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Modeling of DC-link Connected Multiple-converter System Operating as Microgrid

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Original scientific paper

Design and evaluation of dynamic model of multiple-converter system consisting of six power converters connected by DC-link will be presented in the paper. The system has multiple inputs and outputs, providing possibilities to connect several electrical loads and sources of different kinds (dc and ac, low and high voltage). 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.

Key words: Power electronics, Modeling, Simulation, Microgrid, Control

Modeliranje više-pretvaračkog sustava povezanog DC vezama koji radi kao mikromreža. U ovom radu predstavljeni su dizajn i evaluacija dinamičkog modela više-pretvaračkog sustava koji se sastoji od šest energetskih pretvarača povezanih DC vezama. Sustav ima više ulaza i izlaza što omogućuje spajanje električnih opterećenja i izvora različitih tipova (AC i DC, nisko i visoko naponskih). Model je napravljen u Matlabu/Simulinku na osnovu postojećeg modela s ciljem evaluacije različitih strategija upravljanja snagom, pri čemu je jedino bitno prijelazno ponašanje tijekom promjene radnog režima. U budućnosti model će se koristiti kao softver za dizajn i nadgledanje upravljačkih algoritama.

Ključne riječi: Energetska elektronika, Modeliranje, Simulacija, Mikromreža, Upravljanje

1 INTRODUCTION

The power grid is a readily available power source of the electrical energy in modern world. It has been extended even to some very remote areas and at least in developed countries it can be considered both stable and reliable. The energy from the grid can be converted to the required form by the means of AC-DC or AC-AC converters. However, sometimes the national grid is not available, due to the remote location (islands, mountains etc.) or natural disasters. Especially for the military and rescue operations there is a requirement for various power sources of different forms to be used for powering devices like pumps, radios, computers and other electronic equipment in places, where all the available power sources, possibly even the power grid, are relatively weak. In these cases it is very practical to use devices, which can draw energy from multiple sources and distribute it to as many loads as possible.

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 micro-generation 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], with the goal to maximize the efficiency of the overall system under the different operating conditions. 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 consisting of six different converters was designed and built. The main idea was to develop a compact mobile device, in which as many modules as possible could be exchanged in the case of failure or damage. The model of this system was developed in such a way, that it enables fast simulations, focused on the supervisory control and especially power management evaluation.

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. In the next stage the presentation of the supervisory control will be given. 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 automate 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.

2 SYSTEM MODEL

Multi-input/multi-output converter consists of six converter units (C1-C6), which are connected into the system using the DC-link Fig. 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. 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 also outside the workshop was required. As it can be observed from converter schemes in Fig. 2 (a)-(f), converters are built of the equal half-bridge units, which are used as basic power electronics blocks. Based on this requirement the basic power module is designed Fig. 3(a). Microcontroller module is designed with the use of Texas Instruments microcontroller TMS320F2809, and can be used for each converter, as well as for supervisory system Fig. 3(b). Control hardware units are exchanging data using dual CAN bus. The design of a complete system enables the microcontroller units to be exchanged without the need for reprogramming, which is due to the fact that each unit runs the same software and functionality is determined by the hardware in specialized connector.

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

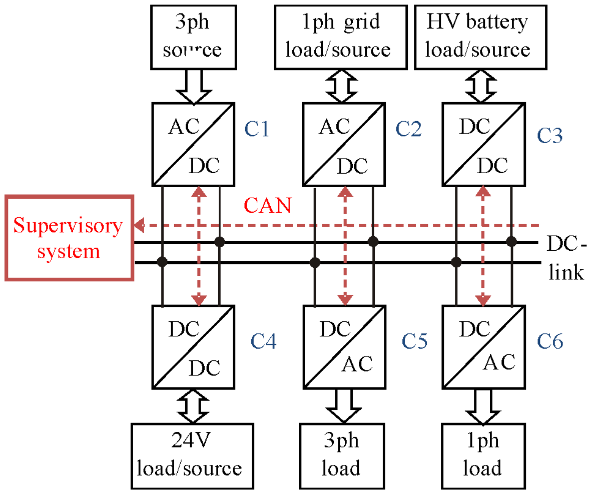
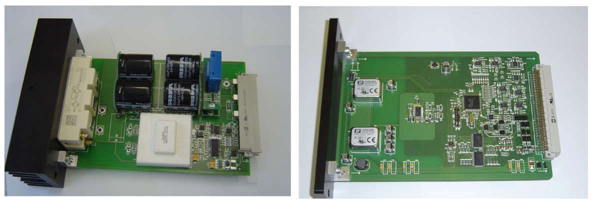


Fig. 1. System layout



(a) (b)

Fig. 3. (a) Power module, (b) DSP module

operation modes, hybrid control approaches have to be applied.

2.1 Modeling of Converter Units

In the modeling of converter units the complexity of single converter control is reduced. 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. 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 Fig. 4. The switching between the voltage and current control can be presented by the use of simple switch, S_{Cx}. For the sake of simplicity only C3 will be considered. The model of the current controlled bi- directional converter is shown in Fig. 5. 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 op-

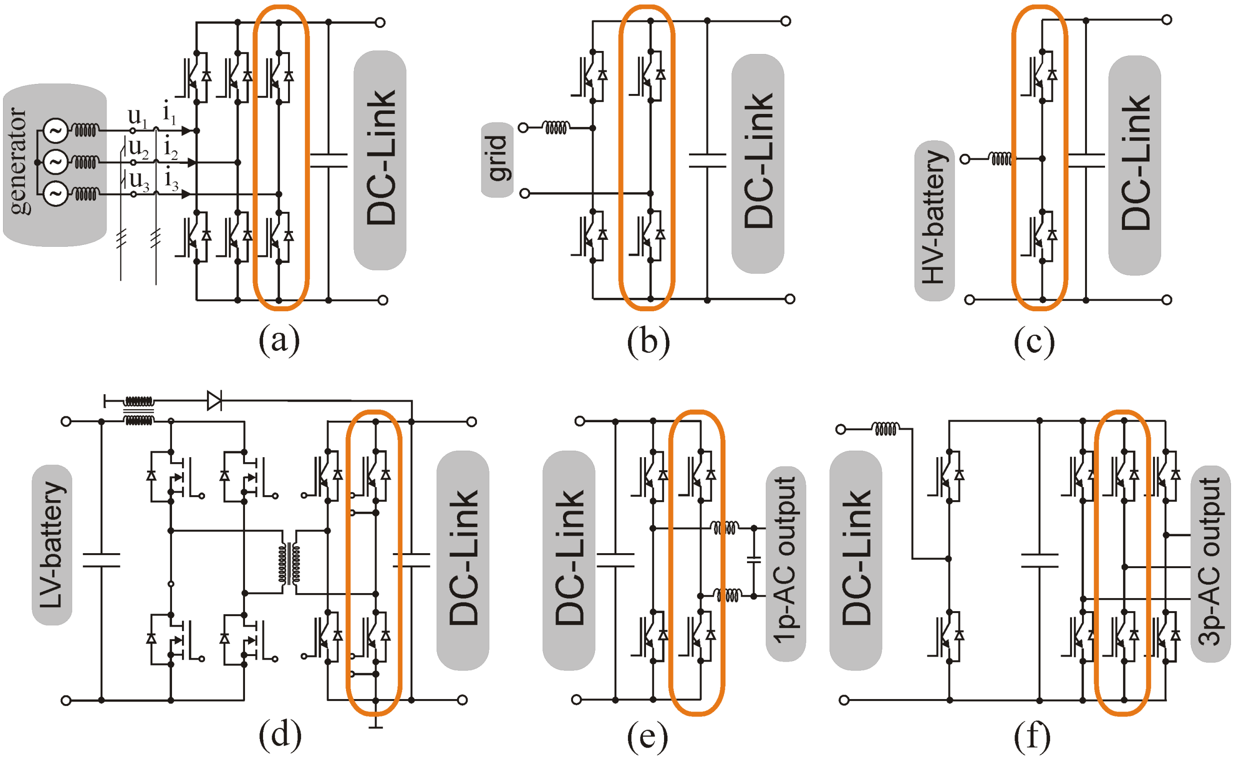


Fig. 2. Converters in system; (a) AC-DC converter-C1, (b) AC-DC converter-C2; (c) DC-DC converter-C3; (d) DC-DC converter-C4; (e) DC-AC converter-C5; (f) DC-AC converter-C6

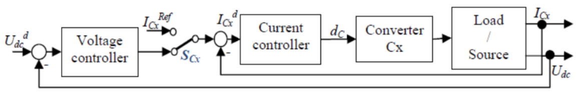


Fig. 4. Single converter control scheme

eration, the current has to be zero before operation can be switched between the load and source mode. A more complex model is not required for the purpose of supervisory control.

Likewise, uni-directional converters are also modeled in a similar way, as presented in Fig. 6 and Fig. 7. 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 control scheme Fig. 4. The model is presented in Fig. 6. One of the converters (master) should be voltage controlled, while other converters must be current controlled. The uni-directional converters, operating as pure loads (C5 and C6, Fig. 7), have no feedback control, only the modulation is performed.

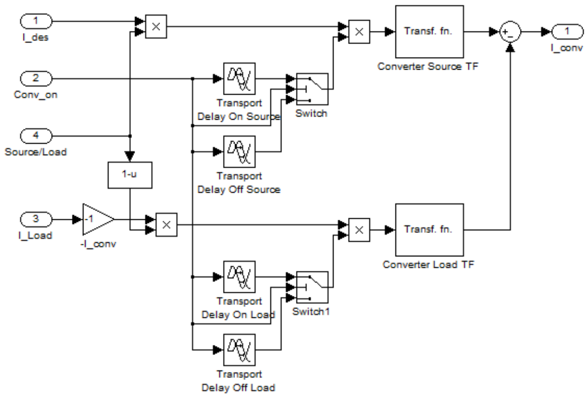


Fig. 5. Simulink model of bi-directional current controlled converter

2.2 Modeling of Converters Interaction

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

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

where i_{Ck} denotes the current of k-th converter from/to DC-link. Simulink model of the current interconnection is

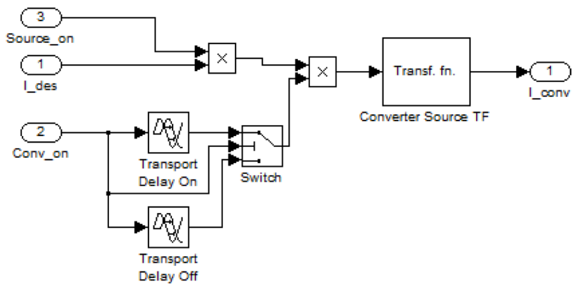


Fig. 6. Model of uni-directional (pure source) converter

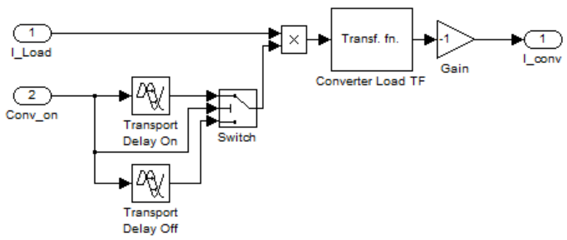


Fig. 7. Model of uni-directional (pure load) converter

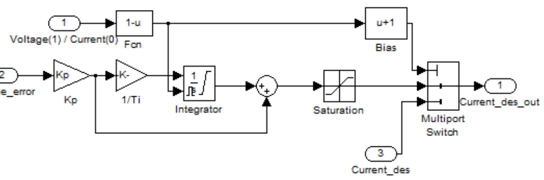


Fig. 8. Simulink model of voltage control algorithm

featured in Fig. 9, making it possible to attach not only passive, but also active power loads. The basic idea is to enable the replacement of the ideal controlled current source, which is used as a replacement for more precise model, with a spice-like converter model in SymPowerSystems (Matlab toolbox), when required. The operation of this converter can then be observed in more details, including switching behavior.

Figure 10 features the Matlab/Simulink subsystem containing the complete system current dynamics. A better representation is given by:

$$\frac{dE_{dc}}{dt} = \sum_{k=1}^{6} p_{Ck} \tag{2}$$

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 by positive value, and when the converter acts as a load; the power is represented by negative value.

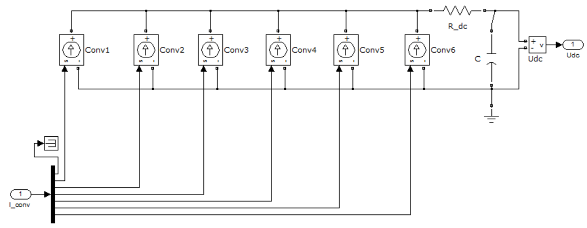


Fig. 9. Electrical interconnection converter units

2.3 Modeling of Power Management Schemes

The calculation of currents for the converters connected to remaining sources is performed in the supervisory system based on (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 presentation of the power management states from the viewpoint of the converters' operation is presented in Table 1. The operation as source is denoted by *s*, whereas the operation as load is denoted by *l*. In case of bidirectional operation the slash sign (/) is used as delimiter. The primary operation is denoted by the capital letter and the secondary by the lowercase letter. The priority of the source (where the operation in regenerative mode for short time is not included, like in the 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.

Stateflow model of power management scheme is presented in Fig. 11. The states marked by grey backgrounds contain sub-states. Only the ONNET state is presented in more details in Fig. 12. An algorithm for the load management is also presented in Fig. 13. The Stateflow representation was used, because 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. 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-code, which is important goal for the future use of the converter system model.

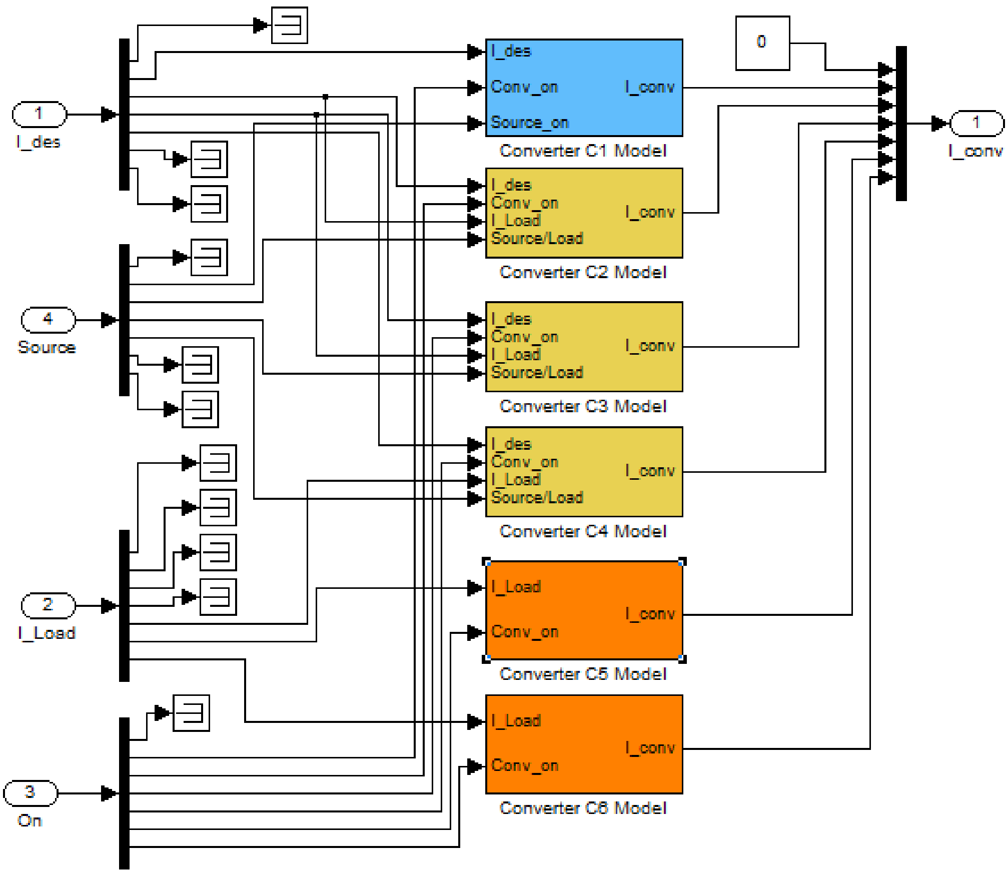


Fig. 10. Current dynamics of the converter system

Table 1. 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

3 EXPERIMENTAL AND SIMULATION RESULTS

3.1 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 in 25 μs time interval, whereas power management algorithm was executed in 10 ms time interval. The multi-converter system is shown 14. Each power module contains an IGBT converter leg, like the one presented in Fig. 3(a). The power modules are fully interchangeable, and thus oversized for the majority of converters. This makes the system more useful for the experimenting purposes.

Some experimental results are presented in 15 and Fig. 16. Fig. 15 features the transition from the state BATTERY to the state ONNET and Fig. 16 shows the transition from the state ONNET to the state BATTERY, The battery current, current to grid and the DC-link voltage are shown. Rapid and stable transition can be observed in both direc-

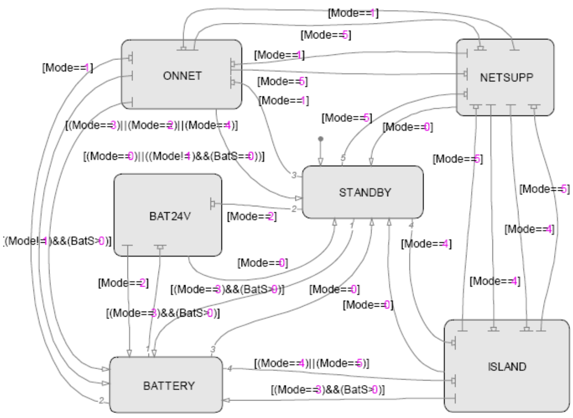


Fig. 11. Stateflow representation of the power management model

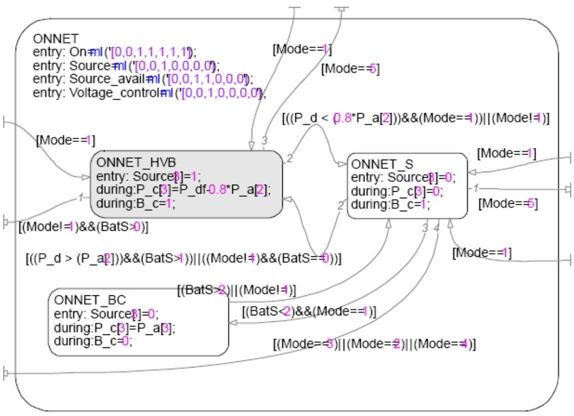


Fig. 12. Stateflow representation of the ONNET operation mode

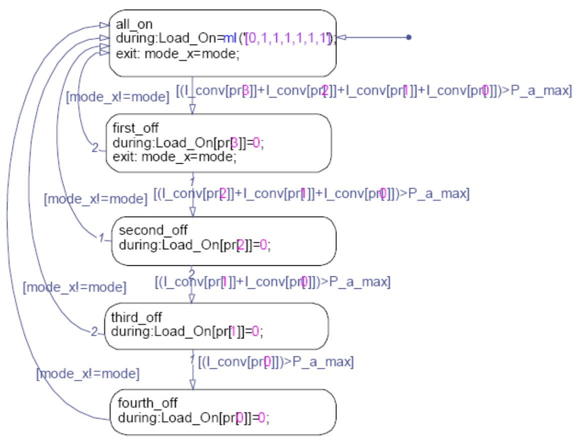


Fig. 13. Stateflow representation of the load management scheme

Fig. 14. Functional prototype of the system

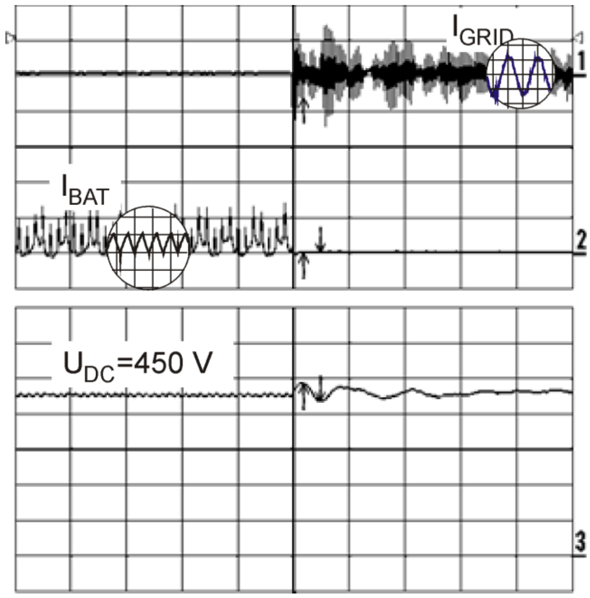


Fig. 15. Transfer from C3 to C2 (1-battery current, I_{BAT}-5A/div; 2-current to grid, I_{GRID} 5A/div; 3-DC-link voltage, U_{DC} 100 V/div, x-axis 1s/div)

tions, resulting only in minimal overshoot on the DC-link voltage.

3.2 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 model, containing all sub-systems described above is presented in Fig. 17. The model additionally includes battery status model to serve as output for testing operation in case of various battery states (low, full, . . .).

Simulation results in Fig. 18 present the transfer from BATTERY mode to ONNNET and back from ONNET to

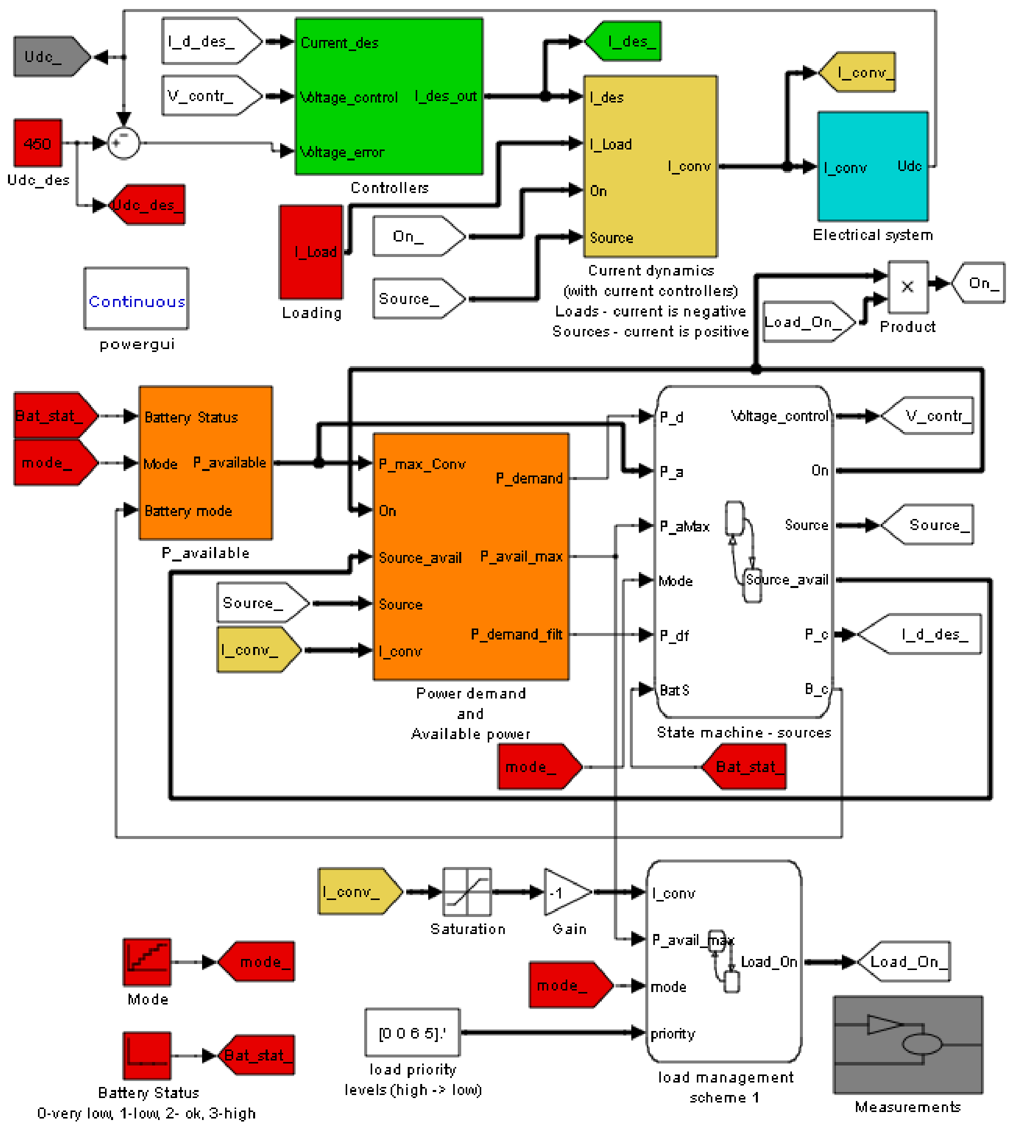


Fig. 17. Complete Matlab/Simulink model of converter system

BATTERY, similar to experimental results, presented in Fig. 15 and Fig. 16. Positive currents are the ones flowing from the converter to the DC-link. Due to the less precise modeling, which is required for the faster execution of simulations, the switching effects are not present.

To show an operation in all the modes, simulation results in Fig. 19 present a run-trough over all the active operating states (presented in Table 1), 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). 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 $0.8\ s$ 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 con-

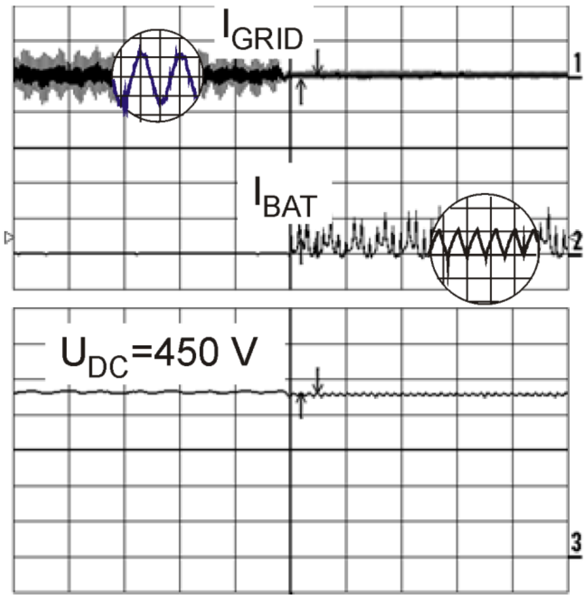


Fig. 16. Transfer from C2 to C3 (1-battery current, I_{BAT}-5A/div; 2 - current to grid, I_{GRID}-5A/div; 3- DC-link voltage, U_{DC}-100 V/div, x-axis 1s/div)

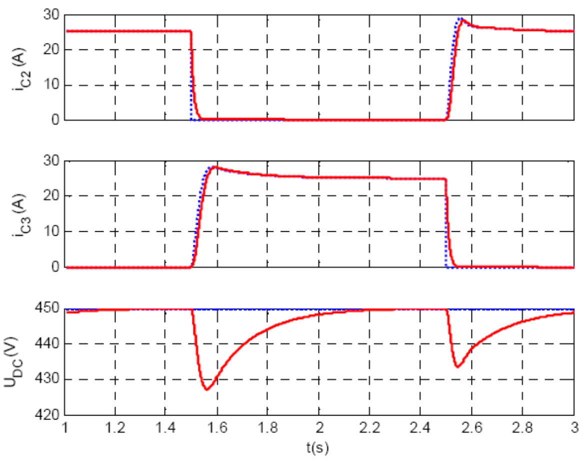


Fig. 18. Transfer from BATTERY mode to ONNNET and back from ONNET to BATTERY

verter C3. 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 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. 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 C3 and in smaller portion by C4. 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.

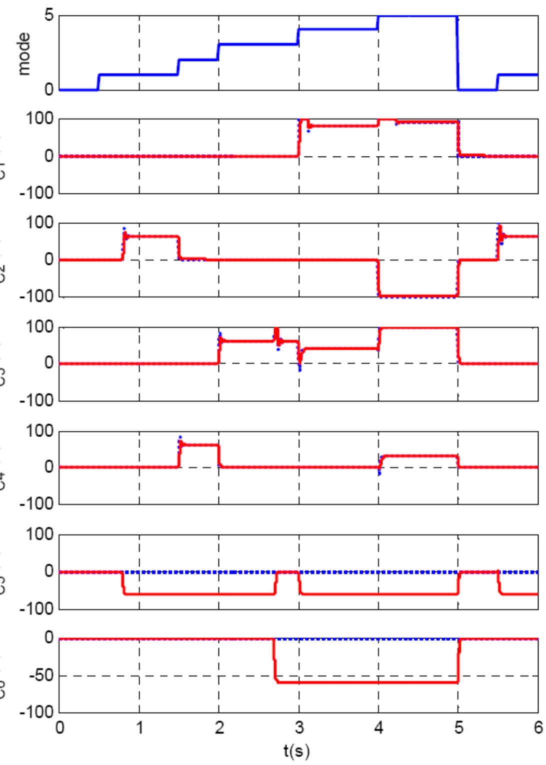


Fig. 19. Simulation results of operation (dotted line – desired value, solid line – actual value)

4 CONCLUSION

Model of the DC-link connected multiple-converter system operating as microgrid has been presented in the paper, together with its elements. Converters have been presented as a pair of controller and converter model, for the cases of uni- and bi-directional operation, as load or source of energy. The control blocks enable feedback control and inclusion of additional, higher-level functions, which introduces the possibility of use for the supervisory control. Electrical connections and current dynamics can be observed up to the sufficient precision for the use in the supervisory control design process.

The presented model is a useful tool for the development of the power and energy management strategies in the multi-converter systems. This is mainly due to the fact that it enables more insight into the operation of the devices, because measurement of all the variables is not practical and costly. In practice it is often impossible to measure some of the states, inputs and outputs of multi-converter systems. In the presented case the currents into the DC-link capacitors cannot be measured, because of their shape. Transformation values obtained from the input currents or other (converter-internal) variables have to be used instead. However, values of DC-link currents can be used in the model of the presented kind, which is its further advantage.

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. Also the creation of a simple interface for the introduction of s-functions into the model is under consideration.

The presented system, apart from its main purpose, can be also used as a valuable 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.

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