Design of Master Control Unit for Laboratory Prototype of Traction Converter for Locomotives

Jan Žák, Zdeněk Peroutka, and Seppo J. Ovaska

***Abstract*—This paper deals with the prototype of a main traction converter with medium-frequency transformer for AC trolley wire-fed locomotives. The attention is paid to the new master control and diagnostic unit. The designed master control unit has been implemented in the LabVIEW environment. Our master control unit ensures an effective human interface between a user and the control hardware. In this case, the master unit makes possible both extensive control and diagnostic operations of the laboratory prototype of the traction converter. The master unit was tested extensively by experiments performed on a designed traction converter prototype of 12-kW rated power.**

***Index Terms*—Control and diagnostic unit, main traction converter, medium-frequency transformer, user interface.**

I. INTRODUCTION

TRACTION AC power systems supplying traction converters operate in Europe with the frequency of 16 $^2/_3$ Hz or 50 Hz. A conventional traction transformer designed for such a low frequency is heavy and needs a large space in the locomotive. Recently, researchers and manufactures are considering the possibility to propose a traction converter containing a medium-frequency transformer. Such a solution can lead to reduction of both weight and size. In recent years, several proposals have been made to compose the main traction converter using a medium-frequency transformer and modern power electronics [1–3].

The motivation for our research has been the obvious demand for implementation of an effective human interface for a recently designed laboratory prototype of traction converter containing a medium-frequency transformer (see Fig. 1), which is used for developing the new generation of locomotive drives for our industrial partner.

When developing a laboratory prototype of the new traction converter, it is necessary to have exact real-time information about the behavior of the whole control system. This information enables us to detect and solve problems that can appear. Even if the development process is supported by extensive simulations, it is practically impossible to include all disturbing factors in mathematical modeling, especially, when dealing with complex problems. For these reasons, it is appropriate to complement the laboratory prototype by a versatile human interface, which could be connected to the microprocessor controller. Such a configuration makes it possible to observe not only the behavior of the tested prototype, but also the behavior inside the control hardware, i.e., we can monitor "soft" signals inside the microprocessor controller (full diagnostic function). Thus, we can observe the detailed state of the entire configuration during the testing procedures. Moreover, the master control unit makes it very simple to command the control system. Finally, the designed unit can serve for presentation and educational purposes.

For similar reasons, many industrial applications are complemented by such a communication interface [4–6]. In this paper, we present the master control and diagnostic unit designed for microprocessor-based control system controlling converters around the medium-frequency transformer (two inverters on the transformer primary side and one voltage-source active rectifier connected to the secondary winding). This unit is running on a personal computer platform and connected to the microprocessor using a universal serial bus (USB) interface.

Switching converters employing power semiconductors might disturb electronic devices in their surroundings. However, in most cases, it is not possible to place microprocessor-based controllers outside this disturbed area. Therefore, it is necessary to select a suitable communication protocol for reliable communication between the human interface (PC) and the microcontroller (DSP). We could either use some industrial standard like MOBUS [7] or develop our own.

II. DESCRIPTION OF DESIGNED CONVERTER PROTOTYPE

The laboratory prototype of our locomotive converter consists of two input voltage-source active rectifiers in series connected to the trolley wire through the input inductance, two voltage source inverters generating two 400-Hz square-wave voltage signals, which supply the two primary windings of the medium-frequency transformer (Fig. 1). The secondary voltage-source active rectifier is connected to the transformer secondary winding and its output supplies the output inverter (the vehicle drive) by DC voltage.

Each group of converters is controlled by its own digital signal processor; each DSP has its own master control and diagnostic unit, which serves as the human interface. The unit makes it possible to carry out system diagnostics for the microprocessor regulator, perform system tuning and setting control commands in the DSP. The laboratory prototype mentioned above uses three different master control and diagnostic

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J. Žák is with the University of West Bohemia, Univerzitní 26, 306 14 Plzeň, Czech Republic (e-mail: janzak@kev.zcu.cz).

Z. Peroutka is with the University of West Bohemia, Univerzitní 26, 306 14 Plzeň, Czech Republic (e-mail: peroutka@ieee.org).

S. J. Ovaska is with the Faculty of Electronics, Communications, and Automation, Helsinki University of Technology, FI-02150 Espoo, Finland (e-mail: seppo.ovaska@tkk.fi).

units. This contribution concentrates on the second unit (MCU 2), which is used for control of converters around the medium-frequency transformer (Fig. 1).

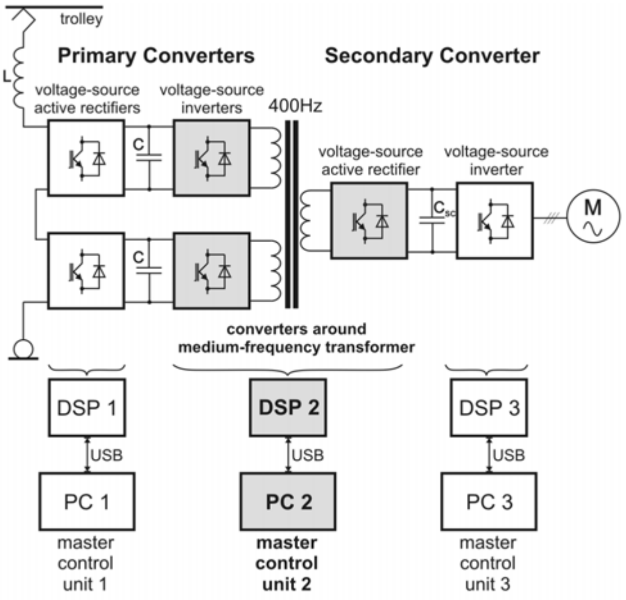


Fig. 1. Configuration of designed laboratory prototype of traction converter with medium-frequency transformer.

III. CONTROL OF CONVERTERS AROUND MEDIUM-FREQUENCY TRANSFORMER

The master unit is the main agent for communication with the user. It ensures transmission of user-set parameters to the digital signal processor (in our case Texas Instruments TMS320F2812), which performs the control of the particular sections of traction converter. The master unit makes possible not only to transmit the control commands, but also provides us with comprehensive diagnostic feedback, so that the user can observe all required signals. The designed unit is hosted on a PC. The communication between both systems is very important for the whole prototype and, therefore, we have chosen the flexible USB as the communication platform. The baud rate was selected 160,256 bits per second—this is a compromise between the computational performance of our personal computer and a sufficient data transmission capacity. We employ our own packet-based protocol. When the DSP is running, it is sending new data continually. The PC sends new data (control commands) only if control commands are changed in the master unit. Received data are processed and interpreted graphically. The detailed configuration of the control hardware is illustrated in Fig. 2.

The converters around the medium-frequency transformer consist of two voltage-source inverters, which supply two primary windings of the medium-frequency transformer, and the secondary voltage-source active rectifier. The DSP controls these inverters to generate a 400-Hz square-wave voltage. The secondary rectifier handled by the same DSP is controlled to provide us with the required output DC voltage of 600 V. Moreover, the secondary rectifier employs the hysteresis control of the secondary winding current—for details about converter control see [8].

The proposed control of secondary voltage-source active rectifier is shown in Fig. 3. First, the instantaneous value of U_c is subtracted from the required U_{cw}. Then, the PI controller sets the required current amplitude I_{mw}, which is multiplied by sign(u_s) in the following step. Thus, the required current waveform is computed. Next, the instantaneous value of i_s is subtracted from i_{sw} and the current error enters the hysteresis control block, which generates firing pulses.

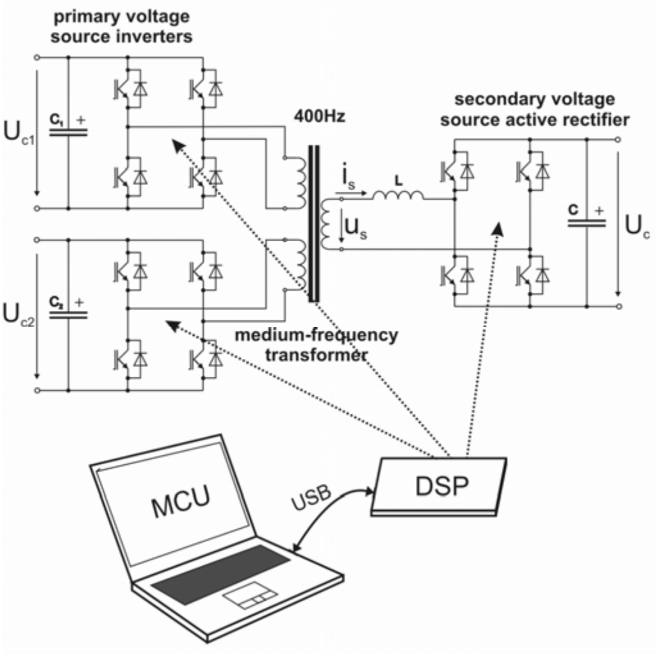


Fig. 2. The implementation structure of the entire system.

The control strategy described above is suitable for the rectifier operation mode. However, in case of the inverter operation mode, the control algorithm must be complemented by a reference shift block (Fig. 3).

In the inverter operation mode, if the input voltage u_s changes its polarity, the voltage applied to inductance L (Fig. 2) is much lower than in case of the rectifier operation mode. Therefore, the di/dt gradient is not high enough to cause sufficient rate of the current polarity change. Thus, the reactive power transmitted in the inverter operation mode increases. The proposed control strategy includes the reference shift block, which shifts the required current i_{sw} waveform ahead by a phase angle ϑ_s. The current starts to change its polarity earlier and the reactive power is reduced. This solution leads to considerable improvement of operation efficiency. The reference shift block is activated only in the inverter operation mode. In case of the rectifier operation mode, there is no phase shift between the required current i_{sw} and secondary winding voltage u_s.

While using hysteresis control of the current, the switching frequency is directly affected by the value of Δi_s. In traction applications, high power semiconductor components must be used and it causes considerable switching frequency limitations. In order to achieve a suitable switching frequency, the value of Δi_s should be nearly half of the nominal I_m.

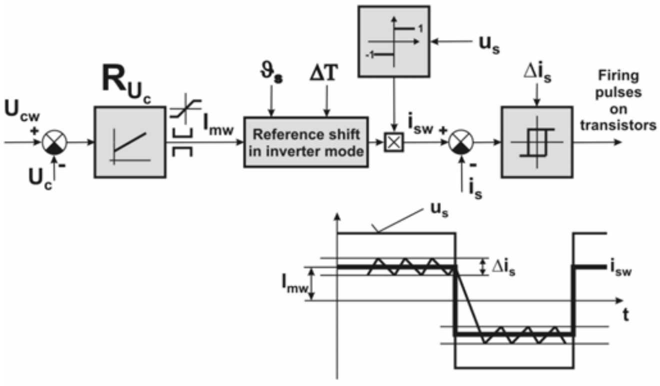


Fig. 3. Proposed control of secondary voltage source active rectifier.

IV. DESIGNED COMMUNICATION PROTOCOL

The communication protocol ensures reliable data transfer through the connection line between the master unit and the digital signal processor, and vice versa. It has to meet several requirements. Especially, the communication has to be fast enough and resistant to electro-magnetic interferences. We designed our own protocol; its simplified packet structure is shown in Fig. 4 and a more detailed one in Fig. 5.

The packet size changes with the amount of transmitted data. Every beginning of the individual packet is signalized by a head, which is unique in the whole frame and cannot be interpreted incorrectly. This head ensures the synchronization of the transmitter with the receiver. Than, the transmitted data elements follow; they are composed of three 16-bit numbers or their multiples. Next, the control byte is transmitted within the frame, which serves for correct packet masking. The cyclic redundancy check (CRC) code is inserted in the end of the frame; it enables the receiver to check over the received data. In case of a transmission error, the data are discarded and a new packet is expected.

The MCU running on the PC enters 6 control commands into one frame and the new frame is transmitted from PC only when the input parameters are changed by the user. On the other hand, the DSP informs the MCU about its state using 15 values in one frame and the DSP transmits these packets continually, because it is necessary to monitor the power and control circuit in real-time.

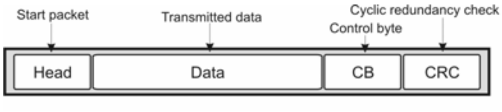


Fig. 4. Simplified packet structure.

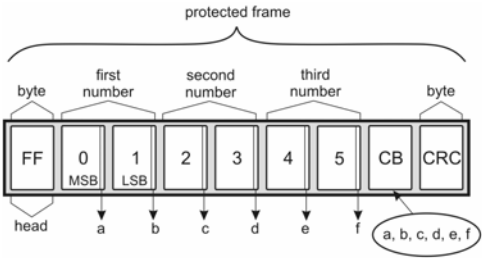


Fig. 5. Detailed packet structure.

V. NOMENCLATURE OF TRANSMITTED DATA

The list of transmitted values is given below. The following list matches the sequence of parameters in one communication frame. Due to the packet structure, it is possible to transmit only packets of $N \times 3 \times 16$-bit numbers, where N is an integer. For this reason, the packet contains also "Reserve values".

A. *Communications PC → DSP*

1.	U_{CW}	Secondary rectifier: output voltage command.
2.	I_{MW}	Secondary rectifier: current amplitude command.
3.	U_{CW}/ I_{MW}	Choice of regulation U_{CW}/ I_{MW} (log. 0/ 1).
4.	Start/ Stop	Start/ Stop of primary rectifiers (log. 0/ 1).
5.	Reserve	
6.	Reserve	

B. *Communications DSP → PC*

1.	U_{C2}	Primary rectifier 2: output voltage.
2.	u_S	Secondary rectifier: input (sec. winding) voltage.
3.	i_S	Secondary rectifier: input (sec. winding) current.
4.	U_{C1}	Primary rectifier 1: output voltage.
5.	U_C	Secondary rectifier: output voltage.
6.	U_{CW}	Secondary rectifier: output voltage command.
7.	I_{MW}	Secondary rectifier: current amplitude command.
8.	i_{SW}	Secondary rectifier: current command.
9.	f_{SPmax}	Average switching frequency.
10.	P_S	Secondary rectifier: active power.
11.	I_{SEF}	RMS value of secondary winding current.
12.	Start/ Stop	Primary inverters: run indication (log. 1).
13.	Start/ Stop	Secondary active rectifier: run indication (log. 1).
14.	Fault	Fault indication (1 = everything OK, other number = fault type)
15.	U_S	RMS value of secondary winding voltage.

VI. DESIGNED MASTER CONTROL AND DIAGNOSTIC UNIT

The master control and diagnostic unit is composed of a few cards. The first card serves for communication setting and transmitted data monitoring. The most important control part is placed on the right side and it is always visible. Thus, the designed structure enables to enter control commands from every panel. The fundamental commands are U_{CW}, I_{MW}, U_{CW}/I_{MW} control selection (for debugging procedure only), primary inverters and secondary rectifier start/stop command, and data flow and graphs locking. This panel also contains three signalization LEDs, which notify us about the state of the controlled power circuit (inverter switching, rectifier switching, error). We can see the configuration of this panel in Fig. 6.

The second panel shown in Fig. 7 is the most important diagnostic panel used during the testing procedure; it contains the employed converter scheme together with the control structure, and displays instantaneous values of several important signals. This panel enables us to check quickly the behavior of the described prototype part.

Real-time displayed waveforms are shown in the next four panels (Fig. 8 – Fig. 11). The waveforms very well correspond to the reality. Finally, we have the option to save the collected data into a file or directly export the graphs.

Port IN: COM7
Bity za sekundu: 160256
Datové bity: 8
Počet stop-bitů: 1.0
Chyby protokolu: 3
Počet přijatých paketů: 613967
Počet správných paketů: 595147
Počet odeslaných paketů: 11

Uc2: 330,7
us: 500,6
is: 16,48
Uc1: 353,5
Uc: 598,6
Ucw: 599,9

Imw: 6,59
isw: 6,59
fSPmax: 3390
Ps [kW]: 4,696
Isef: 9,18
spínání střídače: 1

spínání usm: 1
porucha: 1
Us: 517,5

Typ poruchy: 1
1 = Vše OK
Hystereze [A]: 6

Zvolte cestu k souboru: %
Pokud budete ukládat data, zadejte nejprve cestu k zdi.

Fig. 6. MCU2 – Configuration panel.

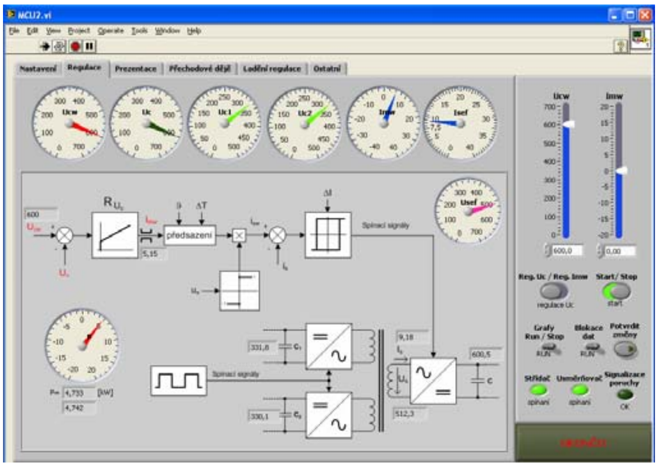


Fig. 7. MCU2 – Control structure panel.

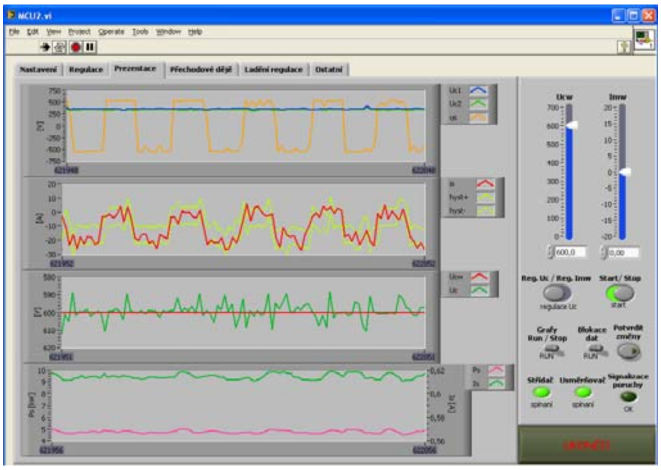


Fig. 8. MCU2 – Basic waveforms panel.

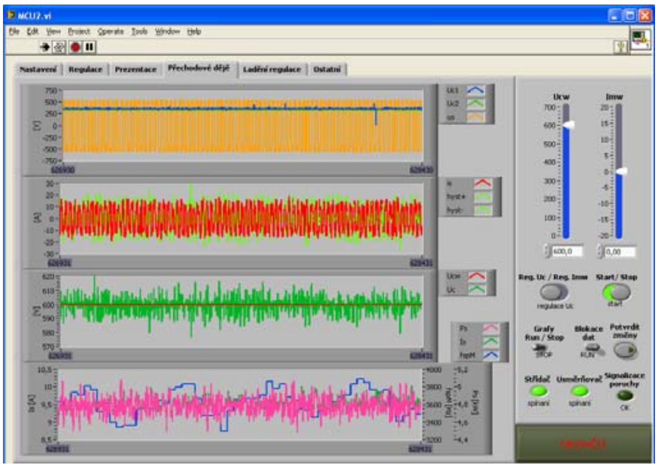


Fig. 9. MCU2 – Transient monitoring panel.

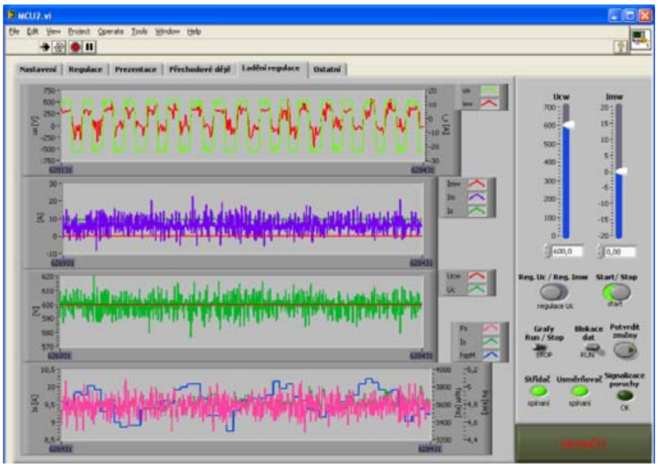


Fig. 10. MCU2 – Panel for control tuning.

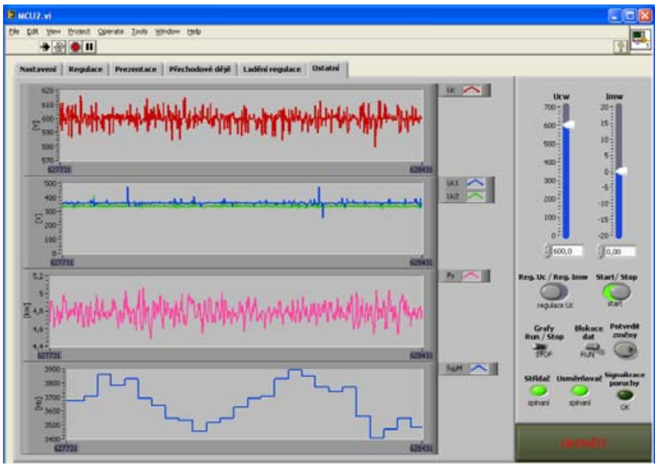
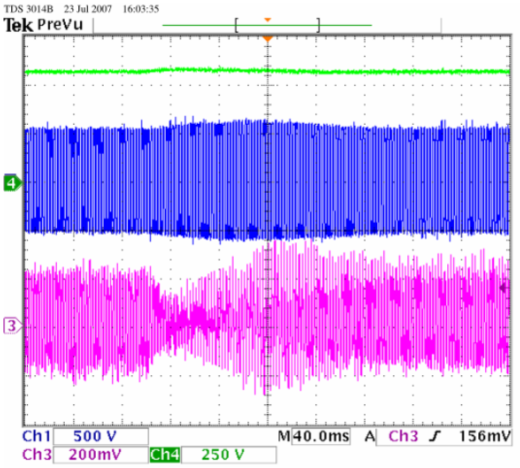


Fig. 11. MCU2 – Other information panel.

VII. SELECTED EXPERIMENTAL RESULTS OF DESIGNED LABORATORY PROTOTYPE

In the laboratory, we need several signals from the microprocessor controller to be displayed and monitored. In case of explored prototype of converter with medium-frequency transformer, we require, e.g., the secondary winding voltage, secondary winding current, DC-link voltage of both rectifiers, as well as transmitted power. Figures below show the important correspondence between the displayed and real data. We can observe the secondary winding voltage, the secondary winding current and the DC-link voltage of secondary rectifier in Fig. 12 under transient conditions (change of the converter operating mode: rectifier mode → inverter mode). These waveforms were recorded by a digital oscilloscope (Fig. 12, Fig. 14 and Fig. 16). Highly comparable waveforms can be seen in Fig. 13, Fig. 15 and Fig. 17, which were recorded by the master unit.

The photography of the designed and tested laboratory prototype of the traction converter is shown in Fig. 18.



Ch4: Rectifier output voltage U_c (250V/div)

Ch1: Rectifier input voltage u_s (500V/div)

Ch3: Rectifier input current i_s (20A/div)

Power:
7 to -5.4kW

Fig. 12. Transient of operation change: Rectifier mode – Inverter mode.

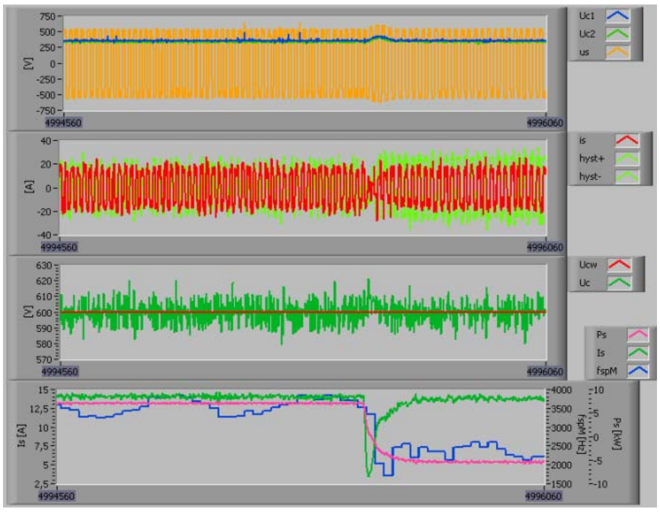
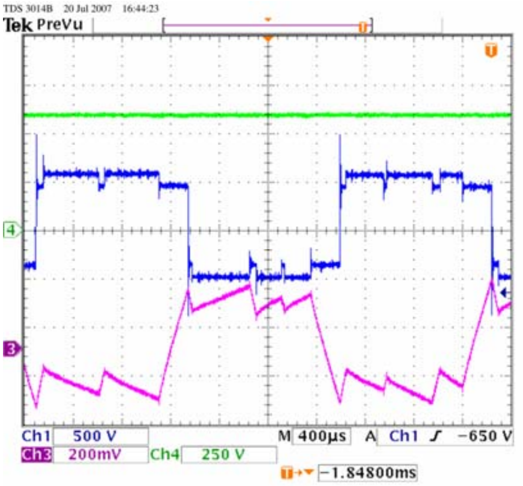


Fig. 13. Transient monitoring panel.



Ch4: Rectifier output voltage U_c (250V/div)

Ch1: Rectifier input voltage u_s (500V/div)

Ch3: Rectifier input current i_s (20A/div)

Fig. 14. Inverter mode – detail 1.

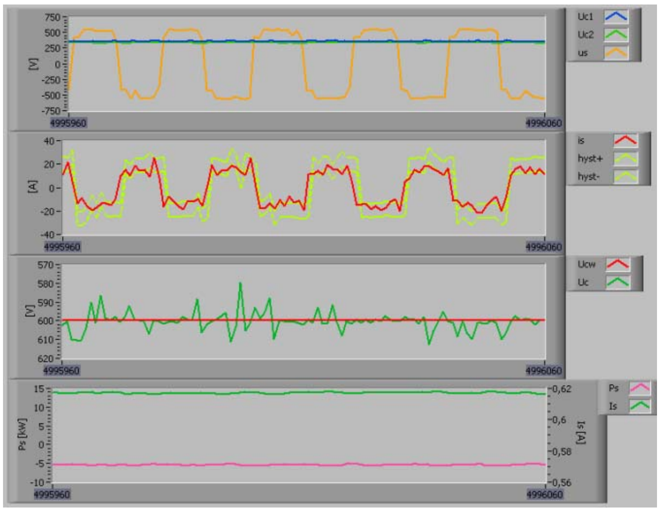
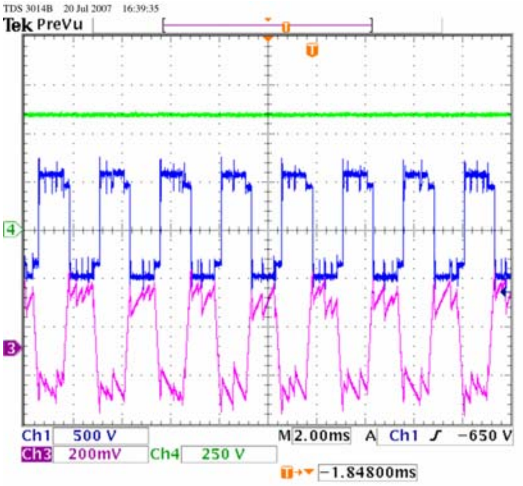


Fig. 15. Basic waveforms panel.



Ch4: Rectifier output voltage U_c (250V/div)

Ch1: Rectifier input voltage u_s (500V/div)

Ch3: Rectifier input current i_s (20A/div)

Fig. 16. Inverter mode – detail 2.

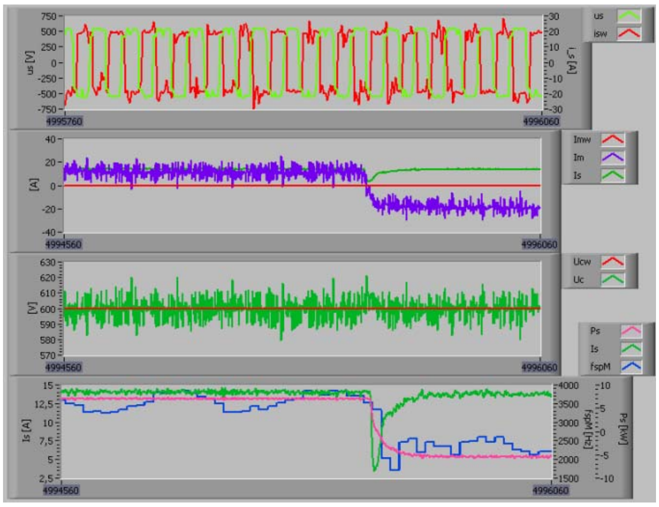


Fig. 17. Panel for control tuning.

Fig. 18. Laboratory prototype of 12-kW rated power.

VIII. CONCLUSION

The proposed master control and diagnostic unit has been implemented and tested in the new laboratory prototype of the traction converter with the medium-frequency transformer intended for locomotive drives. In this paper, only one MCU was described, but the whole converter is controlled via three MCUs. The final unit design (MCU2) is appropriate for tuning and control of converters around the medium-frequency transformer. Output waveforms correspond well to the reality and they complement measurements performed by digital oscilloscopes. We could improve the waveforms' quality by increasing the baud rate, but it would require more computational performance of the PC. The results presented above were achieved using a PC with Windows XP operating system, Intel Core Duo 1.66-GHz processor, and 1 GB of RAM. If we need better transient waveform quality, it is possible to store the data into a buffer in the control hardware and display it later (off line).

The original results of this contribution are summarized below:

- The new communication protocol has been created for reliable data transmission between the master unit and the digital signal processor through the USB interface.
- Our protocol has been implemented in the form of a driver for easy operation.
- The master control and diagnostic unit has been created also in the form of a driver for convenient and fast use in new applications.
- All units are thoroughly verified by experiments performed on the laboratory prototype.
- The proposed master units can also be controlled via the internet using a web browser.
- Our protocol is not the only alternative for communication. We can easily change the communication driver and switch to some conventional communication standard.

REFERENCES

[1] M. Carpita, M. Pellerin, and J. Herminjard, "Medium frequency transformer for traction applications making use of multilevel converter: small scale prototype test results," in *Proceedings of the International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, *SPEEDAM 2006*. Taormina, Italy, May 23–26, 2006, pp. 1095–1100.

[2] J. Taufig, "Power electronics technologies for railway vehicles," in *Proceedings of the Power Conversion Conference*, *PCC '07*, Nagoya, Japan, April 2–5, 2007, pp. 1388–1393.

[3] M. Victor, "Energieumwandlung auf AC – Triebfahrzeugen mit Mittelfrequenztransformator," *Fahrzeugtechnik*, eb 103, Heft 11, pp. 505–510, 2005.

[4] M. Figl, W. Birkfellner, C. Ede, J. Hummel, R. Hanel, F. Watzinger, F. Wanschitz, R. Ewers, and H. Bergmann, "The control unit for a head mounted operating microscope used for augmented reality visualization in computer aided surgery," in *Proceedings of the IEEE/ACM International Symposium on Mixed and Augmented Reality*, *ISMAR 2002*, Darmstadt, Germany, Sept. 30 – Oct. 1, 2002, pp. 69–75.

[5] L. V. Kirkland, "An artificially intelligent-human interface for test/diagnosis," in *Conference Record of the IEEE Systems Readiness Technology Conference*, *AUTOTESTCON '92*, Dayton, OH, Sept. 21–24, 1992, pp. 335–337.

[6] H. Kamata, A. Obata, M. Adachi, and S. Morita, "The human interface in a multifunctional communication terminal," *IEEE Journal on Selected Areas in Communications*, vol. 9, no. 4, pp. 561–565, May 1991.

[7] F. H. Ramirez Leyva, J. P. A. Cuellar, R. G. M. Basilio, and E. E. Justo, "Wireless system for electrical networks testing based on MODBUS protocol," in *Proceedings of the 14th International Conference on Electronics, Communications and Computers*, *CONIELECOMP 2004*, Veracruz, Mexico, Feb. 16–18, 2004, pp. 58–62.

[8] T. Komrska and Z. Peroutka, "Main traction converter with medium-frequency transformer: Control of converters around MF transformer," in *Proceedings of the International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, *SPEEDAM 2008*, Ischia, Italy, June, 11–13, 2008, IN PRESS.

Jan Žák was born in 1982 in Třebíč, Czech Republic. He is a full time PhD student at the University of West Bohemia, Plzeň, Czech Republic, where he received a master's degree (Ing.) in electrical engineering in 2006.

His research interests include power electronics, electrical drives and their control system, human interfaces, as well as communication busses and protocols.

Zdeněk Peroutka (S'00, M'04) was born in 1976 in Plzeň, Czech Republic. He received the master's and PhD degrees in Electrical Engineering from the University of West Bohemia, Plzeň, Czech Republic in 2000 and 2004, respectively.

Since 2006, Dr. Peroutka has served as the Head of the Section of Power Electronics and Control Systems, and Associate Professor at the University of West Bohemia. His research concerns power electronics, electrical drives especially for traction applications, microprocessor-based control systems, and EMC. From his research activities should be highlighted his cooperation with Škoda Plzeň company on the development of traction drives for trolley-buses, trams, light rail vehicles, and locomotives.

Dr. Peroutka is a member of IEEE and EPE.

Seppo J. Ovaska received an M.Sc. degree in electrical engineering from Tampere University of Technology, Finland, an Lic.Sc. degree in computer science and engineering from Helsinki University of Technology, Finland, and a D.Sc. degree in electrical engineering from Tampere University of Technology in 1980, 1987, and 1989, respectively.

He is currently a Professor in the Faculty of Electronics, Communications, and Automation, Helsinki University of Technology. Before joining Helsinki University of Technology in 1996, he was a Professor in the Department of Information Technology, Lappeenranta University of Technology, Finland (1992–1996). From 1980 to 1992, he held engineering, research, and R&D management positions with Kone Elevators and Nokia Research Center, both in Finland and in Kentucky. In the summer of 1999, he was a Visiting Scientist at Muroran Institute of Technology, Japan; in the summers of 2000 and 2001, at Virginia Polytechnic Institute and State University; in the summers of 2002–2004, at Utah State University; and in the summer of 2005, at the University of Passau, Germany. He served the academic year of 2006–2007 as a Professor of Electrical and Computer Engineering at Utah State University. His research interests are in computational intelligence, evolutionary computation, artificial life, and industrial electronics. During his career, he has authored or coauthored more than 230 papers in peer-reviewed journals, international conferences, and edited books. He edited "Computationally Intelligent Hybrid Systems: The Fusion of Soft Computing and Hard Computing" (Wiley-Interscience, 2004), and holds nine patents in the area of systems and control.

Dr. Ovaska was the Founding General Chair of the IEEE Nordic Workshop on Power and Industrial Electronics in 1998. He is a recipient of the Most Active Technical Committee Award (2006) and two Outstanding Contribution Awards (2000 and 2002) of the IEEE Systems, Man, and Cybernetics Society.