

SOFTWARE IN THE LOOP SIMULATION OF AUTONOMOUS HYBRID POWER SYSTEM OF AN AGRICULTURAL FACILITY

Vitalijs Osadcuks, Ainars Galins
Latvia University of Agriculture
vtl@tvnet.lv, ainars.galins@llu.lv

Abstract. Considering the rapid development of renewable energy technologies, particularly solar cells, electrochemical and other types of energy storage as well as power electronics converters, autonomous power supply systems are becoming an alternative to the construction of a new electrical grid connection for micro-scale electric power consumers (by the classification of the European Parliament Directive 2004/8/EK – the maximum simultaneous power up to 50 kW), for example, small agricultural facilities, farms, greenhouses, estates, tourist attractions etc. The article demonstrates use of the software in the loop (SIL) approach in the simulation of renewable resources based autonomous hybrid power supply (HPS) segment and facility-level control systems. Simulation of such type allows to design, test and evaluate control software written in conventional programming languages, but dynamic models of plant, sensors and actuators used are simulated in specialized environment e.g. Matlab Simulink or Scilab Xcos. An example of autonomous HPS of a cattle farm was used as a case study.

Keywords: software in the loop, autonomous hybrid power supply, control system.

Introduction

Depending on locally available resources and electrical load schedule, autonomous hybrid power systems (HPS) can have a large number of different combinations of equipment both functionally and in terms of scale [1]. Irregular and difficult to predict load power distribution during the day and seasonally is particularly characteristic for agricultural facilities, such as farms that specialize in biological processes: dairy and beef cattle, swine growing, greenhouses with automatic plant watering and fertilization, etc. A proper energy flow distribution strategy between irregularly available renewable resources, fossil resource generators, battery charging and electric load would hypothetically result in more efficient use of available renewable resources in hybrid power systems, reduce fossil resource generator operation time and cycles of battery use to ensure continuous power supply to the consumer.

Hybrid power system modelling and simulation environments are available, such as HOMER (Hybrid Optimization Model for Electric Renewables) and Hybrid2, where standard high level control algorithms and strategies are realized. On the other hand research is carried out on advanced facility and segment-level control solutions, where information and communication technologies and artificial intelligence are applied, such as prediction of available power from renewable resource generators by using meteorological forecasts, adaptive control, which uses neural networks to predict and adjust to changing load, intellectual agents etc. Implementation of these methods requires relatively complex programming and interfacing to different software modules, this is not provided by currently available simulation environments.

The article presents a simulation of a cattle farm HPS control system using software in the loop (SIL) approach [2; 3]. The aim of this work is to demonstrate the possibilities of using the SIL approach at the facility and segment level control system simulation, allowing to evaluate advanced resource dispatch strategies for autonomous hybrid power systems including those, which utilize renewable energy sources.

Materials and methods

The main idea of SIL is to model plant, sensors, and actuators in a dynamical environment e.g. Simulink or Xcos separately from the control system, which in turn is implemented in a conventional programming language. Thereby the real control system software is operated with plant, sensors and actuators simulations instead of real devices. Consequently, control software, which has been tested in the SIL mode with minimal modifications can be used in a final controller solution (personal or industrial computer, embedded system etc.). The block diagram of control system and simulation model set for SIL mode proposed by author is shown in Fig. 1.

For the development of control system software Microsoft .NET environment was used. A class library with common autonomous hybrid power system power interfacing, generating and accumulating equipment according to [4] was designed to interconnect the control software with real devices and their simulation models. Simulation model library of hybrid power system equipment was designed in Matlab Simulink environment. The library contains all components of the control loop except the controller and all the models are controllable from a .NET program. For information interchange between the control software and Matlab workspace Matlab Compiler V4 tool (Version 4.0 (R14) Matlab Compiler) from libmx.dll and UtilityMatlabCompilerVer4.MatlabCSharp wrapper class by [5] were used.

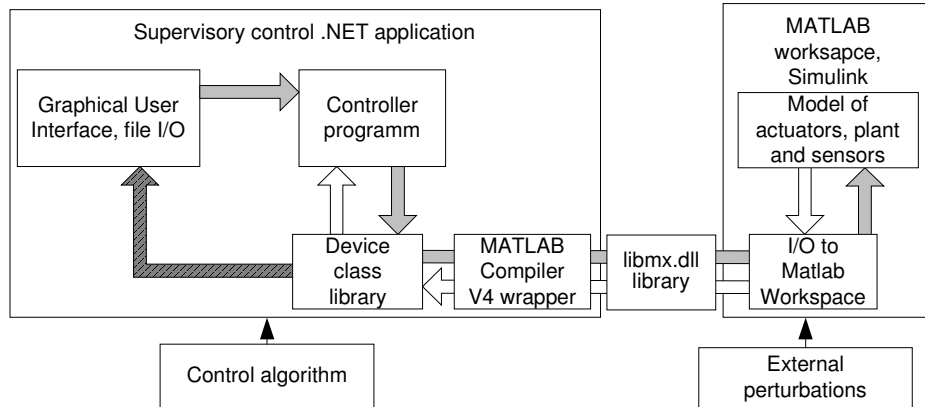


Fig. 1. **Simulation using SIL method:** ← – control and perturbation signals; ← – feedback signals; ← – result of the simulation; ← – inputs of the simulation

The simulation of the model is performed by periods. The control software reads the simulation results, which represent the sensor readings at the end of each period and sends control signals to the model at the beginning of the next period. The simulation process is shown in detail on simulation time t axis in Fig. 2. In Simulink depending on the used solver and rate of signal changes simulation period T is split into steps s_m , consequently for periods of equal timespan there can be a different number of steps. At the beginning of the simulation initial control signals are passed to the model (vector with J elements).

Outputs are read at the end of each simulation period as a matrix of size $[M_i;K]$, where M_i is a count of simulation steps in a period T_i , but K – count of model output signals. The function f_c determines control reference signals for the next period T_i only from output of the last simulation step of the previous period T_{i-1} and returns a signal vector with J elements, which then is sent to the model at the beginning of T_i . Thus, the control system reads the sensor values with a period T , which wherewith is a control period of the controller. Alongside at the beginning of each period states of inertial blocks from the previous period are set to make the simulation process continuous. The simulation results are combined together in all periods, including all steps in each period.

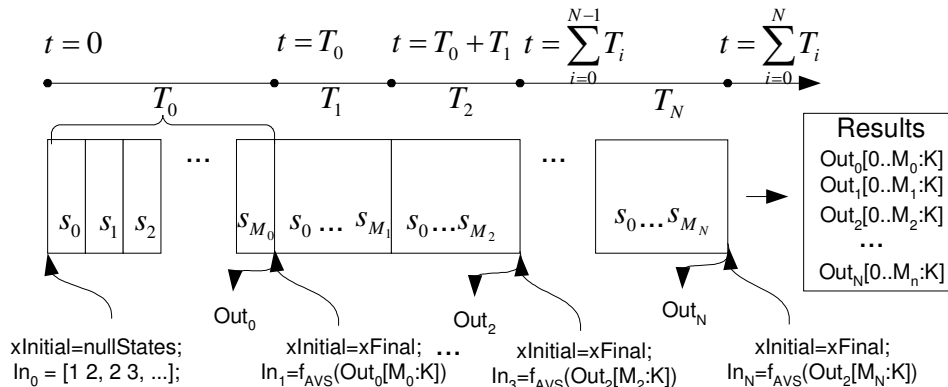


Fig. 2. **Process of SIL simulation on simulation time axis**

Since in the SIL mode .NET program exchanges data with the Simulink model only after the end of each simulation period; the real-time aspect of the controller software operation is not taken into

account, i.e., only functionality of the controller is studied. The SIL simulation method, considering real-time performance of the controller and its software is discussed in detail by [2].

In the case study as the inputs of the simulation electrical consumer data from the LUA Training and Research Centre “Vecauce” cattle farm, which is designed for 530 cows were used. In order to simulate the operation of renewable energy resources (wind and sun) local meteorological information for the year 2007 was used. The chart of electrical load and available renewable resources availability for one week 05.11.2007–11.11.2007 is given in Fig 3. Local temperature data were used at the inputs of simulation in order to consider effects of air temperature on load changes (e.g., operation of electrical heating devices at temperatures below 0 °C).

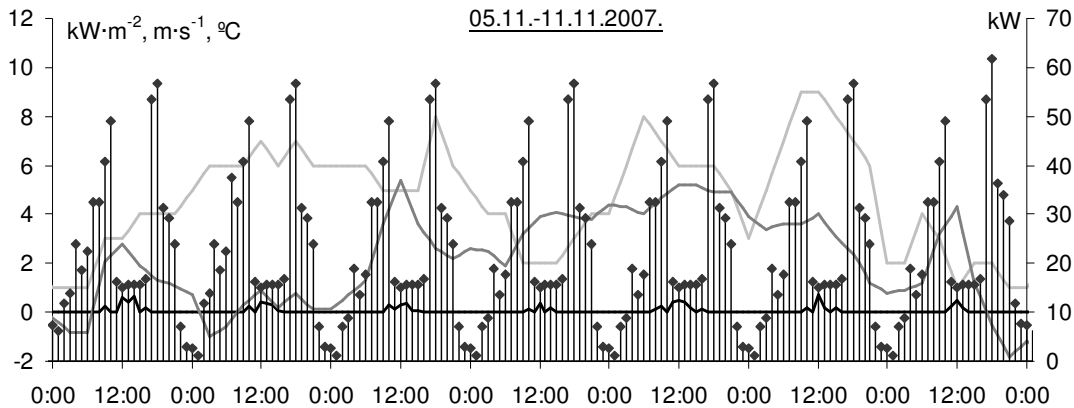


Fig. 3. Meteorological data and load profiles for time period 05.11.2007. to 11.11.2007.:
 ———— – solar irradiation; ———— – wind speed; ———— – air temperature; ◆ – load

An optimal HPS equipment configuration for the given load profile and available resources was found in hybrid power system optimization software “HOMER”, see Fig. 4. The sources of energy are two Fuhrländer 100 kW wind generators WGs1; 40 kW photovoltaic array with an optimal stationary (non-tracking) orientation PV1 consisting of 200 Kioto 195 modules; and a 25 kW combustion engine generator G1, which can operate on fossil or biofuel. The fuel consumption of the generator was assumed constant: 10.06 l·h⁻¹ or 0.4 l·(kWh)⁻¹ at full power, which corresponds to 25 – 30 kW diesel generators available on market [6]. Solar panels were modelled using approach described in [7]. The parameters of the panels were optimized using Matlab Parameter Estimation tool to the U-I characteristics of Kioto 195 PV module. The battery was modelled using generic battery model with constant internal resistance [8; 9]. Wind generators were modelled as look-up tables of Fuhrländer 100 kW power curves.

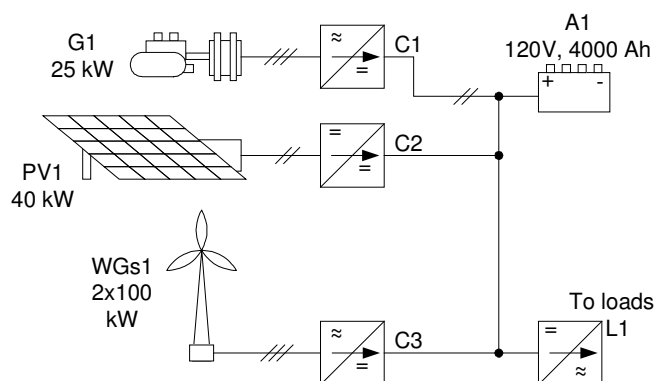


Fig. 4. Simplified connection diagram of autonomous HPS equipment of a cattle farm

For interconnection of the power system equipment 120 V central DC bus with directly connected 4000 Ah deep discharge lead-acid battery A1 is used. The efficiency of power interfaces C1 – C3 and inverter L1 is $\eta = 90\%$. The bus and power interfaces were modelled accordingly to [3].

The equivalent HPS simulation model with control system interface in Simulink environment is given in Fig. 5. Ports “In” and “Out” are used to connect the control software running in .NET environment.

Two standard combustion engine generator dispatch strategies for energy flow distribution between battery charging and load were modelled. The tested algorithms (accordingly to [10]) were cyclic battery charging and load following. According to the cyclic charge algorithm the generator is used only for battery charging and is turned on and off at certain levels of charge of the batteries (50 % and 90 % in the case). In the load following approach the combustion engine generator is used only to compensate excess electrical load that cannot be covered by renewable generators. In order to achieve maximum efficiency in the fuel consumption for the load following strategy the combustion engine generator is turned on only if discharge current of the batteries is 20 A more than can be sourced by the converter C1 at nominal power of G1 and nominal system voltage – 120 V. Thus, it is insured that the generator is operated with a power close to nominal and it compensates the power deficit from renewable resources and does not charge the batteries. In order to avoid deep discharge of the batteries the load following strategy was combined with cyclic charge with a narrow operation interval: G1 is turned on at 40 % discharge level and charging is ended at 60 %. Consequently, according to the load following strategy the batteries then are charged to the full capacity using only renewable resources. The minimum operation time of the generator is 30 min to prevent frequent switching of the generator due to the battery current changes around the start current limit and to conserve fuel.

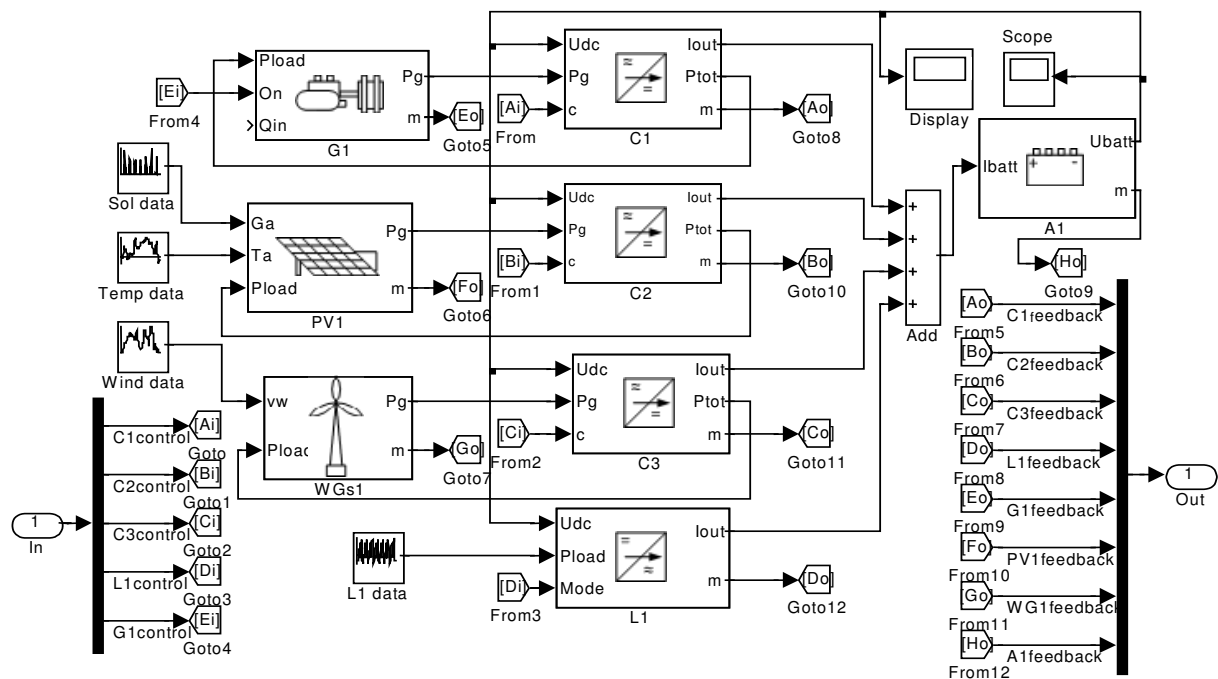


Fig. 5. Simulation model with control system interface for autonomous HPS of a cattle farm

The control period is 60 s, i.e., the program in .NET environment calculates control signals, sets control inputs and continuous states and starts simulation of the Simulink model for 60 s period. After that the results are read from Matlab workspace variables. All simulations were performed using the variable step solver “ode23tb”. The simulation speed with respect to real time for the discussed HPS configuration depends on the intensity of transients in the simulation and is averagely 150:1, i.e., simulation of the power supply and control system for a 7-day period with different control algorithms took approximately 67 min.

Results and discussion

A number of simulations were performed for single day and 7-day periods with different renewable resource availability scenarios. The simulation results for a week scenario with variable wind speed for the time period 05.11.2007 – 11.11.2007 are shown in Figs. 6 and 7.

The charts summarize the load P_l , kW and consumed power from different sources (without 10 % losses in power interfaces): P_S from photovoltaic array, P_V from wind generators, P_C from combustion engine generator, in kW. The state of charge of the batteries (SOC) in % and excess power for photovoltaic array, the wind generator and combustion engine generator respectively P_{excS} , P_{excV} , P_{excG} ,

in kW are given also. The stacked area charts were used to show parts of fossil and renewable generator power in the supply of load.

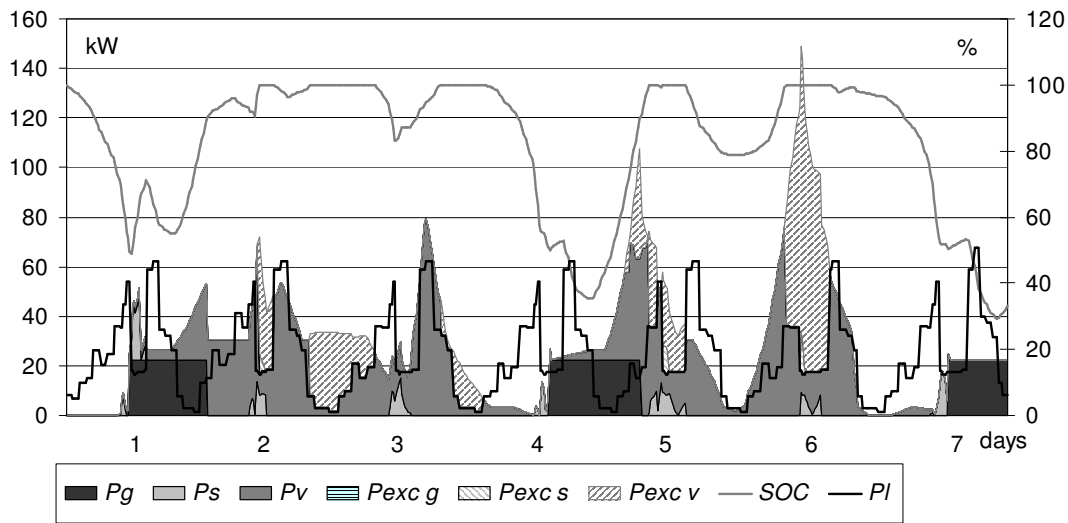


Fig. 6. Simulation results of system operation for cyclic battery charge algorithm

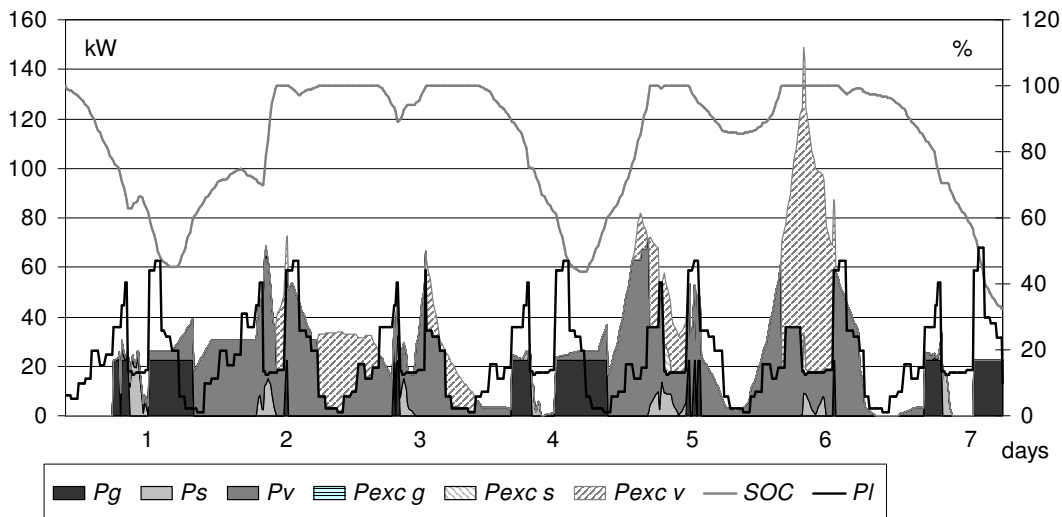


Fig. 7. Simulation results of system operation for modified load following algorithm

The simulation shows that with increased availability of wind resource the combustion engine generator is operating 26 % of total simulation time for the cyclic charge algorithm. It was turned on in three points with simultaneous low availability of renewable resources and load power peaks (Fig. 6), but 63 % of the simulation time SOC of the batteries was above 80 %. For the load following algorithm G1 operated 23 % of time and SOC above 80 % was 55 % of the simulation time. The combustion engine generator is turned on each time when P_l exceeds the sum of P_s and P_v by 27.4 kW (nominal power of the generator and 2.4 kW needed to ensure that the generator will operate at full load).

In both simulations most of the time batteries were fully charged from the renewable resources, graphically the changes in SOC curves are repetitive. Consequently, for the load following algorithm the total operation time of G1 and excess energy from renewable sources decreased by 10.5 kWh (excess photovoltaic energy) and by 71.0 kWh (excess wind energy). The simulation graph clearly demonstrates that for both algorithms on day 6 an excess wind power peak appears, but on day 7 in its turn there is a shortage in renewable resources, therefore, G1 needs to be operated and SOC of the batteries decreases rapidly. The simulation shows that the total excess energy for the cyclic charge algorithm from photovoltaic array is 52.9 kWh and from wind generators – 1436 kWh, for the load following algorithm – 42.4 kWh and 1365.4 kWh respectively. This confirms the assumption on the possible low consumption efficiency of irregularly available renewable resources in changing load

conditions. In addition, if on the next days reduced availability of the renewable resources takes place additional generators with constant resource availability or batteries should be used.

Using the SIL simulation of autonomous hybrid power systems with different resource availability and load-changing scenarios it is possible to modify standard energy flow control strategies and algorithms to achieve optimal resource utilization and decrease the necessary capacity of the generating and accumulating equipment. The developed control software can be used in the implementation of a control system.

Conclusions

1. The main advantage of the software in the loop approach in the evaluation of segment and complex level control systems of autonomous hybrid power supply in comparison to the existing simulation environments is possibility to freely design and modify control algorithms in standard high-level programming languages. It also allows using model driven architecture for software development and implementing the software in final control system solution with minimal changes.
2. The results obtained by the simulation of autonomous hybrid supply and its control system for the LUA Training and Research Centre "Vecauce" type cattle farm (designed for 530 cows) with 200 kW wind generators, 40 kW photovoltaic array, 25 kW diesel generator and 120 V, 4000 Ah battery bank show that in comparison to the cyclic battery charge algorithm renewable resources are utilized more effectively using the load following algorithm: by 5 % in conditions with irregular wind speed. The fuel consumed by the generator decreased by 8 %.
3. The simulation speed of the model against real time depends on the intensity of transients in the simulation and is averagely 150:1. Compiling the Simulink model into standalone library can increase the simulation speed.

Acknowledgements

The research has been carried out with the financial support of European Social Fund – Support for Realization of Doctoral Studies in Latvia University of Agriculture. Agreement No. 2009/0180/1DP/1.1.2.1.2/09/IPIA/VIAA/017.

References

1. Paska J., Biczal P., Klos M. Hybrid power systems - An effective way of utilising primary energy sources. *Renewable Energy*, No. 34, 2009, pp. 2414 – 2421.
2. Youn J., Ma J., Sunwoo M., Lee W. Software-in-the-Loop Simulation Environment Realization Using Matlab/Simulink. *SAE Transactions*, No. 115, 2007, pp. 857 – 863.
3. Osadcuks V., Pecka A., Lojans A. Hardware and software environment for evaluation of control algorithms and strategies of hybrid power systems. In: *Engineering for Rural Development: Proceedings of the 10th International Scientific Conference*. Latvia University of Agriculture Faculty of Engineering, Jelgava 2011, Latvia. pp. 311 – 316.
4. Osadcuks V., Galins A. Application of the object oriented approach in the research of autonomous power supply systems. In: *Engineering for Rural Development: Proceedings of the 5th International Scientific Conference*. Latvia University of Agriculture Faculty of Engineering, Jelgava 2007. pp. 64 – 69.
5. Phan J. *MATLAB C Book*. : LePhan Publishing, 2004. 151 p.
6. Approximate Diesel Fuel Consumption Chart. [online] Diesel Service & Supply [cited 23.10.2010.]. Available: http://www.dieselserviceandsupply.com/diesel_fuel_consumption.aspx.
7. Pandiarajan N., Muthu R. Mathematical modeling of photovoltaic module with Simulink. In: *Electrical Energy Systems (ICEES)*, 2011 1st International Conference, 3-5 Jan. pp. 258 – 263.
8. Battery. Implement generic battery model. [online] Mathworks Inc. [cited 23.10.2011]. Available: <http://www.mathworks.se/help/toolbox/phymod/powersys/ref/battery.html>.
9. Simple, Effective Lead-Acid Battery Modeling Process for Electrical System Component Selection. Robyn A. Jackey. : Mathworks Inc., 2007.
10. Barley C.D., Winn C.B., Flowers L., Green H.J. Optimal dispatch strategy in remote hybrid power systems. *Solar Energy*, No. 58, 1996, pp. 165 – 179.