

Multi-Input/Multi-Output Converter Model in Matlab/Simulink

Miran Rodič, Miro Milanović, Mitja Truntič

University of Maribor

Faculty of Electrical Engineering and Computer Science, Institute of Robotics
Maribor, Slovenia

miran.rodic@uni-mb.si, milanovic@uni-mb.si, mitja.truntic@uni-mb.si

Abstract— Design and evaluation of dynamic model of multi-input/multi-output power converter consisting of six converters connected by dc-link will be presented in the paper. The model was created in Matlab/Simulink based on the existing system, with the goal of evaluating various power management strategies, where only transient behavior in case of changed operating regime is of interest. In future the model will be used as a Software-In-the-Loop development tool for the design of supervisory control algorithms.

Keywords- Power management, Power electronics, Simulation, Modelling, Control.

I. INTRODUCTION

In many applications there is a requirement for multiple power sources to be connected together, providing the power for a single or multiple loads. These power sources and loads are usually of different kinds, providing or requiring power of various types. This is why due to their wide possibilities of use multi-input and multi-output converters are gaining in importance.

For example in electric and hybrid vehicles, distributed generation systems etc., multiple sources of electric energy are available, which have to be connected together in order to maximize the efficiency of the overall system under the different operating conditions. Additionally in such applications it is a normal case to have multiple different loads that require different kind of power sources.

This kind of operation has recently achieved a wide attention due to the extensive use in the electric and hybrid vehicles [1], [2], as well as in the distributed [3], [4] and microgeneration systems [5], [6]. Especially the use in alternative and renewable sources utilization can be counted among the most interesting applications [4], [6], [7]. Due to the nature of this kind of systems, the supervisory control is required, especially for the performance of power and energy management [8], [9], [10]. In [11] an example of multi-input/multi-output converter system is presented, together with some power management schemes.

However, the converters of that complexity become relatively hard to manage, and in the early stage of development, a lot of attention has to be given to the safety of the operation, which has to be set to a much higher level than the one required in the normal operation. Thus the possibilities

of testing new algorithms are limited and information obtained is in many cases not sufficient.

In development of modern industrial applications simulations are an efficient tool, but applied simulation models have to be precise enough to ensure reliable results and at the same time not too complex in order to allow them to be performed in a reasonable time on the available computers, which in our case are PCs.

In the presented case a multi-input/multi-output power converter was modeled and simulated. The model is based on an actual device, developed in the frame of an industrial project. Matlab/Simulink was chosen as a modeling and simulation tool.

The paper will be organized in the way, which will allow the insight into the bottom-up development of the model. After short introduction a complete system will be presented briefly, to give a basic idea of the model requirements. This will be followed by the presentation of the applied converters and their models. In the next step interconnection of the converters will be presented and explained. Next stage will be the presentation of the supervisory control. This is the main purpose of the model, thus it will be presented in more details. Example of a simple supervisory control will be described together with its presentation by the means of state automata in Matlab/Simulink Stateflow tool. Then the results will be presented, first experimental and then numerical (simulation) ones. Finally, the conclusion will summarize the paper and give some ideas for the future work.

II. SYSTEM MODEL

Multi-input/multi-output converter consists of six converter units (C1–C6), which are connected into the system using the DC link. The system layout is presented in Figure 1. Three bi-directional (C2, C3 and C4) and three unidirectional (C1, C5 and C6) converter units (in the terms of energy exchange) are used, one of the unidirectional converter units operates as a pure source (C1), whereas other two operate as loads, one of them as a pure load (C6). The second unidirectional converter operating as load (C5) can sometimes, for a short time, operate as uncontrolled source.

For the short-term transfer operation system is supported by the capacitor banks applied at the DC-link sides of all converters.

The modularity of the system was an important issue due to the demands set, where special attention was on the maintenance. Possibility to exchange both power and controller hardware units was required. All the components (except in part C4) are built from same basic power electronics blocks, which can be exchanged if required. Additionally the control hardware and software can be used not only for converters, but also for the supervisory system (master unit). Control hardware units are exchanging data using CAN bus.

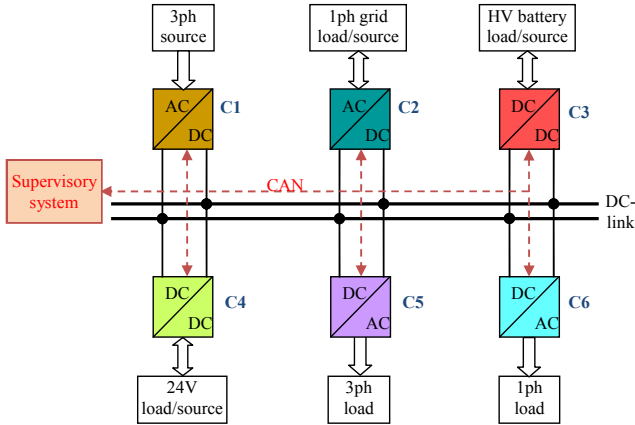


Figure 1. System layout.

The control is performed in two layers, a low level control applied to each of the converters, so called single converter control, and a supervisory level control. In both levels due to the required controlled operation in different operation modes, hybrid control approaches have to be applied.

A. Modelling of Converter Units

In the modeling of converter units the complexity of single converter control is reduced. The start-up behavior is not included and it is assumed that the converter is operating in failure-free operation. Thus only the turning of converter on and off is introduced into the hybrid model besides the transient behavior of the current controlled converter under normal operation.

Due to the space limitations only the bidirectional converter C3 will be presented for the purpose of better understanding of the main idea. The converter is presented in Figure 2, only the main configuration is featured.

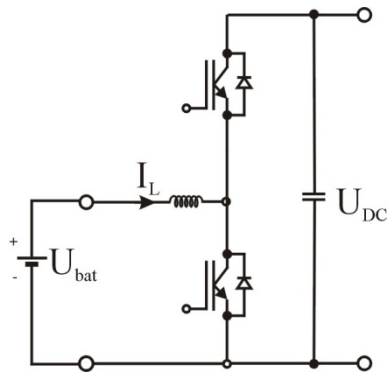


Figure 2. Converter C3.

The most-inner control loop of the inverter is the current

controller. In presented case PI control algorithm has been used, due to its simplicity and relatively high robustness. The converter control scheme, which enables operation as voltage and current controller, is presented in Figure 3. The switching between the voltage and current control can be presented by the use of simple switch, S_{C_x} .

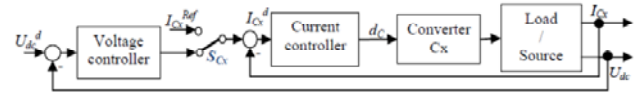


Figure 3. Single converter control scheme

For the purpose of use in the converter system model the current controlled bi-directional converter is modeled in Matlab/Simulink as presented in Figure 4. The converter is modeled by the transfer functions for operation as a load or source. Additionally, delays are introduced representing the time-delay at starting and stopping of the converter. Such a representation is possible, because in order to increase the safety of the converter system operation, the current has to be zero before operation can be switched between the load and source mode.

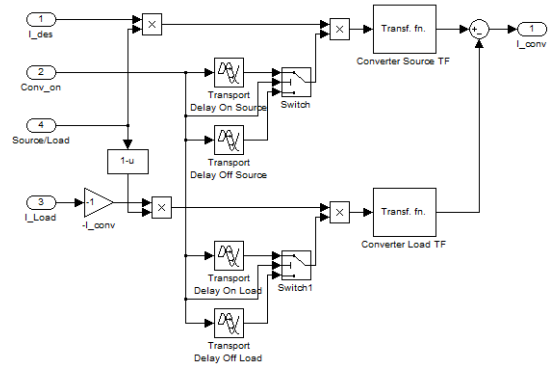


Figure 4. Simulink model of bi-directional current controlled converter.

Likewise unidirectional converters are also modeled in a similar way, as presented in Figure 5 and Figure 6.

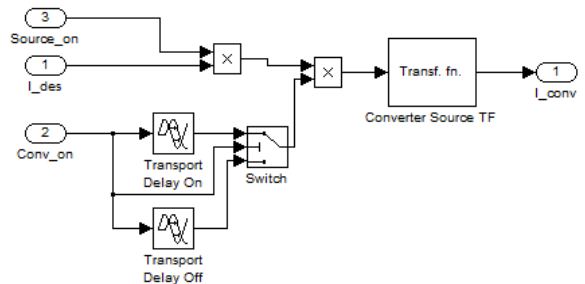


Figure 5. Simulink model of uni-directional (pure source) converter.

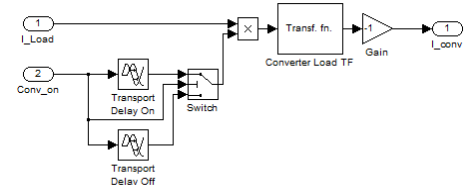


Figure 6. Simulink model of uni-directional (pure load) converter.

All the converters are connected to the single DC-link, the voltage of which has to be kept under control. Since the control, due to the complexity and spatial distribution, cannot be performed with a centralized algorithm, a distributed control is applied. For that purpose all the converters, which can act as sources (C1, C2, C3 and C4), have to be voltage-controlled with a voltage controller, the model of which is presented in Figure 7. Only one of the converters has to be voltage controlled, while other converters are current controlled.

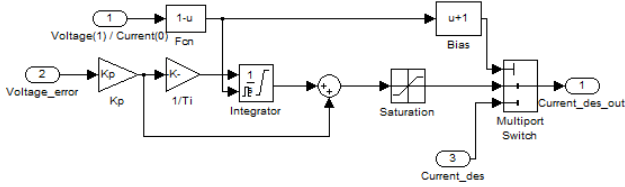


Figure 7. Simulink model of voltage control algorithm

It is also important to note that, due to the large capacitance of DC-link capacitors, current ripple due to the switching and rectification ripple can be neglected for the purpose of power management.

B. Modelling of Converters Interaction

The current balance of the DC-link is calculated based on the well-known Kirchhoff formula:

$$\sum_{k=1}^6 i_{Ck} = 0, \quad (1)$$

where i_{Ck} denotes the current of k-th converter from/to DC-link. Simulink model of the current interconnection is featured in Figure 8, making it possible to attach not only passive, but also active power loads. The basic idea is to enable the replacement of the ideal current source with a more precise converter model in SymPowerSystems (Matlab toolbox), when required. The Figure 9 features the Simulink subsystem containing the complete system current dynamics.

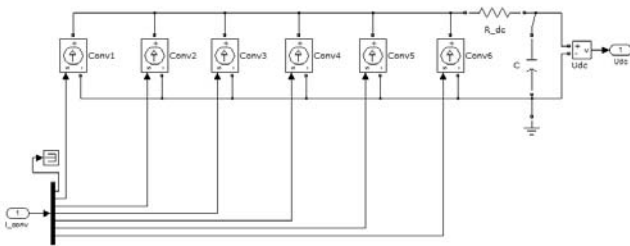


Figure 8. Electrical interconnection converter units.

A better representation is given by equation (2):

$$\frac{dE_{dc}}{dt} = \sum_{k=1}^6 p_{Ck}, \quad (2)$$

where E_{dc} is the DC-link energy, whereas p_{Ck} represents the power of the k-th converter. If the converter acts as a power source towards the DC-link, the power is represented as a positive value, whereas in the case, when the converter acts as a load, the power is represented as a negative value.

C. Modelling of Power Management Schemes

The calculation of currents for the converters connected to remaining sources is performed in the supervisory (master) system based on the equation (1) and (2), together with applied source and load priority schemes.

Different operation modes are applied for the system. In each of them there is one primary power source, which presents the main source of energy and also controls the DC-link voltage, and several (up to two) secondary power sources, which only provide the additional power into the system. The primary power source is voltage-controlled, whereas secondary power sources are only current-controlled.

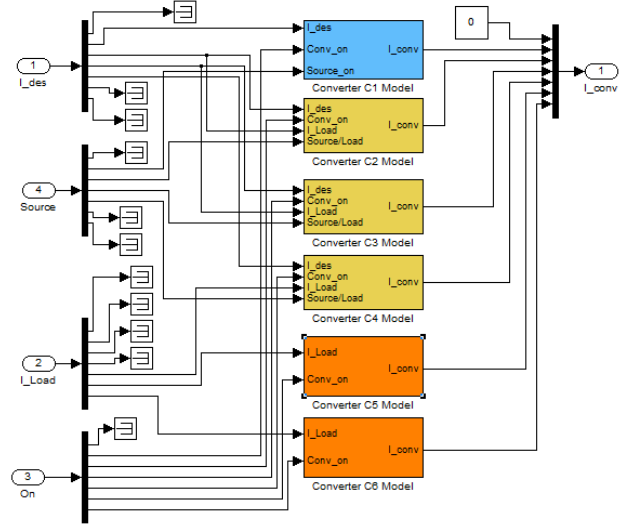


Figure 9. Current dynamics of the converter system.

The presentation of the power management states from the viewpoint of the converters' operation is presented in Table I. The operation as source is denoted by s, whereas the operation as load is denoted as l. The primary operation is denoted by the capital letter. The priority of the source (where the operation in regenerative mode for short time is not included, case of converter C5) is presented by the number in superscript, where 0 denotes the primary source and higher priority is represented by the lower number. Additionally, the primary source converter is marked with the gray background.

TABLE I. POWER MANAGEMENT STATES – CONVERTER ROLES

State	Primary source	Converter					
		C1	C2	C3	C4	C5	C6
INIT	None	Off	Off	Off	Off	Off	Off
STANDBY	None	Off	Off	Off	Off	Off	Off
ONNET	Grid	Off	S ⁰ /l	s ¹ /L	L	s/L	L
NETSUPP	Generator	S ⁰	s/L	S ¹ /l	S ² /l	s/L	L
BAT24V	24V battery	Off	Off	s ¹ /L	S ⁰ /l	s/L	L
BATTERY	HV battery	Off	Off	S ⁰ /l	L	s/L	L
ISLAND	Generator	S ⁰	Off	S ¹ /l	L	s/L	L
FAULT	None	Off	Off	Off	Off	Off	Off

Stateflow model of a simple power management scheme is presented in Figure 10. The states marked by grey

backgrounds contain sub-states. Due to the space limitations it is impossible to include all of them, thus only the ONNET state is presented in more details in Figure 11. An algorithm for the load management is also presented in Figure 12.

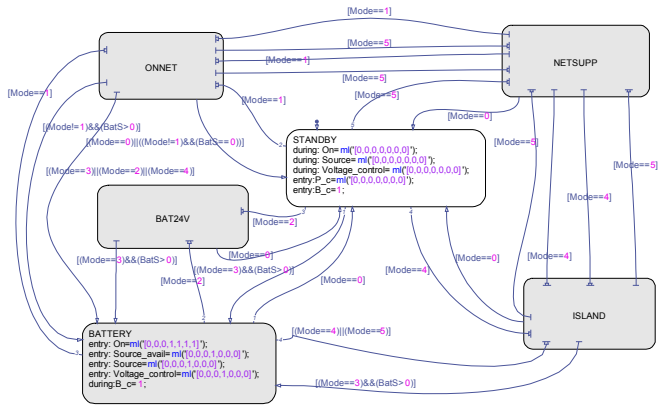


Figure 10. Stateflow representation of the power management model.

The Stateflow representation was used, because in our view it is the simplest way to present such kind of algorithms. Stateflow upgrades the state automata representation of the system by mathematical and logical features, together with the possibility of including events. Furthermore, by designing algorithms in Stateflow it is not only possible to use the Matlab inherent automatic code generation (giving C code as a result), but also to enforce systematic approach on the designer.

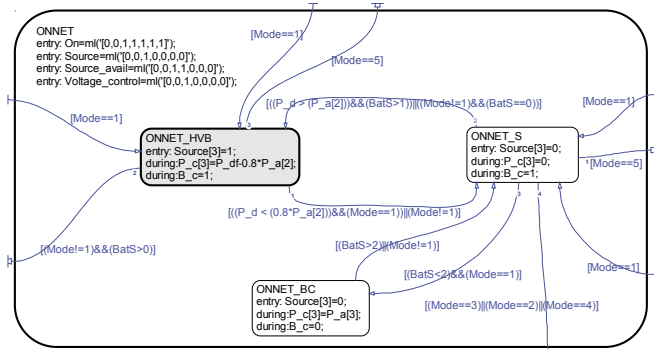


Figure 11. Stateflow representation of the ONNET operation mode.

In Matlab/Simulink it is possible to exchange the Stateflow block with a s-function block, making it possible to evaluate the algorithms written directly in C, which is one of our goal for the future use of the converter system model.

III. EXPERIMENTAL AND SIMULATION RESULTS

A. Laboratory Set-up

Experiments were performed on the custom design hardware, with the master and converter control units using Texas Instruments TMS320F2809 microcontroller. The algorithms for voltage and current control were executed with 25μs sampling time, whereas power management algorithm was executed in 10ms sampling time.

The hardware is presented in Figure 13 and Figure 14. Figure 13 features the complete system, whereas Figure 14 presents a power module used in it. Each power module

contains an IGBT converter leg, like the one presented in Figure 3. The power modules are fully interchangeable, due to the customer demands, and thus oversized for the majority of converters. This makes the system more useful for the experimenting purposes.



Figure 12. Stateflow representation of the load management scheme.

B. Experimental Results

Some experimental results are presented in Figure 15 and Figure 16. Figure 15 features the transition from the state BATTERY to the state ONNET. In the upper half the currents are presented – with 1 the battery current and with 2 the current to grid. In the lower half the DC-link voltage is shown. Figure 16 features the transition from the state ONNET to the state BATTERY, with the numbers marking same signals as in Figure 15. Rapid and stable transition can be observed in both directions, resulting only in minimal overshoot on the DC-link voltage.



Figure 13. Functional prototype of the system

C. Simulation Results

Unlike most of the technical papers simulation results follow the experimental ones. This is due to the fact, that the model and its operation are a result in the presented case.

The Simulink model, containing all the subsystems described above is presented in Figure 17. The model additionally includes battery status model to serve as output for testing operation in case of various battery states (low, full, ...).



Figure 14. Inverter module

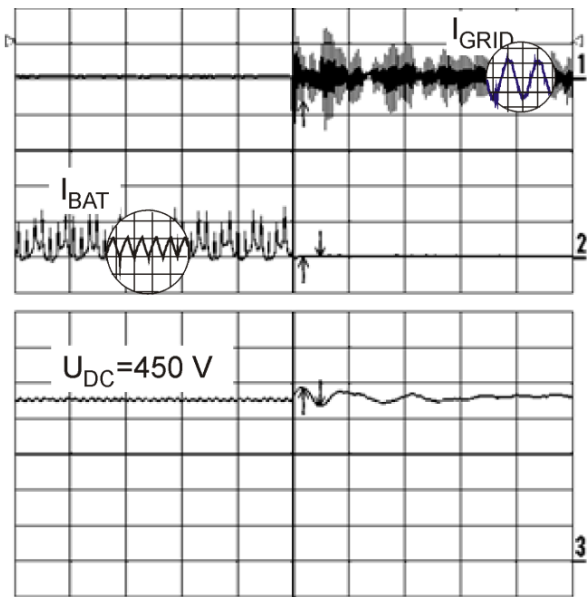


Figure 15. Transfer from battery charging to charging from 1ph ac grid (1 - battery current, I_{BAT} -5A/div; 2 - current to grid, I_{GRID} 5A/div; 3 - DC-link voltage, U_{DC} 100 V/div, x-axis 1s/div).

Simulation results in Figure 18 present a run-through over all the active operating states (presented in Table I), where states are represented by the value of the variable *mode* (0 – system turned off, 1 – ONNET, 2 - BAT24V, 3 – BATTERY, 4 – ISLAND, 5 – NETSUPP). Presented currents would be the ones flowing from the converter to the DC-link. The effects of applied load management scheme are also presented. Converters C5 and C6 are turned on by user and turned off by the load management algorithm based on the priorities set to them.

In the presented case the system is first turned off. Then the ONNET mode is applied, but since there are no power demands presented by attached loads, the power does not have to be provided by converter C2 (which is voltage-controlled). The power demand for the load attached to the converter C5 occurs after 0.8s of operation and is immediately covered by converter C2.

In next step the operation mode is changed to BAT24V. In this mode converter C2 is turned off and converter C4 is

turned on. The power demand presented by load attached to converter C5 is covered from the 24V battery connected to converter C4.

When the mode of operation is changed to BATTERY, converter C3 is turned on and converter C4 turned off. The power is now provided by high-voltage battery, connected to converter C3.

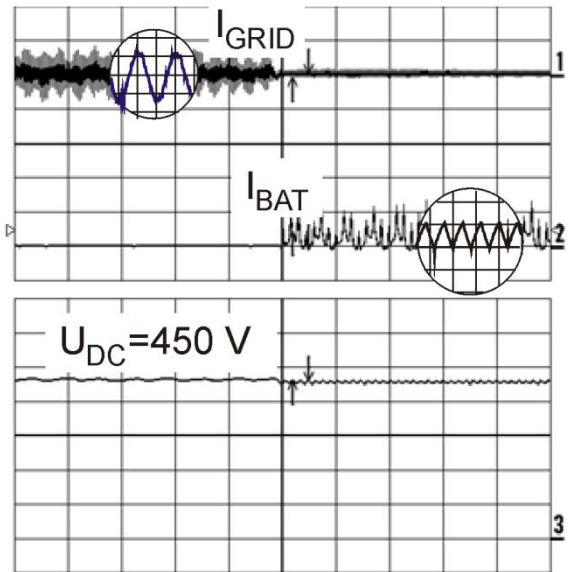


Figure 16. Transfer from charging from 1ph ac grid to battery charging (1 - battery current, I_{BAT} -5A/div; 2 - current to grid, I_{GRID} 5A/div; 3 - DC-link voltage, U_{DC} 100 V/div; x-axis 1s/div).

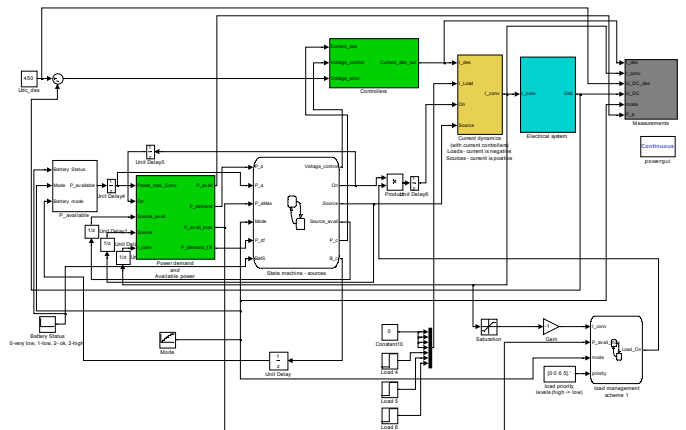


Figure 17. Complete Matlab/Simulink model of converter system.

In the next step, the converter C6 is turned on. Because the priority of load connected to converter C5 is lower than the priority of the load connected to C6, converter C5 is turned off. In this case there is also no possibility to use an additional power source, since the mode BATTERY presents the case of autonomous (quiet) operation.

For the case of higher power demand, with no demand for quiet operation, the operation mode ISLAND is used, which is applied in the next step. Additional power is now provided by converter C1 and the converter C5 is consequently turned on again. In order to achieve the slower high-voltage battery discharge, most of the power is provided by converter C1 and

only a small portion by converter C3 (from high-voltage battery).



Figure 18. Simulation results of operation.

Finally, the last one of modes, NETSUPP, is applied. In this operation it is expected that converter C2 is supporting the power grid by the maximal possible power (this is presented by the negative current for this controller), which is, together with the power required by loads connected to converters C5 and C6 provided not only by the generator (converter C1), but also by the high-voltage battery and in smaller portion by 24V battery.

At the end of test the system is turned off and converters C5 and C6 are also turned off. To demonstrate the possibility of restarting at the end of simulation test the mode is again changed to ONNET.

IV. CONCLUSION

Research and development on the equipment are still active, especially in the power management schemes to be applied. In future we hope to be able to present more contributions in this direction.

However, in order to be able to analyze the operation also off-line, a model of the system was created and is now under evaluation. It can serve as a good study and analysis tool. Next steps in its development will include the possibility of use in HIL (Hardware-In-the-Loop) and SIL (Software-In-the-Loop) systems. The model has to be improved further by extending the dynamic model from the currently used linear approximation to the non-linear representation. We are also considering the creation of a simple interface for the introduction of s-functions.

In practice it is often impossible to measure them, especially because the currents into the DC-link capacitors would have to be measured. Transformation values obtained from the input currents or other (converter-internal) variables would have to be used instead. However, use of DC-link currents can be used in the model of the presented kind, which is a further advantage of its use.

The presented system, apart from its main purpose, can be also used as a valuable research and teaching tool. Special attention will be given to the development of power and energy management schemes, with the focus on the cost functions and introduction of renewable power sources.

ACKNOWLEDGMENT

The work described in the paper was carried out (together with Iskra Avtoelektrika and TECES) in the frame of the project "Mobile Electric Energy Supply with Integration of Alternative Energy Sources", financed by TIA, Ministry of Defense, Slovenia. The ongoing Research is performed in part in cooperation with the Faculty of Electrical Engineering in Banjaluka as a part of project "Improvement of Energy Efficiency of Typical Consumers in Republic of Srpska" supported by Ministry of Science and Technology of RS.

REFERENCES

- [1] L. Solero, A. Lidozzi, J. A. Pomilio, Design of Multiple-Input Power Converter for Hybrid Vehicles, *IEEE Transactions On Power Electronics*, Vol. 20, No. 5, September 2005, pp. 1007-1015.
- [2] P. Pisu and G. Rizzoni, A Comparative Study Of Supervisory Control Strategies for Hybrid Electric Vehicles, *IEEE Transactions On Control Systems Technology*, Vol. 15, No. 3, May 2007, pp. 506 – 518.
- [3] H. Dehbonei, S.R. Lee, S.H. Ko and C. V. Nayar, A Control Approach and Design Consideration of PV/Diesel Hybrid Distributed Generation System Using Dual Voltage Source Inverter for Weak Grid, *SICE-ICASE International Joint Conference 2006*, Oct. 18-21, 2006 in Bexco, Busan, Korea, pp. 672-677.
- [4] A. Hajizadeh and M. A. Golkar, Control of Hybrid Fuel Cell/Battery Distributed Power Generation System with Voltage Sag Ride-Through Capability, *2nd IEEE International Conference on Power and Energy (PECon 08)*, December 1-3, 2008, Johor Baharu, Malaysia, pp. 463-467.
- [5] A. Molderink, V. Bakker, J. L. Hurink, G.J.M. Smit, Algorithms for balancing demand-side load and micro-generation in Islanded Operation, *19th International Conference on Systems Engineering*, pp. 115-120.
- [6] Z. Jiang, Power Management of Hybrid Photovoltaic - Fuel Cell Power Systems, *IEEE Power Engineering Society General Meeting*, 18-22 June, 2006, pp.1-6.
- [7] C. Abbey, J. Robinson, and G. Joós, Integrating renewable energy sources and storage into isolated diesel generator supplied electric power systems, in: *13th Power Electronics and Motion Control Conference*, 2008. *EPE-PEMC 2008*, 1-3 Sept. 2008, pp. 2178-2183.
- [8] J. Zhuo, C. Chakrabarti, K. Lee, N. Chang, Dynamic Power Management with Hybrid Power Sources, in: *44th ACM/IEEE Design Automation Conference*, DAC '07, 4-8 June 2007, pp. 871-876.
- [9] M.E. Torres-Hernández, M. Vélez-Reyes, Hierarchical Control of Hybrid Power Systems, in: *11th IEEE International Power Electronics Congress*, 2008. *CIEP 2008*, 24-27 Aug. 2008, pp. 169-176.
- [10] A.A. Ferreira, J.A. Pomilio, G. Spiazzi, L. de Araujo Silva, Energy Management Fuzzy Logic Supervisory for Electric Vehicle Power Supplies System, *IEEE Transactions On Power Electronics*, Vol. 23, No. 1, January 2008, pp. 107-115.
- [11] M. Rodič, M. Truntič, D. Drevenšek, M. Milanovič, Power management approach for hybrid multi-input/multi-output converter. in: *14th International Power Electronics and Motion Control Conference*, *EPE-PEMC 2010*, 6-8 Sept., 2010, CD-ROM, Paper No. RS-136, pp. T6-6 - T6-13.