

## HARDWARE AND SOFTWARE ENVIRONMENT FOR EVALUATION OF CONTROL ALGORITHMS AND STRATEGIES OF HYBRID POWER SYSTEMS

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**Abstract.** This article presents an environment for design and evaluation of control algorithms and strategies for hybrid power systems, which use renewable energy sources. The environment relies on Hardware In the Loop (HIL) and Software In the Loop (SIL) approaches and allows to use together pure software Matlab Simulink models, physical models and real devices in non-real and real-time simulation modes using common hardware and software tools. The control system itself is implemented in Microsoft .NET environment using object-oriented techniques as a common application for both simulation modes. In order to show the capabilities and performance of the simulation environment renewable energy equipment block library in Simulink and microcontroller-based physical models of DC converters and load have been designed.

**Keywords:** modeling, hardware and software in the loop, control system, hybrid power system.

### Introduction

Instability over a period of time is the main disadvantage of wind and sun, the most conventional renewable energy sources. It is hard to provide a consumer with electrical energy of good quality, especially in isolated small-scale power grids. Therefore so-called hybrid power systems or systems with distributed energy generation are used. Hybrid power systems (HPS) combine several mutually complementing renewable sources with energy storage and back-up powering devices in a single power grid. This allows compensating both short-term fluctuations and transients and long term unavailability of renewable energy sources. Such systems can be implemented with a connection to public power grid and can be used to supply power to the consumer during brownouts and blackouts in so-called islanding mode. Fully autonomous designs are also in use. HPS with distributed generation and energy storage along with cogeneration and multigeneration have begun to play a significant role in energetic in the past decade and it has a tendency to develop in future [1].

There are several possible ways of combining generators, accumulators and loads in a single system: central DC bus, central AC bus and composite architecture where several busses are connected using power interfaces. Use of unified power interfaces also increases modularity of hybrid power system. This results in simpler design, increased reliability, interchangeability of individual modules and reusability, which decrease the costs of implementation [2] In a general case power interfaces handle the power flow from generators to loads and thus are considered as main final control elements or actuators in the control loop of hybrid power systems.

Because of nature of renewable energy a hybrid power system is distributed and stochastic and its configuration can vary significantly depending on the site. Designing control systems in such case is a time-consuming and expensive task; therefore various modeling techniques are extensively used. A variety of mathematical and simulation models are developed, which focus mainly on interaction of individual components of HPS in transients and static modes [3]. These models help to deal with problems related to stability, reliability and behavior in typical solutions, like the wind turbine-diesel generator, battery or wind-solar-battery etc, which are extensively studied by scientists and engineers, e.g. [4]. Theoretical and practical studies are being carried out to generalize control systems of HPS to allow achieve modularity also in a lower level and supervisory control, and data acquisition. For example, Awad et.al., [5] discuss several concepts of microgrid (a type of HPS, which covers larger geographical areas) with different topologies and control strategies. Hajizadeh and Golkar study power flow in a battery/fuel cell system and focus on power interfaces [6].

Researchers also work on optimization models of HPS, for example [7], and optimal configuration searching, planning and strategy making software for use with renewable energy based distributed power systems. HOMER (Energy Modeling Software for Hybrid Renewable Energy Systems) and HARPSim (Hybrid Arctic Remote Power Simulator) [7] are to be mentioned.

In contrast to previously mentioned work where processes in HPS are studied from physical, energetic, tactical and strategic control perspective this article addresses problems related to design-

time of control systems and in particular to design, testing, debugging and evaluation of supervisory control methods and algorithms.

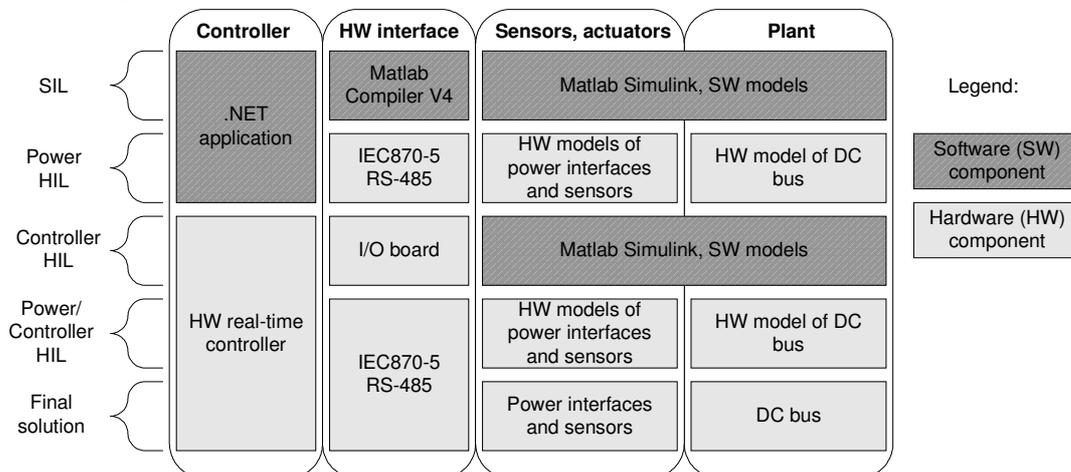
The authors present hardware-software environment based on SIL (Software In the Loop) and HIL (Hardware In the Loop) simulation methods, which have already been applied in the field of renewable energy studies [8; 9]. The environment can be used to evaluate and implement the existing control algorithms for HPS and to design new as well. The discussed approach hypothetically could be used to evaluate control algorithms and strategies for virtually any type and configuration of HPS with required precision, because the configuration, complexity and type of models (virtual simulation, hardware physical model or even off-shelf device) can be easily varied without changes in other parts of the control loop.

**Materials and methods**

In a general case SIL is a software system with closed loops of individual software modules. For feedback control this is a control loop with software implementation of the controller, actuator, plant and sensor. HIL simulation method is where one or more sections of SIL are substituted with a hardware solution. HIL simulation can be divided into two groups: controller and power HIL. In controller HIL hardware implementation of the controller is used, but the rest of the loop is a simulation model. Power HIL assumes plant, actuators and sensors as the hardware part and controller is implemented in software [10].

Classification of SIL and HIL methods for simulation of hybrid power systems based on central DC bus is given in Fig. 1. Specific tools and materials used in the simulation environment presented in this article are depicted, too. The rows summarize and group by methods of simulation and respectively by phases of the development or research all software and hardware components: the first row (SIL) is to be used in the earliest phases of the development and the last row is the final solution. The columns summarize the main parts of a control loop: controller, hardware interface, which handles the signal flow between the controller and the rest of the loop, sensors, actuators and the plant.

The presented environment practically covers the first two phases: SIL and power HIL, but the tools used (Simulink model and hardware DC bus an power interface models) can also be made useful in the next two phases.



**Fig.1. Classification of SIL/HIL methods for simulation of hybrid power systems based on central DC bus**

In the first SIL simulation phase the controller is implemented as MS. NET application. The application is developed in C# language using modified renewable energy equipment class library and algorithms, which are discussed in detail in [11]. DC bus, power interfaces and sensors are modeled in Matlab Simulink. Matlab Compiler V4 tool (Version 4.0 (R14) MATLAB Compiler) from libmx.dll library and UtilityMatlabCompilerVer4.MatlabCSharp wrapper class [12] were used in order to make possible the signal flow between the control algorithm in .NET and the control object in Simulink. The wrapper is originally designed for using only Matlab workspace by executing commands in command prompt. The functionality needed to manage Simulink models was added for the current research.

The simulation environment is shown on an example of HPS based on architecture with all the generators, accumulators and loads connected to DC central bus using power interfaces. The Simulink model of DC bus uses the master-slave parallel-connected voltage and current sources approach discussed in [13]. The bus voltage  $U_{DC}$  is calculated using the sum of current flows from the sinks and sources (1).  $U_{DC}$  is the main process variable of HPS and is affected by the load and distributed generators. The given bus voltage should be kept by supervisory controller in specified limits considering the changing load and available energy resources connected through power interfaces.

$$U_{DC} = \frac{1}{C_{DC}} \int (\sum I_{Gi} - \sum I_{Li}) dt, \quad (1)$$

where  $U_{DC}$  – DC bus voltage;  
 $C_{DC}$  – capacitance of the bus;  
 $I_{Gi}$  – sum of generator currents (sources);  
 $I_{Li}$  – sum of load current (sinks).

In the second phase, HIL simulation, the controller implemented as a .NET application can be evaluated and tested using the scaled physical model of DC bus and its components. The physical models can be implemented with the maximum approximation to final solution thus allowing fine evaluation, testing and debugging the control system in safe controlled environment with minimum funding in the shortest times. For the HIL simulation purposes Buck1 DC converter with step-down architecture and KR100 load switching relay module (4 single pole relays) were used. The devices were developed by the authors for the current research. Both devices are based on PIC24F microcontroller, they are remotely controlled and allow reading telemetry data (instantaneous bus voltage, output current and load configuration) using RS-485 line at 115 kbps as physical communication layer and modified IEC870-5 protocol as data link layer. Main electrical characteristics of Buck1 are summarized in Table 1.

Table 1

**Main electrical characteristics and functions of “Buck1”**

| Characteristic   | Min   | Typ | Max | Unit |
|--|---|-----|-----|------|
| Converter input voltage, $U_{in}$                                | 12  | -   | 25  | V    |
| Converter input current, $I_{in}$                                | 0   | -   | 0.5 | A    |
| Supply voltage, $U_s$  | 11  | -   | 20  | V    |
| Current consumption, $I_s$                                       | 40  | 50  | 100 | mA   |
| Converter output voltage, $U_{out}$                              | 0   | -   | 20  | V    |
| Converter output current, $I_{out}$                              | 0   | -   | 0.5 | A    |
| Operational modes  | Constant $U_{out}$ , constant $I_{out}$ PI controller |     |     |      |
| Controller frequency, $F_{con}$                                  | -   | 1   | -   | kHz  |
| Voltage step response time (2 % setpoint fluctuations), $t_{sr}$ | -   | 5   | -   | ms   |

The next two phases, controller HIL and combined power/controller HIL (Fig. 1) are intended to evaluate, test and debug the hardware controller, which in contrast to .NET software environment can be a hard real-time controller. The last phase depicts components in each part of the loop in a final solution when using the proposed environment in the development of HPS.

## Results and discussion

A test system was developed to demonstrate SIL and power HIL simulation methods in the first two phases according to Fig. 1. The system consists of 3 DC converters and a load block with idle load and additionally configurable 4 load levels. The DC converters each can operate as a voltage or current source and use the master-slave mode to control  $U_{DC}$ . The master converter is controlling constant voltage, but slave current sources compensate load changes thus minimizing the current flow from the master. Calculation of appropriate set-point values for all converters is the responsibility of the supervisory controller of HPS.

Fig. 2 (a) shows a general SIL simulation block diagram using a controller implemented in .NET environment and Simulink model for the rest of the control loop. Fig. 3 shows Simulink model of the discussed system. It contains models of DC bus, 3 DC converters, one idle load and four configurable load blocks (not shown for simplicity). The model uses Input/Output ports for data interchange with Matlab workspace, through which in its turn the data are sent and received to and from .NET application. The application consists of a supervisory controller, class library of DC bus components, UtilityMatlabCompilerVer4.MatlabCSharp wrapper class, graphical user interface and file I/O.

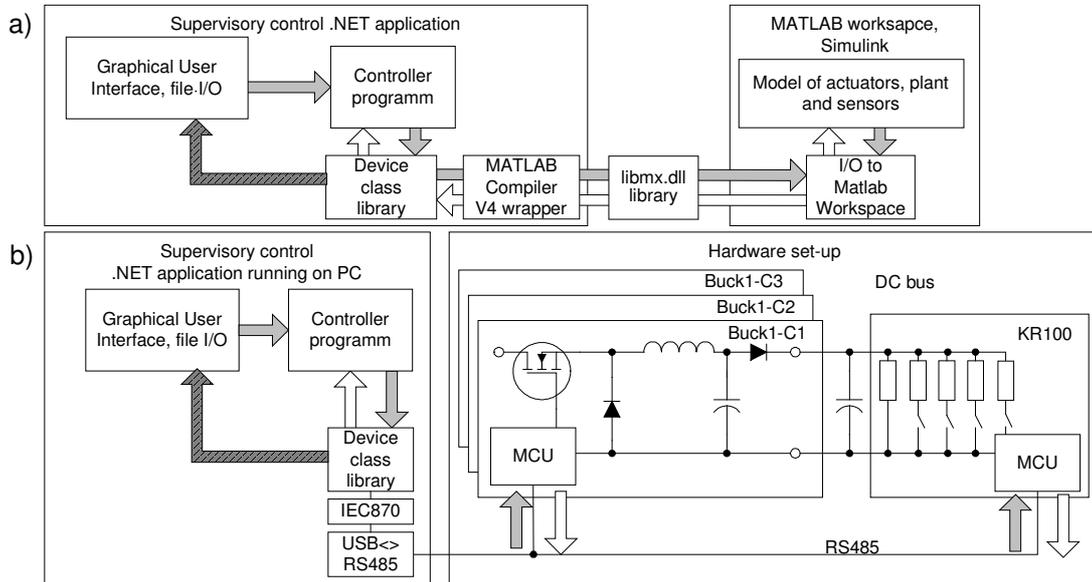


Fig. 2. Experimental system for SIL simulation (a) and power HIL simulation (b): control and perturbations signals ( $\leftarrow$ ), feedback signal ( $\leftarrow$ ), simulation results ( $\leftarrow$ )

The block diagram of power HIL simulation is shown in Fig. 2 (b). It should be pointed out that in realization of the supervisory control system the same .NET class library is used with unified software interfaces for all controllable devices thus the same control algorithm can be used without changes in both SIL and power HIL phases. The supervisory control system with current configuration can poll 3 Buck1 and one KR100 device with a period of 50 ms.

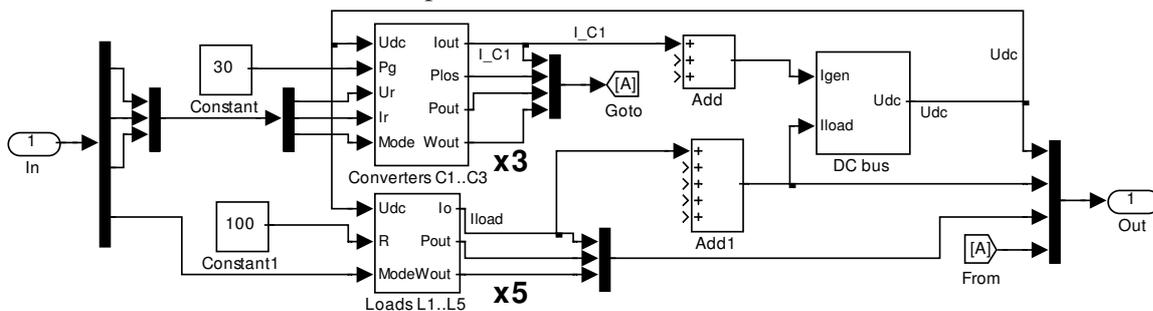


Fig. 3. Simulink model of the DC bus with In and Out ports for SIL interface (only one converter and load block is shown)

The simulation data,  $U_{DC}$  and output current of each converter ( $I_{C1}$ ,  $I_{C2}$  and  $I_{C3}$ ), were gathered in 4 channels from Buck1 readings using .NET application and independently using PicoScope3000 oscilloscope. Fig. 4 shows the experimental set-up of the test system. The SIL and HIL simulation results were compared after execution of various load switching and supervisory control algorithms for converter operation. Fig. 5 depicts both simulation results obtained in Simulink model and in the experimental set-up logged with PicoScope3000 at the period of 22 ms. The following scenario was chosen. The converter C1 is operating in the voltage source mode or bus master maintaining constant  $U_{DC} = 8$  V, but the converter C3 begins to source constant current  $I_{C3} = 150$  mA, if  $I_{C1} \geq 170$  mA, thus decreasing  $I_{C1}$  under increased load condition. The default, non-switchable load in the DC bus is 100  $\Omega$  and it is increased in four steps to 20  $\Omega$  by adding additional 100  $\Omega$  in parallel in each step.

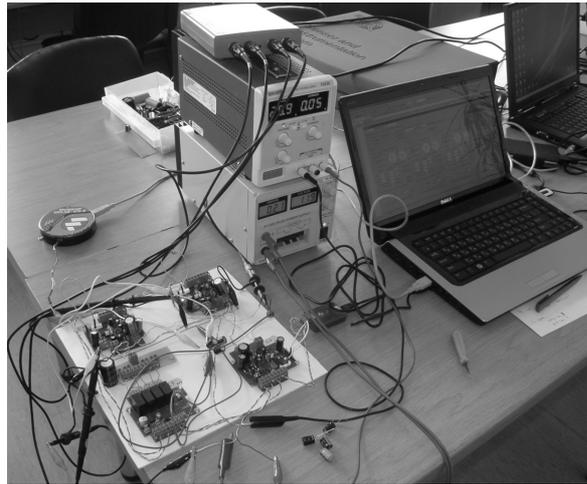


Fig. 4. Experimental set-up

As it can be seen from the graph, C1 keeps constant  $U_{DC} = 8\text{ V}$  in both simulation modes, however, in power HIL simulation a voltage surge of  $16.8\text{ V}$  can be observed as the C3 begins to source current into the bus. The explanation could be that C3 at the moment of switch on charges DC bus capacitor ( $2.2\text{ mF}$ ) and increases the bus voltage. The voltage source drops its output current  $I_{C1}$  to minimum according to its PI regulator settings to decrease  $U_{DC}$  to its reference value of  $8\text{ V}$ , but  $33.3\ \Omega$  load can not discharge the capacitor fast enough. RC time constant in this case is  $\tau = 73.3\text{ ms}$ , but transient according to the graph lasts for approximately  $160\text{ ms}$ . The problem could be solved by calculating an appropriate setpoint for C3 current, increasing the current step response time or giving voltage source the ability to sink current thus operating as additional load ( $I_{C1} < 0$ ). The first method could be preferable to avoid unnecessary losses. The transient is not observable in Simulink model, because DC converters are modeled as non-inertial voltage and current sources.

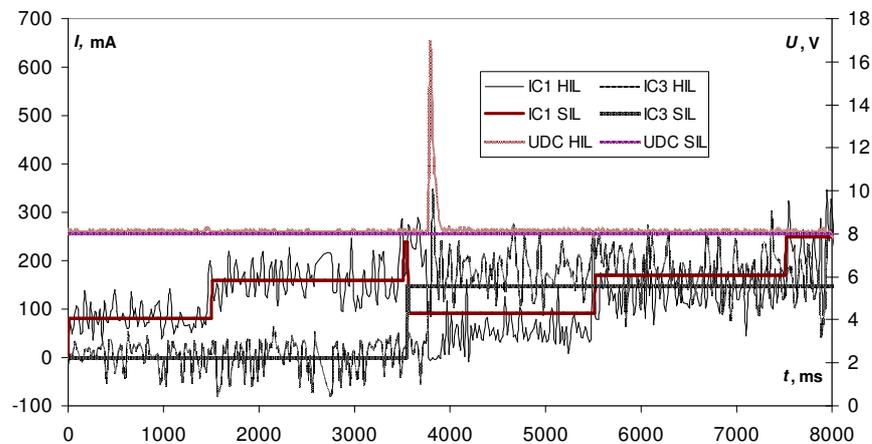


Fig. 5. Results of power HIL simulation

At the load of  $100$  and  $50\ \Omega$  when only C1 is operating results in both simulation modes differ insignificantly, respectively:  $I_{C1}^{SIL} = 79.9\text{ mA}$ , average  $I_{C1}^{HIL} = 82.1\text{ mA}$  and  $I_{C1}^{SIL} = 159.7\text{ mA}$ , average  $I_{C1}^{HIL} = 162.9\text{ mA}$ . Differences in static state become significant when C3 is turned on at the load of  $33.3$  and  $25\ \Omega$ , respectively:  $I_{C1}^{SIL} = 90.5\text{ mA}$ , average  $I_{C1}^{HIL} = 59.5\text{ mA}$  and  $I_{C1}^{SIL} = 170.1\text{ mA}$ , average  $I_{C1}^{HIL} = 138.7\text{ mA}$ , but  $I_{C3}^{SIL} = 149.2\text{ mA}$  and average  $I_{C3}^{HIL} = 182.6\text{ mA}$  (the same for both load levels). This is explained by a problem with Buck1 converter current feedback circuit: it is not linear in the whole range ( $0..0.5\text{ A}$ ) and is calibrated at  $100\text{ mA}$ , but at the setpoint of  $150\text{ mA}$  sources  $30\text{ mA}$  more. As a result C1 also needs less current to keep  $8\text{ V}$  in the bus. The  $140\text{ ms}$  delay in HIL mode before C3 begins sourcing current into the bus is introduced by the converter output capacitor, which is charged in the given time.

It should be noted that the proposed evaluation environment where supervisory controller is implemented as .NET application is a soft real-time system and controller response delays over the

defined 50 ms period may occur, but taking into consideration low dynamic of DC bus when using capacitors or directly connected accumulators and individual hard real-time controllers of power interfaces such approach could be successfully used in testing, debugging and evaluation of supervisory control systems for central DC bus based HPS. On the other hand at the SIL phase thanks to the possibility to stop simulation of Simulink model at any time to wait for the controller response, the delays introduced by .NET environment do not affect results of the simulation.

### Conclusions

1. Overview of application SIL and HIL in various phases of the research and development of supervisory control systems for HPS has been given and common hardware and software testing, debugging and evaluation environment has been developed.
2. The current research focuses on SIL and power HIL methods, but the offered tools can also be used in controller HIL simulation.
3. The proposed environment relies on supervisory controller implementation as MS .NET application, which is not hard real-time system and in power HIL mode allows to perform supervisory control and monitoring of 4 complicated devices and 4 process variables with 50 ms period. Performance is enough for operation of the scaled physical model of hybrid power system based on common central DC bus with varying load.
4. In SIL mode when the actuators, plant and sensors are simulated in Simulink delays of .NET application do not affect the performance of the controller.

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