, TPM2 five channels. Each channel can be programmed to input capture, output compare or buffered edge-aligned PWM mode. Clock source to each TPM can be bus clock, fixed system clock or an external clock from dedicated pin.

A. Circuits design

Hardware of measurement device can be divided into several main functional blocks: two independent power supplies, voltage and current sensing circuits, microcontroller unit, optoisolators, RS232 communication interface and analog output (Fig.1).

Voltage and current sensing circuits perform signal adaptation to range 0 – 5 V acceptable by analog-to-digital converter. Both measurement channels consist of main amplifier and summing amplifier stage adding to the measured signal voltage offset of 2.5 V. The shunt in current measurement subcircuit is able to continuously handle currents of 10 A RMS (14 A peak amplitude), voltage divider is designed for voltages up to 250 V RMS (353 V peak amplitude). Inputs of A/D converter are protected against over voltage by Schottky diodes. Analog-to-digital conversion is performed by external successive approximation 12-bit A/D converter MCP3202 with on-board sample and hold circuitry. It is equipped by 3-wire synchronous serial interface to communicate with microcontrollers. Converter is capable to perform up-to 100000 samples per second at 5 V supply

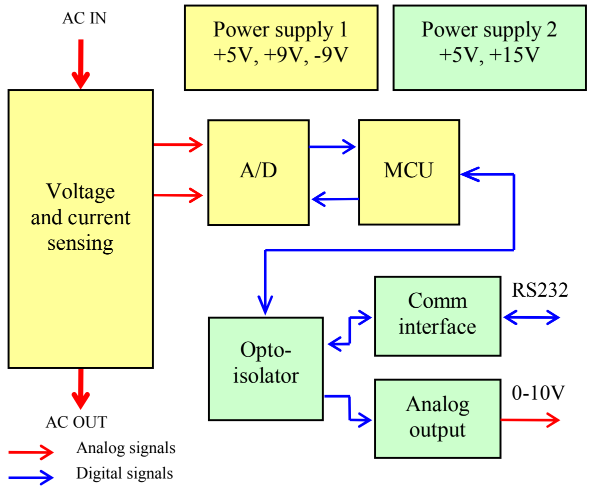

Fig.1 Block schematics of the device.

voltage [5].

Communication interface and analog output circuits are optically isolated from measured circuit by five single channel optocouplers 6N137. They have integrated very high speed photo-detector logic gate allowing transfer rates up to 10 Mb/s. A minimum common mode rejection (CMR) value is 5 kV/μs. Communication interface uses two optocouplers for receive data and transmit data signals, analog output three optocouplers for serial peripheral interface (SPI) signals.

Analog output utilizes 12-bit digital-to-analog converter MCP4921 with SPI interface and rail-to-rail output amplifier [6]. It is followed by amplifier stage with gain of 2 adapting D/A converter output to unified voltage range 0 – 10 V.

Device contains two independent power supplies providing all necessary voltage outputs. Power supply 1 is dedicated for circuits galvanically connected to the mains voltage – voltage and current sensing, A/D converter, and MCU circuits. Power supply 2 provides supply for galvanically isolated circuits – communication interface and analog output which are connected to external devices.

III. Device Firmware

Firmware of the device was created in C language using integrated development environment CodeWarrior IDE. It is based on real-time operating system RTMON for HC08, which was developed on our department especially for microcontroller-based embedded systems with CPU08 main processor core. So software is formed of RTMON OS core and individual processes which perform all necessary tasks. Each process activity is controlled by operating system core on the basis of process priority and other information stored in the task descriptor.

Routines working on the foreground are called by timer subsystem with sampling period so the execution is very time-critical. The purpose of these routines is voltage and current sampling and computing sums of their squares. To achieve highest possible computing speed resulting in higher sampling rates, squares are not computed by standard routines but they are fetched using macros from precalculated results table stored in FLASH memory. This table contains 2048 records of double word values allocating 8192 bytes of FLASH memory.

High-level firmware functions such as communication with supervision system, command processing, measured values computations and others are written as RTMON processes which description is provided in corresponding chapter.

A. Real-time operating system RTMON

RTMON is preemptive multitasking operating system which is simplified to great extend to allow easy use for programmers. It is written in C language with the exception of small platform-specific code written in assembler. The scheduler assigns time slices to processes based on their priority. The priority is integer in the range 1 to 254. Priority 0 is the highest and is reserved for the RTMON initialization process and priority 255 is the lowest and is reserved for the idle process (called dummy in RTMON).

RTMON allows execution of two different types of processes (tasks): normal processes which execute only once (such process typically contains infinite loop) and periodical process which is started automatically by RTMON with given period. These periodical processes are useful for many applications, for example, in discrete controllers which need to periodically sample the input signal and update the outputs.

The priority of each task must be unique, so that in each moment one task (the one with highest priority) can be selected and executed on the CPU. The scheduler does not support cyclical switching of several processes with the same priority on the CPU in round-robin fashion; it simply chooses the task with highest priority from the list of tasks which are ready to run. Processes can be created on the fly, but it is not possible to free and reuse memory of a process. No more than the maximal number of processes can be created, even if some processes were previously deleted.

There are only two objects (data structures) which RTMON contains: process (task) and queue. The queues are buffers for transferring data between processes. It would more properly be called mailboxes in our implementation as each queue can contain only 1 message. Several queues can be created, each containing a message (data buffer) of certain size. The size can be specified when creating the queue and is limited by the total size of RAM reserved for all buffers of all the queues (queue pool size). Processes can read and write data to the queue and wait for the queue to become empty or to become full. This allows for use of the queue also as a synchronization object (semaphore) [4], [8].

B. RTMON processes

Structure of the measurement device firmware is depicted in the Fig. 3. It consists of eleven processes each performing its specialized tasks. Process switching on central processing unit is controlled by real-time operating system core.

Process 1 “System Initialization” is the highest priority process

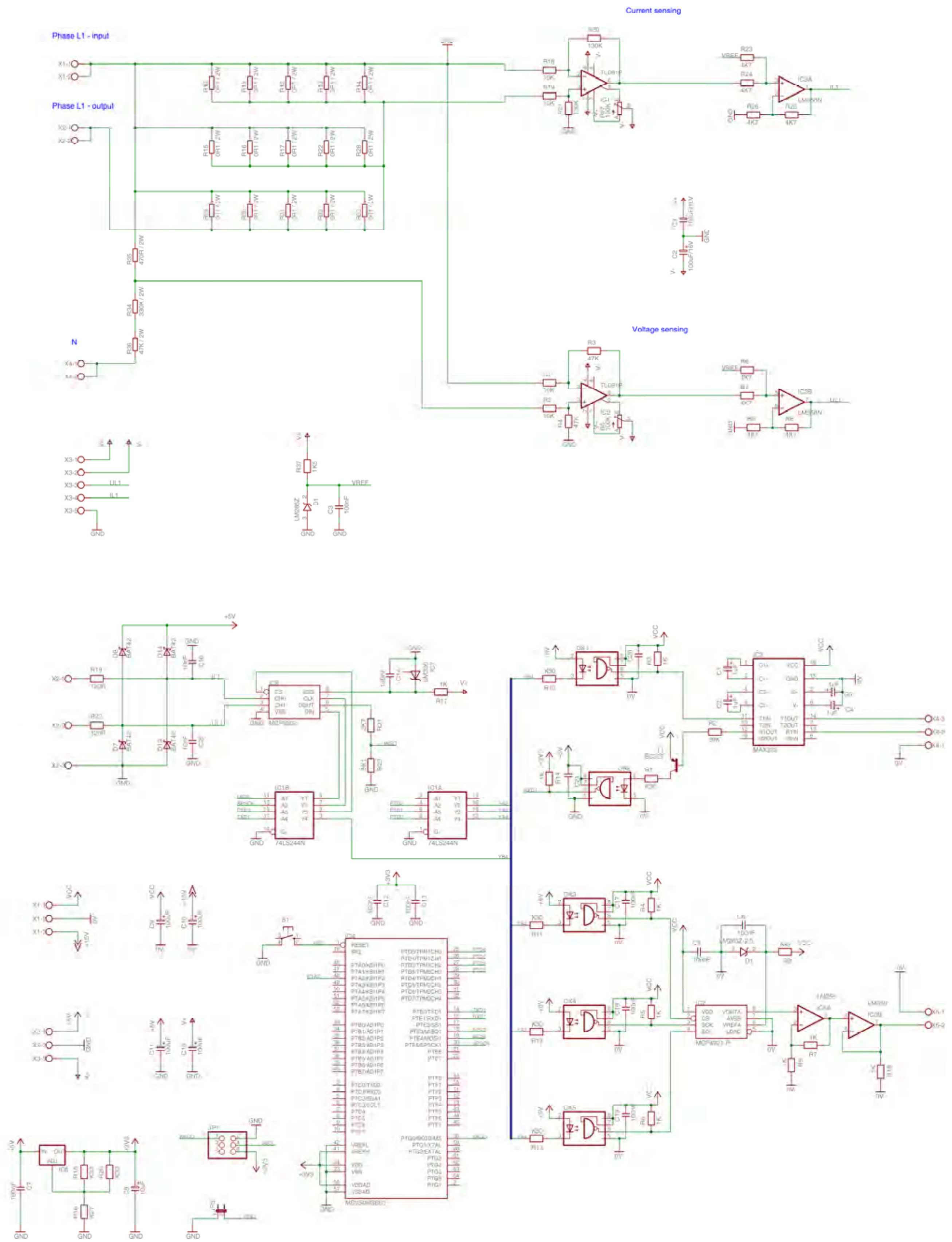

Fig.2 Schematics of the power analyzer device

which performs measurement device hardware initialization after power on or reset. First of all it initializes microcontroller hardware modules used for power analyzer operation - setups serial communications interface, serial peripheral interface for communication with A/D and D/A converter, timer subsystems and finally initializes all necessary data structures. Because of its highest priority no other processes can be switched by RTMON core into the "run" state before this process is completely finished. After all initializations are done it suspends itself.

Process 2 "Command processing" performs all tasks related to command interpretation and execution. It waits for complete command string in the receiver buffer which is serviced by communication process. When command is completely received in the buffer, process will decode it and executes required action by sending corresponding service code via synchronization object to the service process.

Process 3 "Communication" provides communication via asynchronous serial interface with the supervisory system. It receives characters from UART interface and stores them to the command buffer. When this buffer contains complete and valid command process commits it to the process 2 for next processing. It generates responses to all commands regarding to defined communication protocol include error processing. It has defined lowest priority among of all processes so it is not possible to communicate with the power analyzer if it is in busy state – for example if last command is not completely processed yet.

Process 4 "Watchdog" periodically checks correct function of all running RTMON processes by polling their status. Device is automatically stopped when any fault state is detected. Error code is send to the SCI interface in this case.

Process 5 "Services" includes all needed functions related to results computations and data processing.

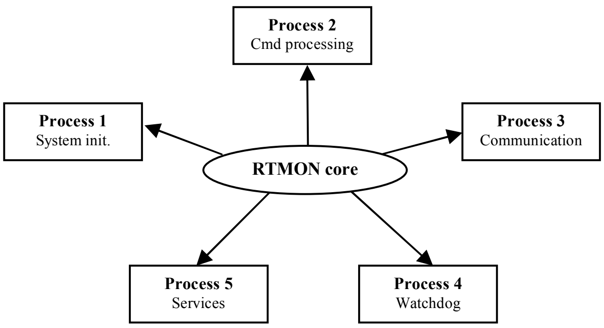

Fig. 3 Firmware structure of the device.

C. *Implemented algorithms*

The main requirement on measurement device was the ability to evaluate true RMS values of voltage and current and real power independently on the shape of input signal waveforms. Due to this fact it is not possible to use equations derived for harmonic shape of voltage and current. Thus to obtain right values of measured quantities integral equations must be utilized. Because fully digital processing is used these equations must be converted from time-integrals to sums. The accuracy depends on sampling frequency after this modification. RMS values of voltage and current are evaluated by equations (1) and (2), real power by equation (3).

$$V_{RMS} = \sqrt{\frac{1}{T_P} \cdot \int_0^{T_P} v^2(t)dt} \approx \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} v_i^2} \tag{1}$$

$$I_{RMS} = \sqrt{\frac{1}{T_P} \cdot \int_0^{T_P} i^2(t)dt} \approx \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} i_i^2} \tag{2}$$

$$P = \frac{1}{T_P} \cdot \int_0^{T_P} v(t) \cdot i(t)dt \approx \frac{1}{n} \cdot \sum_{i=1}^{n} v_i \cdot i_i \tag{3}$$

Where n is number of samples, vi sampled voltage and ii sampled current. Apparent power is calculated from RMS voltage and current by equation (4). Power factor is evaluated as a ratio of real power to apparent power (5).

$$S = V_{RMS} \cdot I_{RMS} \tag{4}$$

$$\cos\varphi = \frac{P}{S} \tag{5}$$

D. *Communication protocol*

In order to achieve compatibility with many software platforms, universal ASCII-based communication protocol was chosen. Very advantageous is the possibility to send all implemented commands using generic terminal program that is included in most operating systems. Communication starts with character "~" followed by command code which is represented by one character. Each command is terminated by CRLF sequence with ASCII codes 13 and 10. Device responds by "~" leading character followed by value or values separated by spaces. Response is terminated by CRLF sequence. Implemented commands are provided in the Table I.

Table I Communication protocol commands

Command	Description
~V	Measure actual RMS voltage, current and real power
~W	Send voltage and current waveforms
~X	Software reset of the device
~R <val>	Set range of the analog output
~M <val>	Set mode of the analog output
~C	Send periodically RMS voltage, current and real power every 100 ms
~S	Stop periodical sending of measured values

E. Evaluation software for PC

All measured values are visualized with “Power monitor” software which was created in Microsoft Visual C++ 6.0. Main window of the program is depicted in Fig. 4. On the bottom left part of the window is located “Device controls” controls group allowing user to choose communication port number, mode of analog output and its range. With “Aout mode” combo box can be selected which measured value will be transferred to analog output. There are available 3 options: real power, voltage and current. Analog output range can be selected by next control “Aout range”. Voltage and current ranges are fixed to values of 300 V RMS and 10 A RMS but real power ranges are scaled to 100, 250, 500, 1000 and 2500 W. Button “Connect” opens communication port and connects program with measurement device. Successful connection is indicated by popup window informing about device serial number and firmware version. All measured quantities are displayed with 100 ms period in the group “Measured quantities”. There are displayed actual values of RMS voltage and current, real power and power factor. In the “Graph and data logger controls” group user can select which measured values will be included in the data logger file and which one will be displayed in the graph. Graph axes range can be modified by “Xrange”, “Ymax” and “Ymin” edit boxes. Data logger can be started by clicking on “Start” button.

Power analyzer device is capable to transfer 500 samples length voltage and current waveforms acquired at 5000 Hz sampling frequency after receiving corresponding command. This data can be used for further processing of voltage and current waveforms. For this purpose the script in Matlab 6.5 environment which can connect to the device and download both waveforms was created.

IV. VERIFICATION AND RESULTS

Power analyzer device was calibrated with precision factory calibrated True RMS DMM Mastech MS-8218. Resulting calibration constants were saved to FLASH memory of main microcontroller of the device. Correct function was verified by measurement of all types of standard loads (resistive, inductive and capacitive) with correct results.

Examples of acquired voltage and current waveforms including current magnitude spectrum measured with different types of electric loads are in the Fig. 5, Fig. 6, Fig. 7 and Fig. 8. Measured values for each electric load type are provided in the Table II.

Table II Measured values for different electric loads

Load type	U [V]	I [A]	P [W]	cos φ
PC 300 W PSU	224.6	0.54	92.9	0.77
Notebook 65 W PSU	225.3	0.35	39.0	0.50
Solder station	225.1	0.23	50.4	0.96
Unloaded transformer	226.4	0.20	10.0	0.22

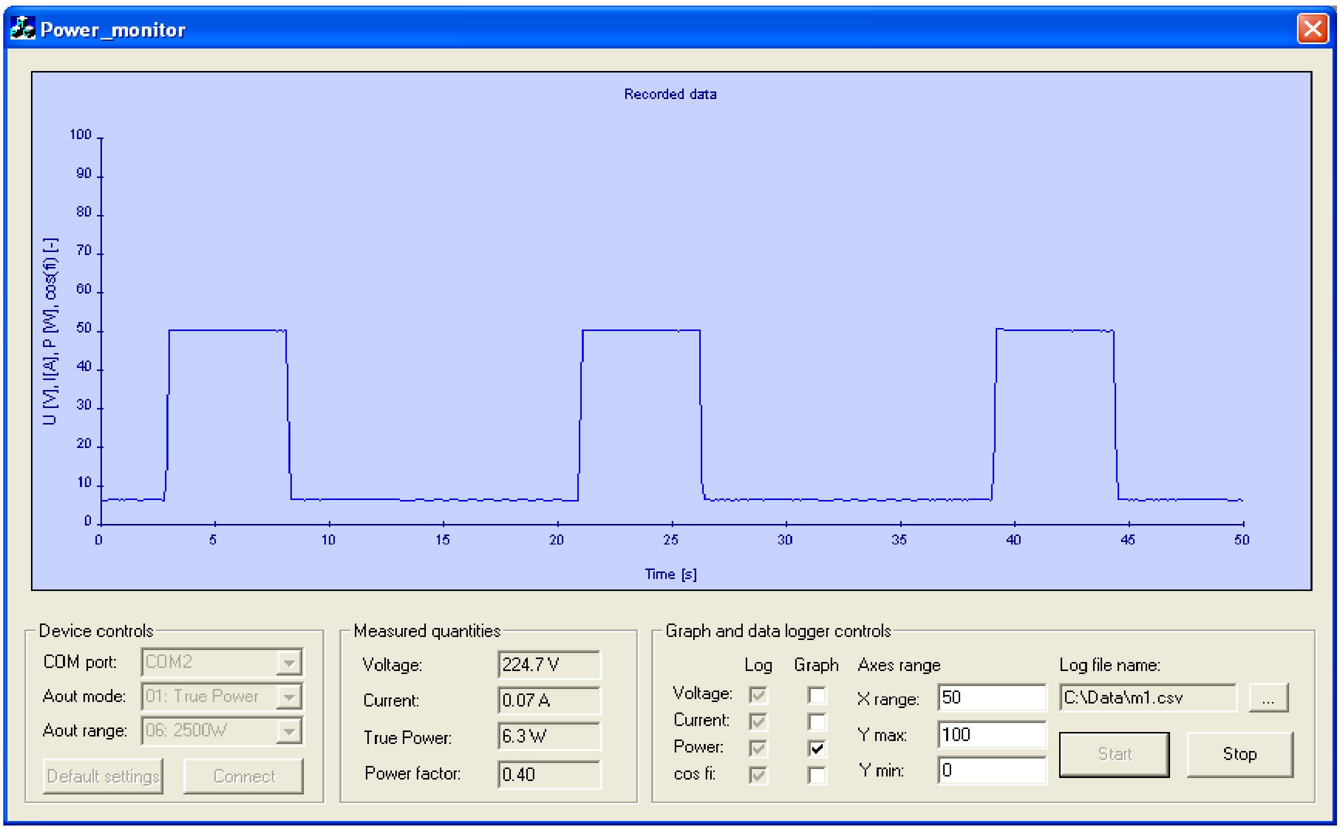

Fig. 4 Main window of the evaluation software.

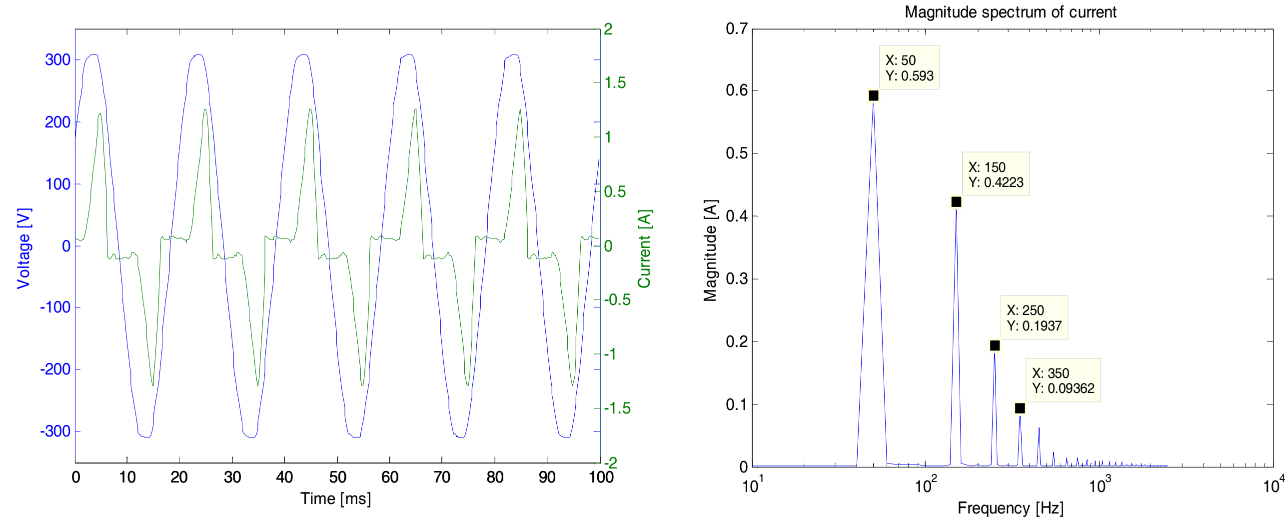

Fig. 5 Personal computer with 300 W PSU.

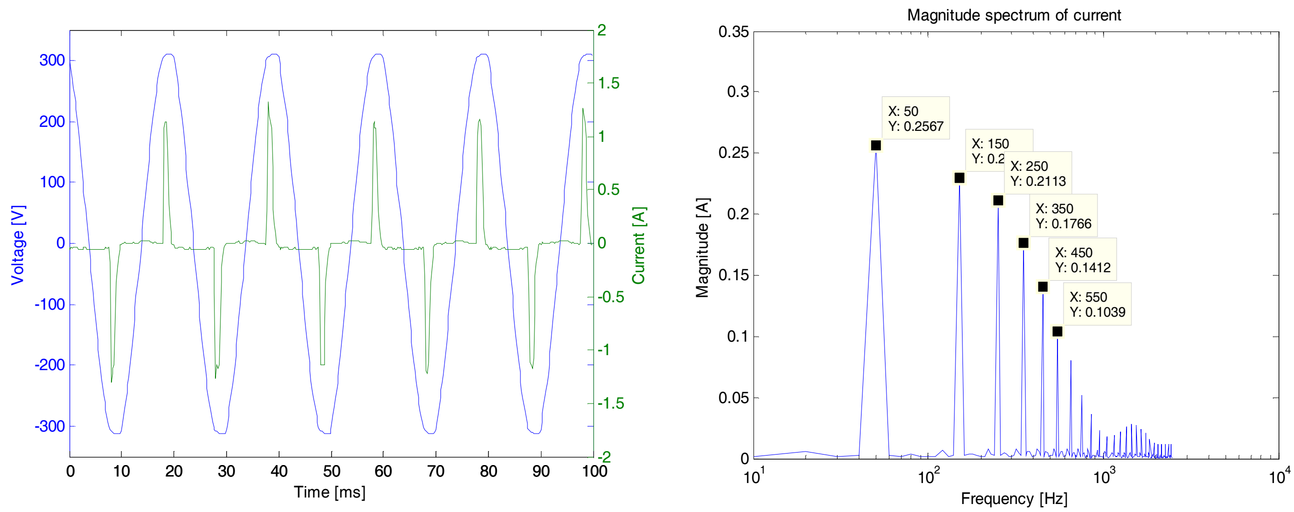

Fig. 6 Notebook computer with 65 W PSU.

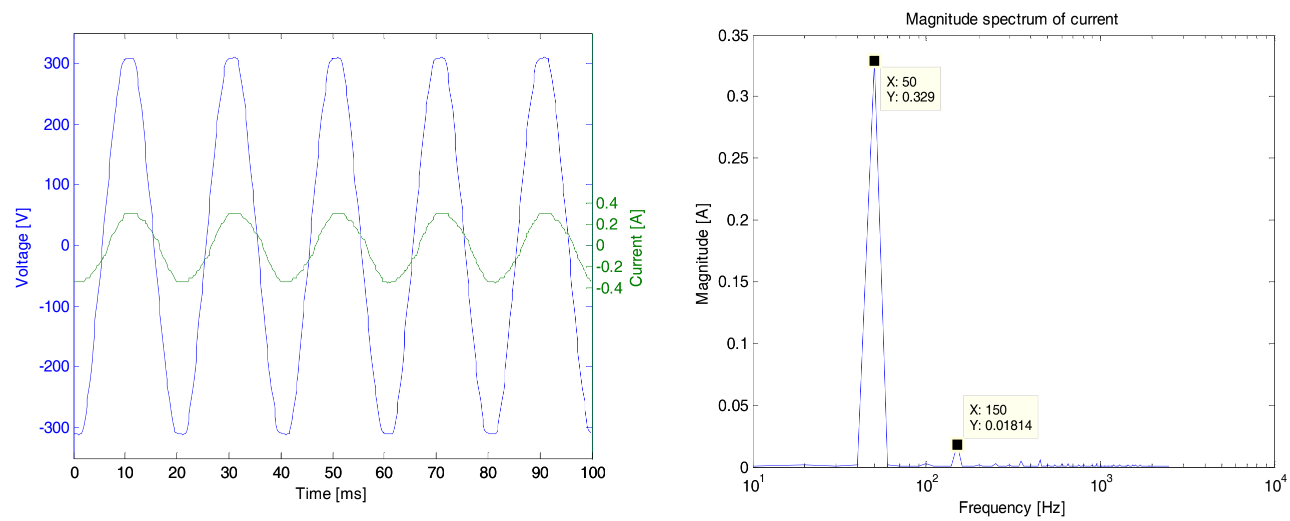

Fig. 7 Solder station – heater on.

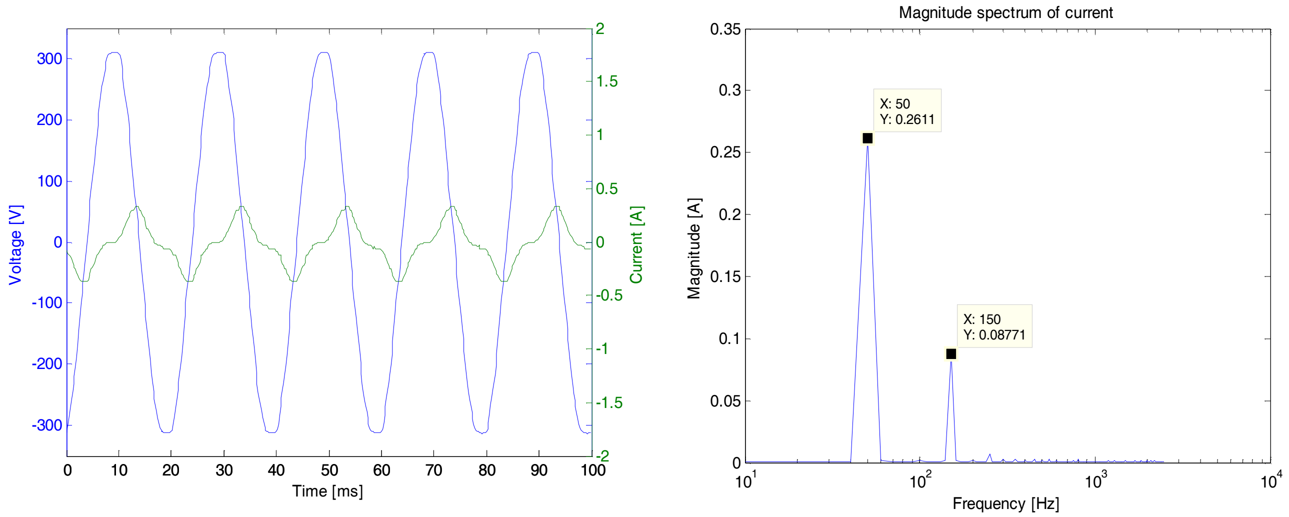

Fig. 8 Unloaded 50VA transformer.

V. Conclusion

Paper proposes design of microcontroller based measurement device which can evaluate all basic electrical quantities in alternating current circuits – true RMS voltage, true RMS current, real power and finally power factor. All measured values can be transferred via standard serial communication interface RS232 for visualization and archiving purposes. It is also possible to acquire voltage and current waveforms with sampling frequency of 5000 Hz. Developed data visualization program can display and visualize in graphical form all measured values which can be additionally archived to the file in standard CSV format compatible with MS Excel software. For voltage and current waveforms analysis was created script in Matlab 6.5 environment which can connect to the device and download them to the specified data vectors.

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