# Final Report

## Multichannel Intelligent Electrical Energy Conversion Systems (Contract no: OTKA-NNF 78703)

The project aimed at the research of a newly proposed, future intelligent electrical energy distribution system for the residential area. In the local, low-power electrical distribution system the primary emphasis was laid on the supply of consumers requiring low direct voltage (i.e. cell phones, computers, printers, electric shavers, digital cameras, video-cameras etc.). At these systems, the lack of standardization eventuates that the rated voltages and powers, necessary for powering consumers, differ considerably in the range of 0-250W. Research was conducted both in relation with new control solutions and converter topologies. Since one of the base elements of the system is the control unit, which contains logical circuits used for logical operations and digital signal processing, its cheap and energy saving realization was also an important research aspect. The topic of the presentation at the international conference Inter-Academia'2009 and the related journal paper was focused on the theoretical investigation of logical circuits based on molecular electronic devices. The Coulomb-coupled, protein based electronic circuit elements may be the future's fundamental components of energy saving, cost-effective, environmental friendly, logical and digital signal processing electronics.

Stepping from the level of the circuit components onto the level of the topology, the opportunities of the application of modular, parallel dc-dc converters were studied. Their application at power supplies includes a number of favorable properties. A decentralized, agent-based control architecture for parallel connected dc-dc converters was developed. Two kinds of agents were distinguished: control agents, which are assigned to each of the converters and consumer agents, that are attached to the load. These agents co-operate in order to satisfy the following criteria: they should maintain the reference voltage at the output also under varying load conditions; besides, they should optimize the system operation along with predefined target functions. The main features of the proposed control algorithm are as follows: modular structure – under growing number of converters, a system reorganization capability through newly added agents is required. Adaptivity – the multi-agent system is able to manage a wide range of the load current and output voltage. The proposed architecture was implemented first by computer simulation software and later by electrical circuitry in the laboratory, bringing in many interesting simulation and measurement results. In these cases, the operation of four paralleled converters was simulated. It was pointed out that the evaluation logic placed in the control agent was so fast that the load current and voltage transients, starting due to the changing load, had not been settled yet, while switching the converter on and off took already place due to the evaluation logic. These two effects could not be completely separated in the signals. In the output voltages, the moment when the character of the transient's settling is changing (the signal is breaking) can be considered as the instant, when the effect of the evaluation logic evolves.

In the course of simulations, contrary to real-time systems, computing capacity had practically no upper limit, in principle any kind of complicated algorithm could be simulated. Because of this, in the simulation, the evaluation logics can be run even in every sampling period, that is immediately able to reorganize the parallel system structure by switching converters on and off. At the simulations, the circuit parameters were considered as ideal ones. In the laboratory implementation, the switches were substituted by semiconductor MOSFETs that have finite switching speed. The input voltage of 9V was assumed as ideal. In the course of the

laboratory measurements, the development board was also burdened by electromagnetic disturbances, so these effects also modified the laboratory measurement results compared to the simulation. The comparison of the quantitative results shows that the settling of the transients were slightly slower during the laboratory implementation. Comparing the output voltages, it became visible that swinging was characteristical in only one direction (in the other direction, it was remarkably small). These directions were identical with the initial directions of the voltage transients in the case of the laboratory implementation. This effect is caused by the load change directly. Comparing the simulation and measurement results, more order of magnitude difference did not come forward in overshooting of the voltage transients. The current signals received from the laboratory implementation and their transients were also compared and the results were published. In this stage conventional (so-called hard-switched) dc-dc converter topologies were applied, later research was also conducted to the applicability of dual channel resonant dc-dc converters, revealing their benefits and disadvantages.

Continuing the research, the next aim was to operate the dc-dc converters under optimal circumstances that could be achieved by the intelligent distribution of the load currents among the converters. Since converters are non-linear coming from their operation principles and construction, they required a special approach from the control side. To optimize the power transfer, a multi-variable cost function to the system of ‘n’ parallel converters was elaborated and proposed. The task was the minimization of the cost function. Since the aim of optimization can change in industrial practice depending on the application areas, three kinds of target functions were proposed in the project. The aim of optimization was the loss minimization in the first case, the minimization of the output voltage ripple in the second case, and the third one implied hybrid solutions. Considering different parameters, the examinations were carried out with special attention to the effect of sudden load change. Matlab Simulink-based simulations were complemented by laboratory measurements. dsPICDEM SMPS buck development boards were applied at the laboratory set-up, that severally included two independent synchronous dc-dc buck converters. The control software run in a dsPIC30F2020 microcontroller. The results were published at the conference Saupec’ 2010.

In addition to research on the control side, research on topologies was also conducted with special attention of applying quasi-resonant dc-dc configurations. Dual-channel, resonant dc-dc converters were proposed, that included high-frequency transformers for the galvanic isolation between the input and output side. Between the channels, it is possible to control the power transfer, that is essential in the case of this application. The benefit of the solution is that the system can operate in soft-switching mode, when the voltage and/or the current is zero on the semiconductor switches in the moment of switching. As a result of this fact, switching losses can be reduced considerably, leading to the increase of the overall efficiency of the system. Within the control agents, a discrete-time control to keep the output voltage on a constant value was developed and proposed. To determine the main parameters of the converter configurations (capacitance of the switched capacitor, inductance in the positive and negative channel, capacitance of the output filter capacitor, the boundary of the continuous and discontinuous conducting modes) a design process was proposed and published. The theoretical considerations were also supported by simulation and laboratory measurement results.

Within the confines of collaborations with Japanese research institutes in the project, it was possible to adapt a part of the results into electric cars especially those ones related to the advanced control of dc-dc converters. The prototype of the experimental electric car was built

in Japan. The completed prototype was entered on a contest amongst Japanese universities organized on Shikoku Island, where we successfully obtained the first place in the mini category. The aim was to cover maximum distance while the electric cars' rated power was limited by the rules. In addition to the control of dc-dc converters, extra emphasis was laid on developing effective methods to estimate the charge level of the applied battery. It was based on a database built from many preliminary measurement results.

By the discrete-time, non-linear control placed in control agents, the dynamic properties of the electrical energy conversion system could be considerably improved. The solution, that included more local sliding mode controller, was presented at the conference EPE-PEMC'2010; the publication was nominated for Best Paper Award. Tests were carried out for such cases when the load changed largely and stepwise, while maintaining the prescribed constant voltage on the paralleled outputs was required. The decentralized control of the system, by switching the parallel converters on and off, and by the local controllers, was able to overcome the challenges even under significant load changes, and the change of the output voltage remained in the prescribed range constantly without overloading the circuit components. The proposed solution increased the reliability of the parallel converter system so that the efficiency also increased meanwhile. The additional research results on the control side and the collected experiences about the reliability studies were published in two papers at the conference AACS'2010, in addition to the aforementioned publication.

Detailed knowledge about the static and dynamic behavior of dc-dc converters is an important aspect in the design of local control algorithms placed in control agents. A web-based computer application was successfully developed and made available to our students that facilitates the automatic generation of the continuous and discrete time linearized models in the vicinity of the operating point in form of both state space models and transfer functions, after entering the circuit parameters of the converter. The application is also capable of visualizing the models, namely, to represent Bode plots and zero-pole plots. Beyond the design procedure, it became a useful part of the university education too, since students could follow the occurring changes easily. The results were published at the conference IPEC'2010.

Research also expanded onto another group of electrical energy conversion circuits, the so called pulse-width modulation (PWM) inverters, examining subharmonic behavior that is detrimental in these applications. It was explored that such operating state may occur, when the value of the frequency modulation rate is low. The results on the calculation of subharmonics were published in another paper at conference EPE-PEMC'2010. The subharmonic wave was calculated with two kinds of approaches, which brought the same result according to expectations. In this case, the name 'subharmonic' according to the theory of Fourier series may be misleading, because the real subharmonic on the output of the PWM inverter is only a component and its role is marginal here. Actually, the primary source occurs at the carrier frequency and at the side-band harmonics. As a compromise, the name 'quasi-subharmonic' was proposed. It was pointed out, that the period of the quasi-subharmonic wave is equal to an integer number multiple of the real subharmonic of the Fourier series.

Research on the control logics and digital signal processing electronics was continued too. At the conference Inter-Academia'2010, the newest results were published relating to the construction of Coulomb-coupled, protein based arrays, suitable for high-speed logical operations and fast calculations. A procedure was introduced based on Coulomb-coupling, offered as an alternative compared to the earlier published results. Although it is temporarily in the phase of theoretical research, synthetic protein design techniques already exist, and the

practical realization will be possible by the evolution of production technologies with nanometer precision.

Following that, special emphasis was laid upon the operation of the formerly proposed parallel dc-dc conversion architecture under severe (critical) working conditions in the frames of reliability analysis and tests. First, the laboratory tests were extended to measure four parallel converters in accordance with the simulation model. Solving the proper communication between the microcontrollers was a preliminary requirement for the further research. This was a part of the physical implementation of the data and information exchange among every single intelligent agent. Laboratory test results confirmed the former results obtained for the earlier investigated two parallel converters. It means that even if sudden alterations in the load current take place the conversion system stayed stable and did not cause intolerably high voltage or current transients. The control algorithms were further refined in the agents to improve even more the dynamic performance. The results were published in Special Journal Issue of World Academy of Science, Engineering and Technology and presented at conference “ICECE’ 2011”.

Considering the system reliability and robustness the operation and decentralized control of parallel DC-DC converters working under faulty conditions were also investigated. During the simulations and laboratory tests certain converter cells were suddenly turned off, imitating malfunctions in them to see the automatic reconstruction capability of the system. The agent-based control showed increased flexibility in the case of artificially generated malfunction or fault, significantly increasing the reliability. The distributed intelligence within the agents facilitated the re-optimization of the converters’ operation and current sharing in line with the system control strategy. The practical implementation of the agents was accomplished by embedded software. Inherent digital control algorithms provided broad flexibility to redefine the main control objectives whenever it was necessary. The results were sent to conference “IEE Japan National Convention, 2011”.

The communication possibilities and schemes with the external loads were also researched. The implementation itself depends very much on the objective of the design. Very low cost solutions allow only for the storage of minimum amount of data that cannot be updated. At the other end of the spectrum there are industrial grade data transmission protocols that can be used to update the status of the load in real time for the control agent. Information about the loads can be useful especially if consumers with a wide range of rated voltages and currents are to be connected to the converter. The user is then spared the task of setting the appropriate voltage (and current) level, a task the user might forget and can thus lead to damage in the load. An application that might require a more elaborate communication scheme is a battery charger. It is common knowledge that batteries are best charged not continuously, but by alternatively charging and then discharging for a short period. The load could provide the microcontroller the information about optimum timing beside rated voltage and current value. Also the battery pack can notify the microcontroller about the completion of the charging process and request to be disconnected, saving energy and extending battery life this way. Three alternative solutions were proposed for the communication. The simplest solution consists of using a voltage divider mounted in parallel with the load. By connecting a given voltage across the resistors, the voltage drops can be used to reveal the voltage and current requirements of the load. Considering a voltage divider made of three resistors in series, two of the voltages across these resistors will be carrying the useful information. A more elaborate solution proposed is to use a PROM chip to store the essential information about the load. The consumers could be fitted with an identical chip that will be programmed only once, during

manufacturing. The most complex alternative is the communication by means of industrial grade communication bus. If the data about the load is to be updated in real time, then assuring a high speed the communication channel is essential.
Implementing a full communication network makes sense in applications like battery chargers. The battery packs in today's mobile devices and laptop computers come with microcontroller technology included. These microcontrollers have several tasks to accomplish, such as: voltage regulation, battery monitoring, battery protection, charge management and even communication with the host application. In most applications SMBus (System Management Bus) or the related PMBus (Power Management Bus) communication protocols are used, which are both derived from the well-established I2C (Inter-Integrated Circuit) communication protocol. Their functionalities are extended for this intelligent load vs. control agent communication.

The research on subharmonics generated in PWM inverters was also continued. The failures of the PWM converter, applied in those systems converting renewable and waste energies into electrical energy, were connected with phenomena caused by subharmonic components generated by the space vector modulated (SVM) PWM converter. Both the simulation and the laboratory test results confirmed that the high level of subharmonic flux components generated by the PWM converter applying space vector modulation could result breakdown of the system. The dc current generated in the stator winding by the converter could also lead to the damage. Three different sampling techniques, the Regular Sampled SVM, the Naturally Sampled SVM and the Oversampled SVM were compared by simulation. The last two techniques were prone to generate subharmonic voltage when the frequency ratio is low mf (mf = 15 or lower). The test results confirmed that on the one hand NS-SVM is prone to generate subharmonics and on the other hand RS-SVM can also generate subharmonics due to the imperfect operation of the controller. The results showed that the benefits offered by the SVM were limited, applying low mf values. Even though the level of subharmonic voltage is low, the subharmonic stator flux can be surprisingly high due to its very low frequency. It was shown that high subharmonic flux is generated in the close vicinity of mf when mf is even integer and it is not multiple of three. The results are being published in "IEEE Transactions on Industrial Electronics" and conference ISIE'2011. The papers have been accepted for publication. In case of paper in "IEEE Transactions on Industrial Electronics", although during the anonym review process of the journal no information about the authors could be provided, but in the final paper the acknowledgment stating that the project was financed by OTKA and the Norwegian Financial Mechanism will be included in accordance with the project contract.
In addition to the already published papers two more papers are currently under preparation:

1. Following the fact that our former paper "Sliding Mode Agent-Based Control of Parallel Buck Converters" was nominated to Best Paper Award at conference EPE-PEMC'2010, we received a request from IEEE Transactions on Industrial Electronics to publish the results in that journal too. Now the new paper is being extended with the most recent results and prepared for submission.
2. Another paper showing the newest test and reliability analysis results will be presented at conference AACS'2011.

Furthermore the results obtained so far also constitutes parts of the Ph.D. dissertations of three young researchers in the project, namely, Peter Bartal, Tibor Daniel Sepsi and Peter Stumpf.
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