

Model Based Design and Hardware in the Loop Testing in Power Electronics Courses

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Abstract – In this paper a low cost virtual test bed for educational purposes is developed and tested. Hardware-In-the-Loop (HIL) design concept as an experimental part of power electronics is considered. Software simulations lead to develop control of the studied system. Before a real-time implementation of the control, HIL simulations could be a very useful intermediary step. Thus a hardware device is introduced in the loop in order to take its real constraints into account. Used equipment is general purposes and can be utilized for controller implementation as well as virtual plant model. Simulations are performed under different conditions and results are presented graphically using virtual instruments on the designed front panels.

Keywords – Hardware in the loop, Power Electronics, DC/DC converters, Buck Converter.

1. Introduction

Systems are created to solve problems. One can think of the systems approach subject System Analysis and Design, mainly deals with the software development activities. System development life cycle means combination of various activities. In other words we can say that various activities put together are referred as system development life cycle, Fig. 1.

Due to the rapid development of digital-processor technology, embedded control systems (from now on simply called electronic control systems - ECS's) control many devices we use in our everyday life. Moreover, many of these systems operate in safety-critical situations and therefore call for rigorous engineering. This crucial point is the reason why so much research effort is put into the development of methodologies for the design, development, and implementation and, in our case, testing of ECS. In developing such products and systems, the testing and not the design usually is the more expensive, time-consuming and difficult activity [1]. Hardware-in-the-Loop simulation (from now on called HIL simulation or HIL's) is a kind of real-time simulation where the input and output signals of the simulator show the same time dependent values as the real process with various dynamic performance [2]. Such simulators allow us to test the real embedded control system (ECS) [3, 4] under different real working

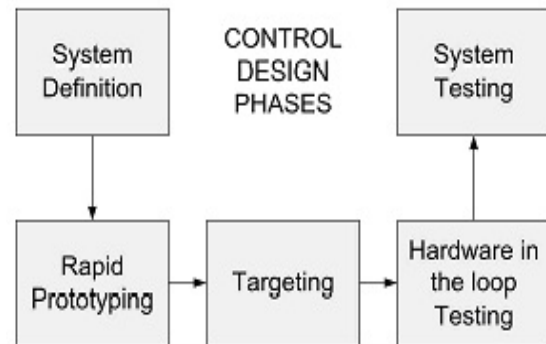


Figure 1. System Development Life Cycle.

loads and conditions. Other simulation methods do not allow us to test the real embedded control system as a complete system. Often the controller part, which is only about 20-30 % of the ECS software, or the software components are tested independently. HIL's makes it possible to test the complete ECS. Moreover, the temporal logic tester and the fault generator allow us to automate the testing procedure, which otherwise is done manually by an operator.

The original motivation behind constructing laboratory scale models of power electronic circuitry was to offer the students an environment for a complete engineering design, starting from modelling and simulation and ending with the experimental verification of a wide range of design strategies. A typical integrated real-time control and simulation environment contains three main parts: analysis and simulation software, a target controller and an experimental set-up. The software includes controller design/analysing tools, real-time code generators and a compiler. The target hardware can be based upon DSP techniques or other low-cost alternatives such as PC-based controllers or microcontrollers can be used.

Usually the costs of the first two components are much lower in comparison with the costs of the experimental setup. Capturing the realism of power electronics problems requires a complex power converters, both costly and inflexible, in some cases potentially dangerous for the students.

The concept of "hardware-in-the-loop" (HIL) method is to use a simulation model of the process and the real target hardware. The simulation model provides all the process signals in real-time that are

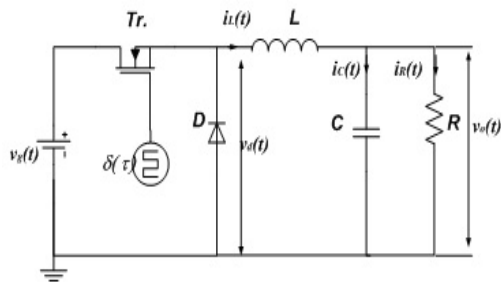


Figure 2. Buck Converter.

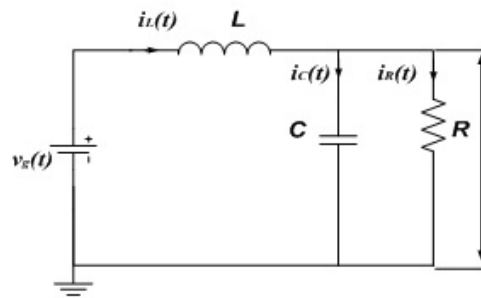


Figure 3. On State - Buck Converter.

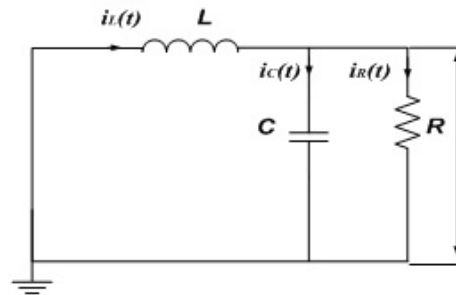


Figure 4. Off State - Buck Converter.

next converted by D/A modules and supplied to the controller as voltages. The control signals are produced by the controller and supplied via A/D converters to the simulation model. It is the purpose of this configuration to make the hardware component behave as closely as possible to these that would be encountered in the real system.

The paper is organised as follows. In the next section an overview of the different models of DC – DC converters is given. Section three and four presents the mathematical model development and its implementation to the simulation hardware utilizing LabView development environment [5]. Results of simulation are commented in section five.

2. DC/DC Converters overview

DC/DC converters are widely used in industrial applications and computer hardware circuits [6][7]. DC/DC conversion technique has been developed very quickly.

Buck converter is a step-down converter, which is shown in Fig. 2, the equivalent circuits during switch-on and -off periods are shown in Figs. 3 and 4. Its output voltage and output current are

$$V_2 = DV_1 \quad (1)$$

and

$$I_2 = \frac{1}{D} I_1 \quad (2)$$

This converter may work in discontinuous mode if the frequency f is small, conduction duty D is small, inductance L is small, and load current is high.

3. Model based design

In Model-Based Design there would be a system model at the center of the development process. The significant feature of this design is that it facilitates quicker and more cost-effective development of dynamic systems.

Modeling is the representation of physical phenomena by mathematical means. In engineering, it is desired to model the important dominant behavior of a system, while neglecting other insignificant phenomena. Simplified terminal equations of the component elements are used, and many aspects of the system response are neglected altogether, that is, they are "un-modeled". The resulting simplified model yields physical insight into the system behavior, which aids the engineer in designing the system to operate in a given specified manner.

Converter systems invariably require feedback. For example, in a typical DC-DC converter application, the output voltage $v(t)$ must be kept constant, regardless of changes in the input voltage or in the effective load resistance R . This is accomplished by building a circuit that varies the converter control input, i.e., the duty cycle $d(t)$, in such a way that the output voltage $v_o(t)$ is regulated to be equal to a desired reference value. To design the system of Fig. 2, we need a dynamic model of the switching converter. How do variations in the power input voltage, the load current, or the duty cycle affect the output voltage? What are the small-signal transfer functions? To answer these questions, we will extend the steady-state models to include the dynamics introduced by the inductors and capacitors of the converter.

Without loss of generality to explain the procedure of model development in LabView environment a simplified circuitry is utilized. Simplifications are performed in the load circuit where a resistive load is

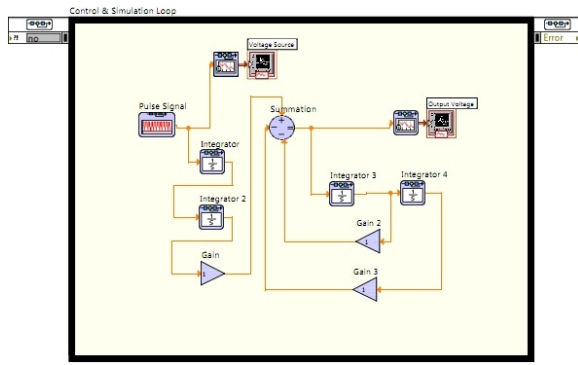


Figure 5. Block diagram model based design of converter.

supported. For model development a circuit on Fig. 2 is used.

Fig. 2 shows principal circuit of buck converter consisted of ideal elements. Steady state is reached and, therefore, the control signal, $\delta(t)$, consists of pulses with constant width. The time intervals where the control signal $\delta(t)$ is high are called t_{on} and the once where $\delta(t)$ is low are called t_{off} . The switching period, T_s , is the time between two successive positive flanks of $\delta(t)$ and hence equal to the sum of t_{on} and t_{off} . The ratio of t_{on} to T_s is called the duty cycle or the duty ratio and it is denoted by $d(t)$. The duty cycle is constant in steady state and equal to D (the dc value of $d(t)$). During t_{on} the transistor operates in the on state and during t_{off} the transistor operates in the off state. The voltage across the diode, $v_d(t)$, is equal to the input voltage, $v_g(t)$, during t_{on} and equal to zero during t_{off} . The diode voltage is filtered by the $L - C$ low pass output filter. The corner frequency of this filter is chosen to be much lower than the switching frequency to obtain small magnitude of the ripple in the output voltage, $v_o(t)$. Consequently, the output voltages is approximately equal to the mean value of the diode voltage and lower than $v_g(t)$. The voltage across the inductor, $v_L(t)$, is equal to the difference between $v_d(t)$ and $v_o(t)$. During each time interval, the slope of $i_L(t)$ is almost constant since $v_L(t)$ is almost constant. The inductor current is equal to the transistor current, during t_{on} and equal to the diode current, during t_{off} . The capacitor current, is equal to the difference between $i_L(t)$ and the load current. The mean value of capacitor current is zero in steady state. The converter can be described as switching between different time invariant systems and is subsequently a time-variant system. While the transistor is on, the voltage across the diode is equal to the input voltage, as shown in Fig. 3.

The circuit in Fig. 3. can therefore be used as a model of the buck converter during t_{on} .

While the transistor is off, the voltage across the diode is equal to zero and the circuit in Fig. 4. can be used as a model.

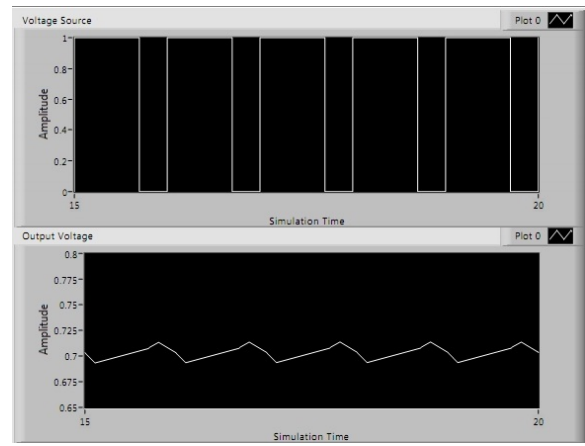


Figure 6. Simulation diagrams.

In this paper O_n state and O_{ff} state model is considered as the same circuit where $v_g(t)$ is a pulse train ideal voltage source. Inductor current can be the sum of capacitor current and load current, as follow,

$$i_L(t) = i_C(t) + i_R(t) \quad (3)$$

Therefore inductor current and voltage relation can be expressed as:

$$v_L(t) = L \frac{di_L(t)}{dt} = v_g(t) - v_o(t) \quad (4)$$

$$i_L(t) = \frac{1}{L} \int (v_g(t) - v_o(t)) dt \quad (5)$$

Replacing the expressions for capacitor and load current

$$i_C(t) = C \frac{dv_C(t)}{dt} = C \frac{dv_o(t)}{dt} \quad (6)$$

$$i_R(t) = \frac{1}{R} v_R(t) = \frac{1}{R} v_o(t) \quad (7)$$

in equation 3 we obtain

$$\frac{1}{L} \int (v_g(t) - v_o(t)) dt = C \frac{dv_o(t)}{dt} + \frac{1}{R} v_o(t) \quad (8)$$

If the expression (8) is multiplied with $1/C$ both side and integrated

$$\frac{1}{LC} \int \left(\int (v_g(t) - v_o(t)) dt \right) dt = v_o(t) + \frac{1}{RC} \int v_o(t) dt. \quad (9)$$

Different arrangement of expression is presented as

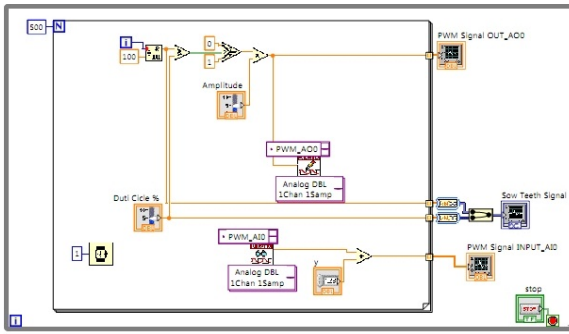


Figure 7. Block diagram of PWM signal generating device.

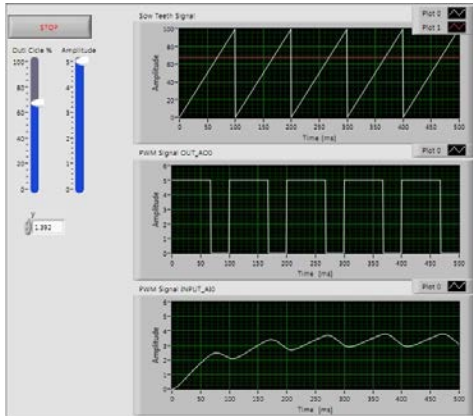


Figure 8. Front panel of PWM signal generating device.

$$v_o(t) = \frac{1}{LC} \int \left(\int (v_g(t) - v_o(t)) dt \right) dt - \frac{1}{RC} \int v_o(t) dt \quad (10)$$

or

$$v_o(t) = \frac{1}{LC} \iint v_g(t) dt dt - \frac{1}{LC} \iint v_o(t) dt dt - \frac{1}{RC} \int v_o(t) dt. \quad (11)$$

Equation (11) containing integrals and differentials can be presented by the LabView block diagram in on the Fig. 5. Simulations are performed on normalizes values of components of the system and results are presented on the Fig. 6.

4. Test bed design

The core platform of the presented hardware-in-the-loop approach is the Virtual Test Bed (VTB). The VTB is a dedicated environment for simulation and virtual-prototyping of complex systems. The VTB allows for handling natural power flow, signal and data coupling between interconnected devices and offers a combination of both topological and

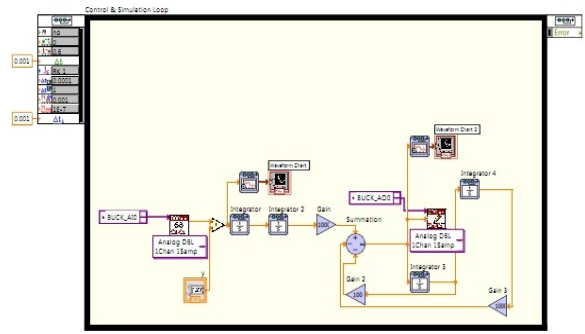


Figure 9. Block diagram of BUCK Converter Model.

mathematical expressions in model formulation for a comprehensive and efficient modeling process. The VTB also supports multiple-layer modeling, wherein each layer can describe a different model complexity or a different behavior. In addition to the powerful capabilities for modeling, the VTB is endowed with mechanisms for both wrapping and co-simulating with models developed in LabVIEW.

A. Controller design

LabView environment is very powerful tool for model design and simulation. To operate with buck converter a Pulse Width Modulated (PWM) signal is required. The Fig. 7 shows simplified model for PWM signal generation.

Pulse width modulated signal can be obtained by a comparison of instantaneous value of saw-tooth signal and referent voltage. Varying the referent voltage the result is the difference between t_{on} and t_{off} , resulting the different duty cycle.

Accompanying front panel to block diagram above is presented on Fig. 8. The diagram on the top of the front panel window shows the comparison between saw-tooth signal and referent voltage. The graph in the middle represents the pulse width modulated signal. The graph at the bottom will be used in the simulation to show the feedback signal generated by the plant model.

B. Virtual Plant Design

Developed Buck converter model is realized utilizing National instruments I/O modules for acquiring and generating analogue signals, Fig. 10. The equipment is further used for behavior testing of prototype of the buck converter governor realized by the I/O modules too. Utilizing the equation 11 obtained earlier the resulting plant model is as follows

Accompanying front panel is presented on the Fig. 11. The diagram on the top represents the excitation pulse width modulated signal at the input of the model. The second diagram represents the output voltage of virtual model of the buck converter.

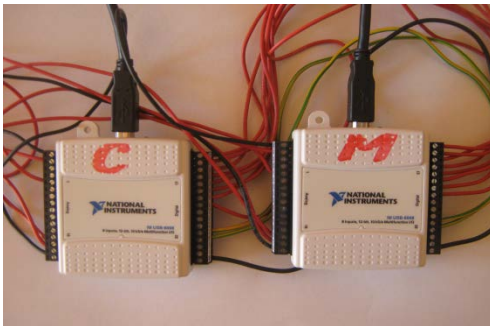


Figure 10. Virtual Test Bed Hardware.

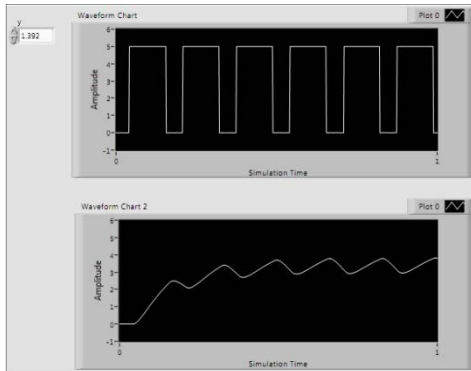


Figure 11. Front panel of BUCK Converter Model.

That output voltage can be returned back to the controller as a feedback control signal for regulation purposes.

C. Controller under test

Buck converter controller algorithm implemented in the I/O National instruments module equipped with digital inputs and outputs as well as analogue inputs and outputs. National instruments I/O module is HIL testing equipment where a buck converter model is implemented and is connected to the controller ports, Fig. 10.

Hardware-in-the-loop (HIL) simulation provides an effective platform by adding the complexity of the plant under control to the test platform. The complexity of the plant under control is included in test and development by adding mathematical representation of all related dynamic systems. These mathematical representations are referred to as the plant simulation. Hardware-In-the-Loop differs from real-time simulation by the addition of a real component in the loop. Plant model should run in real-time, electrical interfaces of the controller are

emulated; control model is converted to controller code.

5. Conclusion

HIL simulation reduces development time and enables various tests that cannot be achieved on the actual system for cost or security reasons (fault operation for instance). "Signal level HIL simulation" is very often used in industry to check controller boards and process controls. Its "power level" and "mechanical level" extensions are growing because they are a promising intermediary step before integration of electric drives in actual systems. Because of the increasing complexity of the systems under test, the organization of the HIL simulator is of prime importance to assess the best performance.

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