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DSP - FPGA Based Computing Platform for Control of Power Electronic Converters

Abstract*. Modern power electronic converters (PECs) require electronic controllers with high capabilities of implementing new and more complex algorithms combined with internal high-speed communications interfaces. This paper presents the design and implementation of a research/industrial multiprocessor controller based on a floating-point digital signal processor (DSP) and field programmable gate array (FPGA) developed in the Laboratory of the Electrotechnical Institute, Warsaw, Poland. The DSP-FPGA platform configuration, and also current and voltage sensors used in PECs are discussed. Although, the developed digital platform can be used in a variety of PECs, this paper focuses on an example of a 15kVA DC-AC high frequency AC link converter for auxiliary power supply used in DC traction. The novelty of the presented converter topology lies in passive components elimination by offering an all silicon solution for AC–AC power conversion part. Selected experimental oscillograms illustrating operation of the developed converter with DSP-FPGA control are added.*

Streszczenie. *Nowoczesne przekształtniki energoelektroniczne wymagają wydajnych platform obliczeniowych pozwalających na implementacje złożonych algorytmów i szybkich wewnętrznych interfejsów komunikacyjnych. Artykuł ten prezentuje projekt i implementację płyty sterującej zawierającej procesor sygnałowy i układ programowalny, którą opracowano w Instytucie Elektrotechniki w Warszawie. Powstała platforma może być wykorzystywana do sterowania różnego rodzaju urządzeń energoelektronicznych, w tym artykule przedstawiono jej implementację w przetwornicy 15 kW AC-DC z wysokoczęstotliwościowym przekształtnikiem sprzęgającym AC do zasilania elektronarzędzi w trakcji elektrycznej. Innowacyjność prezentowanej przetwornicy polega na eliminacji elementów pasywnych poprzez zastosowanie bezpośredniego sprzęgu AC-AC. Przedstawione zostały również wybrane oscylogramy eksperymentalne prezentujące pracę powstałego urządzenia sterowanego przez platformę DSP-FPGA.* ***Platforma programowa DSP-FPGA do sterowania przekształtnikami energetycznymi***

Keywords: *Digital signal processors (DSPs), field programmable gate arrays (FPGAs), control of power electronic converters (PECs), high frequency AC link converters, current and voltage sensors for PECs.*
Słowa kluczowe: *procesor sygnałowy, układ programowalny, sterowanie przekształtnikami energoelektronicznymi, wysokoczęstotliwościowe sprzęgi AC, czujniki prądu i napięcia.*

Introduction

Power Electronic Converters (PECs) are widely used for energy processing in industry, transportation, renewable energy systems, smart grids, house equipments, etc [1]. The main features of modern PECs such as high efficiency, low weight and size, high power densities and fast operation are achieved thanks to use of *switch mode operation*, in which power semiconductor devices are controlled in *on-off* fashion (its means that operation in active region is eliminated). This leads to different types of pulse width modulation (PWM) which is the basic energy processing technique used in PECs. In modern converters, PWM is a high speed process ranging – depending on rated power, used power semiconductor components and application – from a few kHz up to several MHz [1]. Another energy processing methodology, which also requires fast and large number of calculations, is Model based Predictive Control (MPC) [2], [3]. In the MPC systems the PWM and control processes are unified in a single controller which on-line selects the PEC state minimizing the predefined cost function.

At present, for executing PWM, control and supervision algorithms of PEC systems, the control electronics can be configured as follows [4]:

- single chip based on fixed-point digital signal processor - DSP [5],
- single-chip based on field programmable gate arrays - FPGA [6], [7], [8], [9], [10],
- systems with floating-point DSP and an FPGA [11], [12], [13], [14], [15].

Single chip system with DSP includes the control algorithm and power electronic interface modules (pulse width modulation – PWM generation, current and position sensors readings, etc.) in a unique chip. This guarantee that controller is compact, cheap, and data transfer between processors is eliminated.

Single chip system with FPGA can provide higher effectiveness in repetitive and large computation than fixed point or floating point DSPs. This allows reduction of the program execution times. Therefore, even very sophisticated and complex algorithms running in floating point DSPs can be executed faster in FPGAs.

In the combined floating point DSP – FPGA system, the DSP is usually used for complex control and estimation algorithms execution, whereas the FPGA is used for simpler control algorithm, monitoring and handling of output peripherals for PEC power transistors.

This paper presents a novel powerful floating point DSP-FPGA computing platform developed in the Electrotechnical Institute (IEI) which can be used for research and industrial applications of PECs. Although, the developed platform can be applied in a variety of PEC topologies, this paper focuses on an interesting example of a 15kVA DC-AC high frequency transformer AC link converter for auxiliary power supply from a DC traction line.

Configuration of digital platform

The block scheme of developed digital platform is shown in Fig. 1. It consists of the floating-point DSP TMS320F28335 from Texas Instrument and the FPGA Cyclone II EP2C8144T8N from Altera.

The basic data of both FPGA and DSP systems are given in Table 1. The main task of the DSP is to make measurements of analog signals and switch them into digital form, and then make arithmetic calculations according to the control algorithm. On this basis the DSP will generate the corresponding PWM signals, which after passing through the FPGA will control operation of the power transistors.

It is also possible that the FPGA can generate the PWM signals based on information received from the DSP. This solution is especially useful in the case of control systems with a large number of power transistors or in systems where is necessary to keep the complex timing relationships between signals.

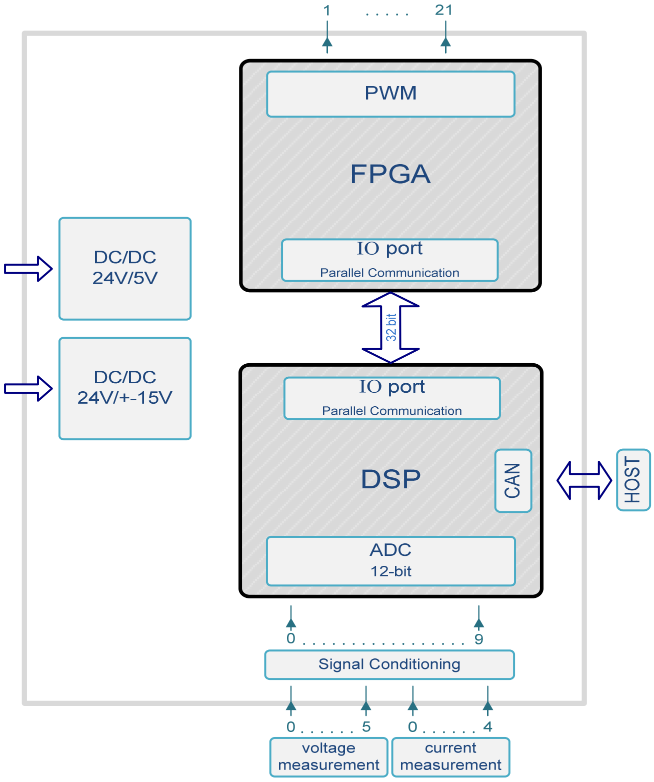

Fig. 1. Block scheme of the DSP- and FPGA-based platform for PECs

For high-speed communication between DSP and FPGA systems the 32-bit reconfigurable bus is used. Depending on the needs, all the bus lines can be used to transfer data, but there is also the possibility of using some of the bus lines for synchronizing DSP and FPGA. Both the DSP and the FPGA can generate a synchronization signal, thus, both can operate as a supervisory system. Thanks to this solution an increased versatility and flexibility of digital platform is achieved because the user implementing the control algorithm is able to decide how to use the various bus lines.

The system has the possibility of generation of 21 independent, fully-configurable PWM signals. Through the use of the FPGA each of the generated signals may have a different frequency, independent from the frequency of other channels. Depending on needs, it is also possible to synchronize the various signals to each other and also to obtain the required timing relationships between the signals.

Digital platform was equipped with 5-isolated analog inputs to measure the alternating voltage of 500V maximum amplitude, and in the four inputs which may cooperate with current transducers delivering the output current of +/- 100mA. The signals from the analog input are delivered to signal conditioner where they are suitably amplified and then converted into unipolar signals with amplitude accepted by the 12-bit A/D converter built-in DSP. These transducers can measure the voltage between 0-3V.

For communication with the environment, the platform uses CAN bus, which is a widely applied industry standard. This solution allows controlling the operation of the platform using a variety of devices such as, for example programmable logic controllers (PLCs). It is also possible the visualization of the system, operation, and the ability to increase its capabilities by connecting additional external sensors.

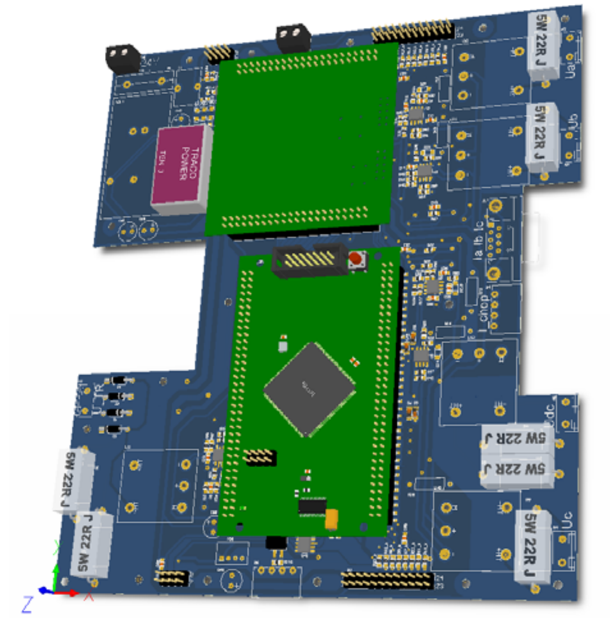

Fig. 2. View of the control board with DSP and FPGA

Table 1: Basic data of DSP and FPGA units

FPGA	EP2C8144T8N
LEs	8256
M4K RAM blocks	36
Embedded Multipliers	18
PLLs	2
User IO	85
Maximum Operating Frequency	320 MHz

DSP	TMS320F28335
Speed	150MHz
Flash	512kB
RAM	68kB
ROM	16kB
12-bit ADC	16 channels
ADC conversion time	80ns at 25MHz clock
PWM	18 channels
GPIO	88 pins
CAN	2 modules

Table 2: Some performance figures for current sensors used in PECs

Sensor	Accuracy	Frequency Bandwidth	Max di/dt	Circuit Isolation	Operating Temperature	Relative Cost	Size
Shunt Resistor (Low Inductance)	+/- 2 to 5%	DC to 10MHz	several kA/µs	No	-55 to 125°C	Low	Medium To large
Current Transformer	+/- 2 to 5%	50Hz to 1MHz*)	several kA/µs	10 kV	-50 to 150°C	High	Medium to large
Rogowski-Coil	+/- 0.02%	0,1 to 300 MHz	100 kA/µs	10 kV	-40 to 125°C	High	Large
Hall Effect Open Loop	+/- 2 to 10%	DC to 50 kHz	Moderate	2 - 5 kV	-40 to 125°C	Medium	Medium to small
Hall Effect Closed Loop	< +/- 1%	DC to 800 kHz	50-500 kA/µs	2 - 5 kV	-40 to 105°C	High	Medium to large
Magneto-Resistive (MAR) Effect	< +/- 1%	DC to 2 MHz	1kA/µs	3 - 5 kV	-40 to 150°C	Medium	Very Small

*) Current transformers are designed for low or for high frequency operation

Current and voltage measurement

In PEC systems the fast and accurate instantaneous current and voltage measurement is a key requirement because of converter switch mode operation producing pulsed and high frequency distorted waveforms. Also, for converter feedback control loops as current, voltage, active and reactive power, active power filters etc., high accuracy and fast dynamic sensors are required. Currently, various technology and specification are available. Just the LEM Company offers sensors with over 3500 current and voltage specifications in 8 different technologies [16]. Bellow we present a short overview and characterization of current and voltage sensors suitable for PEC systems.

A. Current sensors

The current sensors for PECs should meet the following general requirements:

- circuit isolation,
- fast response (di/dt), newly offered wide band power semiconductor (SiC and GaN) devices are able to switch with values of several kA/µs [17], [18],
- high bandwidth including DC, for measure superimposed high- and low-frequency currents,
- high accuracy to be used in current feedback control,
- high stability with varying temperature,
- low cost,
- compact size,
- high reliability,
- high noise immunity.

Several methods of current sensing are used in PECs. An overview of basic performance of existing current sensing technologies is shown in Table 2.

Shunt resistors are the most cost effective sensing elements, having compact package profiles, suitable for DC or AC measurement (see for example MP 900 and MP 9000 series from Caddock [19] or PLV series from PRC [20]). Since shunts lack galvanic isolation, some isolation techniques (for example isolation amplifier AMC series from TI [21]) have to be applied. This increases the complexity and cost.

Current transformers have been widely used for AC current sensing with its bandwidth up to tens of MHz. This sensing technique provides galvanic isolation and consumes little power, however is not suitable for DC current sensing. Two class of current transformers are available: high volume, low price, low frequency (50 – 400 Hz, for example SCM series from DENT Instruments [22]), and low volume, high cost, high frequency (for example CTL series 1 kHz – 1 MHz from U.R.D. [23]).

A *Rogowski coil* is an air-cored coil placed around the conductor in a toroidal fashion and has good linearity due to absence of magnetic material. It has excellent performances for measure currents in a very large frequency bandwidth providing high isolation, however like current transformer is not suitable for DC current sensing. Recently, several types of Rogowski probes are developed [24] and offered on the market (see for example LEM~flex and PRiME from LEM [16]) including very small size (see for example series CWT from PEM [25]). However, in power electronic circuits the Rogowski Coils are rather used for testing and investigation not for feedback control or protection.

The *Hall sensor* is a magnetic field sensor based on the Hall phenomenon. It is an isolated, non-intrusive device that can be used for both DC and AC current sensing. It usually cost more than a current transformer or a Rogowski coil. A Hall sensor has normally a limited peak current due to core saturation and has limited bandwidth (< 1MHz). In addition, it is very sensitive to external magnetic fields. The Hall Effect sensors mainly operate in closed loop modes for better accuracy and wider dynamic range (see for example series LA from LEM [16] or series ES and MP-EL from ABB [26]). For very high currents in the range of kA so called *electronic technology* is applied in which magnetic circuits are not used. Several Hall sensors located around the primary winding measure the flux generated by primary current and an electronic conditioning circuit provides output voltage exactly proportional to the measured primary current (see for example NCS series from ABB [26]). Among of variety of Hall Effect sensors are also, open loop low current (< 70A), miniature size sensors directly mounted on PCB and suitable for SMD automatic assembly (see for example Minisens FHS 40-P/SP600 in IC SO8 packaging from LEM [16]).

The *magneto resistive sensors* are based on the anisotropic magneto resistive (AMR) phenomenon occurring in ferromagnetic materials, such as nickel-iron layers structured as strip elements, whose specific impedance changes with the direction of an applied magnetic field. In recent years the usage of AMR current sensors in the field of power electronics is increasing continuously [27]. This is because among important advantages of AMR sensors are high accuracy and high dynamic range, as well as robust and compact design (see for example CMS3000 an ASIC type series from Sensitec [28]).

B. Voltage sensors

For measurement of DC and fast changing AC and pulsed instantaneous voltage in PEC systems, voltage sensors should meet general requirements similar to current sensors and in many cases also similar technology is used as for example Hall Effect sensors. The main difference from a current sensor is the addition of an internal primary winding with a large number of turns creating the necessary ampere-turns to measure the small primary current that is directly proportional to the sensed voltage. Therefore, for measure this small primary current rather compensated closed loop current sensors are used to build high accuracy voltage sensors. To limit the input current and specify the measured input voltage, an input resistor has to be placed in series. This input resistor can be placed internally during the manufacturing process (see for example calibrated EM010 series from ABB [26]) or connected externally allowing users some flexibility in the specification of voltage rating (see for example not calibrated LV series from LEM [16]).

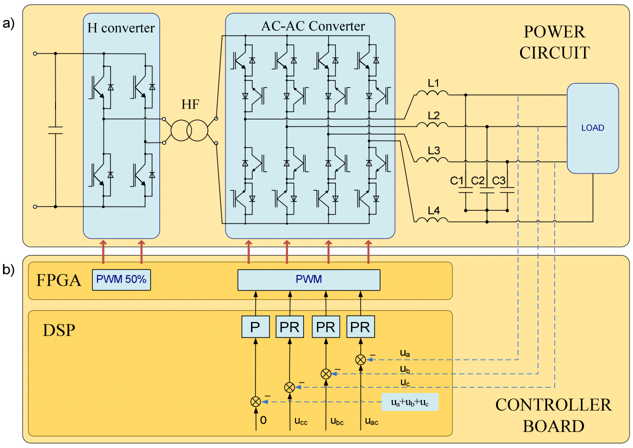

Fig. 3. a) Block scheme of high frequency AC link single-to-four-leg AC-AC converter; b) DSP-FPGA control circuit.

Because of large number of turns in the primary and large series resistance, the Hall Effect voltage sensors have narrower frequency bandwidth than current sensors. The LEM Company offers fast closed loop double core technology CV series which achieves dv/dt 800 V/µs and 10Hz - 800 kHz frequency bandwidth [16].

An important group of voltage sensors is *electronic technology* based on isolation amplifier. Here are representative AV 100 and DV series from LEM [16] and VS traction series from ABB [26]. Generally, this technology covers wide range of voltage sensors from several V up to kV.

Control of high frequency AC link single-to-four-leg converter

A. Topology of power converter

The flexibility of the presented DSP-FPGA platform enables easy adoption for variety of application. One of demanding and interesting examples is DC–AC converter consisting of single-phase H bridge, AC link with high frequency transformer HF, and AC-AC converter with bi-directional switches as presented in Fig. 3a.

The goal of the presented design was to build a compact converter with galvanic isolation from the traction DC line for supplying welding machines, angle grinders and other this type devices available on the market. In the classical solutions [1] the secondary side converter is constructed as AC-DC-AC topology which input circuit contains rectifier, capacitor and choke. However, in our design it was replaced by the additional six active switches resulting in elimination of passive components. It allows for direct connection between high frequency transformer and four-leg converter. Additionally, the four-leg converter enables operation with three- and single-phase unbalanced loads. Due to the elimination of passive components, the AC-AC four-leg converter is more compact, robust, and reliable when compared to conventional AC-DC-AC topology, and allows for about 20-30% the physical space saving. For the construction of the converter power transistors modules IRG7PH46UDPBF with 1200V and 40A ratings were used. The transformer was wound on the three toroidal cores of nanocrystalline material VITROPERM 500 F from company Vacuumschmelze with primary winding N_1=35 and secondary N_2=58.

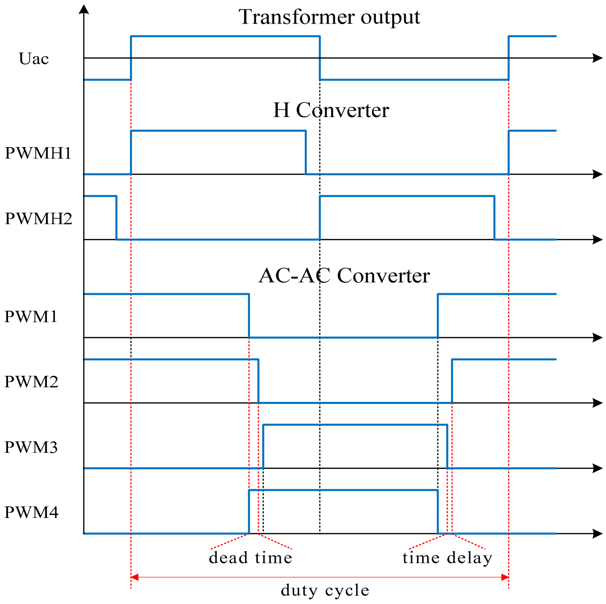

Fig. 4. Synchronized switch states for one leg of each converter.

B. PWM, measurement and control

The Controller Board included PWM generation and voltage regulation block of the converter is shown in Fig. 3b. The power converter with overvoltage protection circuit requires 21 synchronous PWM signals. This requirement cannot be satisfied by any standard micro-controller. Therefore, we combine features of DSP and FPGA as presented in Sections 2 and 3. Both embedded chips together provide floating-point calculations and many discrete signals. But each of them plays its own role. The DSP is responsible for execution of the arithmetic part of the control algorithm and FPGA for the discrete signal distribution to power IGBT transistor switches.

The FPGA task is processing of PWM duty cycles received from the DSP in a way providing synchronous operation of both converters connected through high frequency transformer. An example of gate drivers signals generated by the FPGA to one leg of H-bridge and one leg of bi-directional four-leg AC-AC converter are shown in Fig. 4.

The arithmetic part of the control algorithm was designed in a way allowing for separate control of each phase of the converter. This approach simplifies the control of the four-leg converter and allows eliminating coordinate transformations [1]. Additionally, we have replaced conventional PI regulators operated in association of coordinate transformations by proportional-resonant regulators [1].

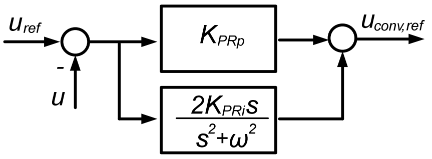

Fig. 5. Block scheme of proportional-resonant regulator according to Eq. (1).

Table 3: Basic data of voltage and current sensors used in the experimental converter

Voltage sensor	LV 25-P
Technology	Hall Effect Closed Loop
Voltage range	V_{PN} =+/- 550V
Primary rated current	I_{PN} = 10 mA$_{rms}$
Secondary rated current	I_{SN} = 25 mA$_{rms}$
Measuring resistance	R_M = 270Ω
Accuracy	+/- 0.9%, T_A = 25°C
Supply voltage	+/- 15V
Response time	40 µs
Ambient operating Temp	0 - 70°C

Current sensor	LA 55-P/SP1
Technology	Hall Effect Closed Loop
Current range	I_{PN} = +/- 50 A$_{rms}$
Secondary rated current	I_{SN} = 25 mA$_{rms}$
Measuring resistance	R_M = 200 Ω
Accuracy	+/- 0.9%, T_A = 25°C
Supply voltage	+/- 15V
Max di/dt	200 A/µs
Frequency bandwidth	0 – 200 kHz (-1 dB)
Ambient operating Temp	-25 – 85°C

The basis of the resonant regulator is generalized integrator, which has a very high gain for the resonant frequency and almost zero gain for other frequencies. The transfer function of the ideal proportional-resonant regulator PR is expressed as follows:

$$G_{PR}(s) = K_{PRp} + \frac{2K_{PRi}\cdot s}{s^2+\omega^2} \tag{1}$$

where K_{PRp} is the proportional gain of the regulator, and a K_{PRi} is the gain of the integrator.

The transfer function of resonant controller PR (1) contains two imaginary poles tuned to the fundamental frequency ω of the grid voltage. Therefore, the controller PR is able to reduce to zero in the steady state error of not only the amplitude but also the phase.

For voltage feedback loops the LEM sensors LV 25-P were used and for current protection LA 55-P/SP1 sensor. The main data of voltage and current sensors are given in Table 3.

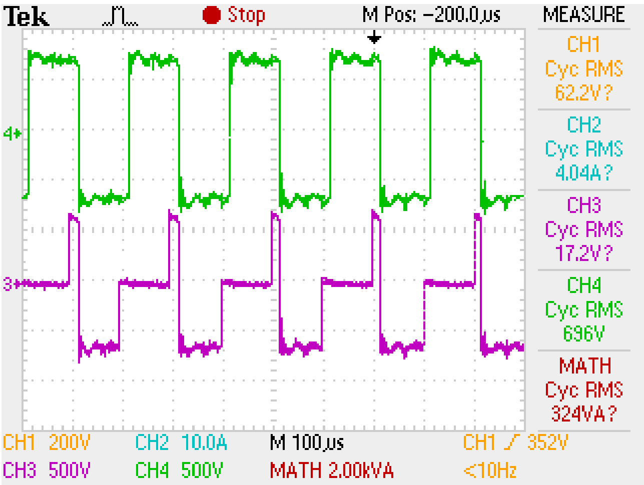

Fig. 6. Oscillograms for nominal voltage operation.
From the top: green – voltage on the transformer output, violet – voltage on the power transistor of 3-phase converter.

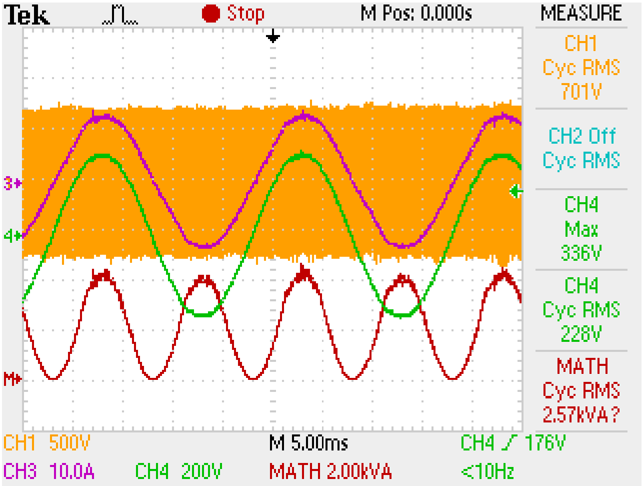

Fig. 7. Operation of the AC-AC converter for 7.8kW resistive load. From the top: yellow – HF transformer output voltage, green – phase voltage, violet – phase current, red – power in one of phase load

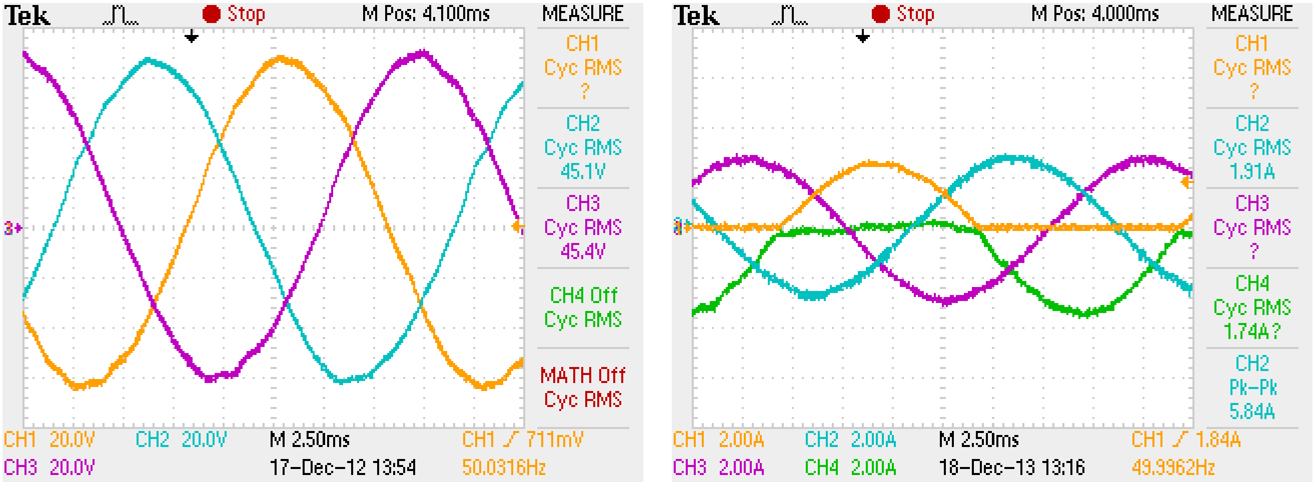

Fig. 8. Oscillograms illustrating operation of proportional-resonant regulators for unbalanced load of four-leg AC-AC converter with half-wave diode rectifier in one of phases. (From the left: phase voltages *abc*; from the right: phase currents *abcn*)

Experimental results

Selected experimental oscillograms illustrating operation of the converter are shown in figures 6, 7 and 8. The switch mode operation is illustrated in small time scale (100 μs) in Fig. 6, whereas in Fig. 7 the 50 Hz phase voltage (green) and phase current (violet) is shown on the background of 20 kHz transformer output voltage (yellow) in 5 ms time scale. Finally, Fig. 8 shows oscillograms illustrating phase voltages (left) and phase currents (right) of four-leg AC-AC converter under unbalanced load with half-wave diode rectifier in one of phases. As it can be seen the proportional-resonant regulators guarantee operation with symmetrical currents even in the case of unbalanced and nonlinear loads.

Summary and Conclusion

The paper describes the configuration and implementation of a novel research/industrial multiprocessor controller based on a floating-point digital signal processor (DSP) and field programmable gate array (FPGA) developed in the Laboratory of the Electrotechnical Institute, Warsaw for modern control and investigation of PWM based power electronic converters (PEC). An important part of control and protection circuits of PEC systems, namely, current and voltage sensors are shortly review and discussed. Although, the developed digital platform can be used in a variety of PEC topologies, this paper focuses on an interesting example of a 15kVA DC-AC high frequency AC link converter for auxiliary power supply used in DC traction. The novelty of the presented converter topology lies in passive components elimination by offering an all silicon solution for single-phase to three-phase AC–AC power conversion part. The operation of the developed converter and DSP-FPGA digital computing platform is validated by selected experimental oscillograms.

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