

Evaluation on the capabilities of MATLAB Simulink's Embedded Coder for rapid prototyping of micro-controller based control systems for switching converters.

Thilo Steinbock^{*} Clemens Kerssen[†]

^{*} Research Assistant at Science Center for eMobility, power electronics and decentralized energy supply (EMLE), University of Applied Science Lübeck, thilo.steinbock@stud.th-luebeck.de

[†] Head of Science Center for eMobility, power electronics and decentralized energy supply (EMLE), University of Applied Science Lübeck, clemens.kerssen@th-luebeck.de

Abstract

Switching converters play a crucial role in modern power electronics, offering efficient voltage conversion in various electronic devices. This paper presents an approach to the rapid prototyping for micro-controller based control systems, applied to the buck-converter topology. The methodology utilized features from MATLAB Simulink and its Embedded Coder extension to model and implement the control system, enabling a simplified transition from simulation to hardware implementation. For this purpose the paper evaluates two control systems, namely the error-amplifier and the PID controller. Comparative analysis reveals insights on the startup behavior, RMS voltage, peak-to-peak voltage and maximum voltage. While the simulation outperformed the measurements of the hardware implementation in most parts, this paper still underscores the utility of MATLAB Simulink's Embedded Coder for rapid prototyping and hardware-in-the-loop development of switching converter control systems.

1 Introduction

In this paper the rapid prototyping for a micro-controller based buck-converter control system is described. For this a preexisting hardware implementation is portrayed in a MATLAB Simulink model. On top of this model the control system for a buck-converter topology is implemented. To compare the simulation and a real world implementation, the control system is run on an STM32 development board. Results of the simulation and measurements are compared and evaluated, leading to a conclusion, if the process of using Simulink simulations and the Embedded Coder extension is fit for rapid prototyping in this field.

2 Material and Methods

Starting point for the control system is a buck-converter board designed by the author. This board is a minimal implementation of a DC-DC buck-converter, consisting only of the absolutely necessary parts. The simulations are performed using MATLAB Simulink, while utilizing parts from the Simscape library.

The Embedded Coder extension for Simulink is used, to bring the control system into the real world. It generates corresponding C or C++ code from the simulation

model, that can be run on a variety of micro-controllers and development-boards.

In this paper the STM32 NUCLEO-144 H743ZI2 development board from ST Microelectronics is used. The board consists of an STM32 micro-controller, a ST-Link debugger, I/O-ports and all necessary peripherals. The STM32 platform was chosen, because it is widely used and a lot of resources are available for development. This board is supported in the Embedded Coder extension.

3 Implementation

3.1 Simulation

To create a simulation, both the principle of a buck-converter and the specific aspects of a Simulink simulation have to be taken into consideration. Fig. 1 shows the schematic of the buck-converter.

Main parts of the buck-converter are the inductor (L2), the capacitor (C1), the diode (D1) and the P-channel MOSFET (Q2). A P-channel MOSFET was chosen to reduce the overall component count. Using an N-channel MOSFET in this application would require a high-side driver along with additional supporting components, increasing circuit complexity. All these components are represented in Simulink

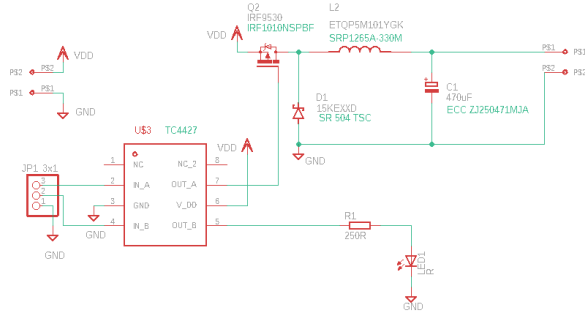


Figure 1: Schematic of the buck-converter

with the corresponding models. Symbol U\$3 is a TC4427 MOSFET driver IC. In Simulink, the buck-converter is represented from a system perspective. There is no need to transfer the MOSFET driver IC into the simulation model. This is due to the fact, that the MOSFET model in Simulink takes a binary signal to be turned on and off. Electrical characteristics for driving the gate of the MOSFET don't have to be taken into consideration.

R1 and LED1 also don't have to be taken into consideration. The LED's only function is to give a status feedback of the condition of the buck-converter. The resistor R1's purpose is to limit the current for the LED. Both are left out of the simulation, because the status of the buck-converter can be seen in Simulink directly using displays, scopes or the Simulink Data Inspector.

All input and output connectors are also ignored, because electrical connections are done in the simulation itself. Lastly a load of $10\ \Omega$ is implemented at the output of the buck-converter.

Table 1 summarizes all the parts, that are implemented in the simulation.

After implementing all the components as their respective Simulink blocks, the simulation model can be seen in Fig. 2

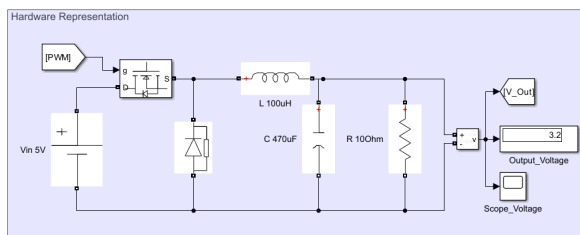


Figure 2: Simulink model buck-converter

All electrical components are represented using blocks from the 'Specialized Power Systems' section of the Simscape Electrical library in Simulink. The capacitor, inductor, input voltage source and load are all represented as ideal components. The MOSFET is modeled as a generic component and is not N- or P-Channel specific. The MOSFET and the diode have non ideal properties, which are predefined in the simulation blocks. Based on the data sheet specifications, the forward voltage of the diode has been set to 0.55 V. Lastly, the output voltage is measured and displayed.

The most simplistic approach to a closed-loop control system is the error-amplifier [1]. This control method is implemented, by defining a target voltage and subtracting the measured output voltage of the simulated buck-converter from it. The value after the subtraction can either be taken directly, or be modified with a constant gain (This modification makes the error-amplifier into a proportional controller.

In the following it will still be termed an error amplifier). After this, the saturation of the control system is limited, from 0 to 1. This is necessary, because the value represents the duty cycle in the following parts of the control system. A value greater than 1 indicates a duty cycle greater than 100%, which is not a valid value. After this step, the duty cycle is used in a PWM generator to create a signal for switching the MOSFET in the simulation.

For a more sophisticated control system, instead of the error-amplifier, a PID controller is used to generate the duty cycle. Simulations for both approaches are now able to run and will compared in Section 4. The initial values for the PID controller were derived from Young, "PID Parameter Tuning for Buck Controllers Based on an Improved Differential Evolution Algorithm" [3]. The initial Values are Proportional = 0,020015, Integral = 35 and Differential = $1e-6$. The input voltage of the buck-converter is 5 V and the switching frequency of the PWM for the MOSFET is 30 kHz.

3.2 Hardware Implementation

As explained, the hardware implementation consist of the buck-converter board and a STM32 NUCLEO-144 H743ZI2 development board. Both are connected using suitable GPIO pins. To ensure safe operation of the development board, the output voltage of the buck-converter can not be measured directly, but needs an additional voltage divider circuit. This voltage divider has to be compensated inside the control system by multiplying with a constant value. The power for the buck-converter is supplied by an external power supply. For communication between the development board and Simulink a USB connection to a PC is used.

A second Simulink model is created, in which the control system from the previous simulation is copied. To control hardware with this control system, the existing signals are used, while the simulated buck-converter is deleted. Blocks from the Simulink Coder Support Package for STMicroelectronics Nucleo Boards [2] replace previously existing blocks and/or connections. The previously used PWM Generator is replace by a PWM Output, which is specific for the development board. The measurement of the output voltage can't be taken directly from the model anymore. Instead a Analog Input block is used. The pin defined in this block is connected to the voltage divider circuit. The analog input pin has a maximum voltage of 3.3 V. To get the voltage of the input pin of the analog input it's value is multiplied by 3.3. Additionally the ration of the voltage divider needs to be taken into consideration to get to the corrected output voltage of the buck-converter

Nr.	Type	Partnumber	Description
1	MOSFET	IRF 9530	P-Channel, -100 V, -12 A, $R_{DS(on)} = 0.3 \Omega$, TO-220AB
2	Diode	SR 504 TSC	Schottky, 40 V, 5 A, DO-201AD
3	Capacitor	ECC ZJ250471MJA	Electrolytic, 470 μ F, 25 V, 105 °C, Low ESR, 10×10 mm
4	Inductor	PAN ETQP5M101YGK	SMD, Power Inductor, Iron Powder Core, 100 μ H
5	Resistor/Load	VIS 5296	Ceramic, 10 Ω

Table 1: Complete Parts List with Specifications

All connections have been implemented and the previously used control systems are uploaded with the use of the Hardware Support Package. Using the "Monitor & Tune" function, live feedback of the running hardware implementation is used to get a first impression on the workings of the control system.

4 Comparison

For comparison of the simulation and hardware implementation, both are run with the error-amplifier and the PID control system. Values for the simulation are taken directly from the model and measurements from the hardware implementation are obtained using the "Monitor & Tune" function and the Data Inspector of Simulink. Furthermore the collected data is exported to the MATLAB workspace for further evaluation.

The startup-behavior and average values over a time frame of 10 seconds are compared in the following. Fig. 3 shows the startup voltage of both simulations and measurements.

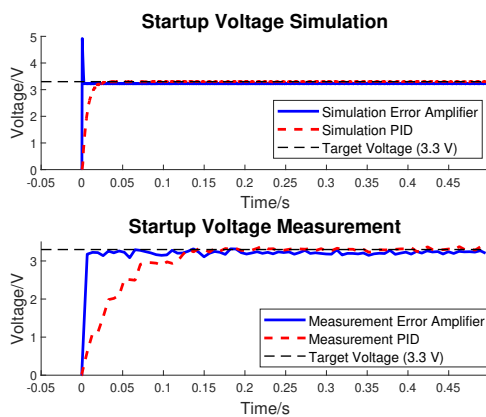


Figure 3: Comparison of startup Voltages

The results show a shorter startup time of the simulations compared to the measurements. Furthermore, the error amplifier has a faster rise up of the voltage, both in simulation and measurement. The simulated error amplifier shows a significant overshoot on startup. In an actual implementation a soft-start should be implemented to prevent this overshoot at the cost of the fast startup time.

The values shown in Table 2 are calculated after a startup time of 1 s to ensure that the startup voltages don't interfere with the calculations for the running operation.

Type	RMS/V	Vpp/mV	Max. V/V
Sim. Err. Amp.	3.228	23.30	3.241
Sim. PID	3.300	43.83	3.320
Measure. Err. Amp.	3.219	356.81	3.646
Measure. PID	3.299	257.51	3.429

Table 2: Measurements after startup

The RMS voltage of the error amplifier control system doesn't reach the target value. This is shown in both the simulation and measurement. The simulated PID controlled system reaches the exact target RMS voltage down to the 3rd decimal point in the simulation. The measured RMS voltage has an error from the target of only 1 mV.

For the Vpp (voltage peak-to-peak) both simulations get lower values than the measurements. The simulated error-amplifier gets a Vpp of 23.30 mV and the PID controller 43.83 mV. In the measurements the PID controller outperforms the error-amplifier with a ≈ 100 mV lower Vpp.

The maximum reached voltage in the measurements of the error-amplifier is ≈ 200 mV higher than the PID controllers.

5 Conclusion

Section 4 shows, that the simulations consistently had better results than the measurements. This was both seen in the faster startup behavior in the simulation and the calculated voltages during the running operation. The only exception from this is the overshoot on startup of the simulation using the error-amplifier.

To now evaluate, if MATLAB Simulink is suitable for the rapid prototyping of micro-controller based control systems for switching regulators, we will first look at the possibility of deriving hardware from only the simulation. Following that will be an evaluation on the use of MATLAB Simulink's Embedded Coder together with the used STM32 development board as a HIL (hardware-in-the-loop) system for development.

Taking into consideration, that the simulation for the most part had better results than the measurements we have to look critically at the possibility to derive hardware directly from a MATLAB Simulink simulation. The general working principle of switching converter circuit can be represented sufficiently in the simulation. Both control systems could be implemented and evaluated in the simulation, with each one delivering vastly greater results than the measurements.

Here we have to take into consideration, that our simulation is a mix out of ideal and generic components. Parasitic resistance, capacitance and inductance have not been taken into consideration for the capacitor, inductor and ohmic-load in the simulation. The simulated diode and MOSFET have non-ideal characteristics, their values have not been modified fully after the used components in the scope of the simulations. Furthermore the layout of the buck-converter on the PCB has not been taken into consideration. Correct layout and power integrity have to be considered while designing switching converters and can have a tremendous effect on functionality [4]. It is expected, that implementing these non-ideal characteristics would lead to a more detailed simulation outcome. Also the drive circuitry of the MOSFET, in this case the TC4427 low-side gate driver has not been modeled in Simulink, because the Simulated MOSFET only takes an input signal of 1 or 0 (on or off) and does not consider voltages or currents.

Taking the previously explained deficits of the simulation into consideration, we can come to a conclusion for deriving hardware from the simulation. General working principle of a switching-converter can still be tested and necessary components for our hardware implementation can be defined. On top of this we need to design the drive circuitry outside of the simulation. Seeing that the PID controlled system had better results than the error-amplifier in the simulation we can get an estimate for sizing our micro-controller for driving the converter.

For evaluating the use of MATLAB Simulink's Embedded Coder, we were able to see several advantages during the design of the control system. Firstly, the control system could be designed while not having hardware to test on. Different control systems can be evaluated, while hardware is still in production or is not available. During testing on the hardware we can use Simulink and our micro-controller as a HIL system. Utilizing the "Monitor & Tune" feature of the Embedded Coder, we can modify parameters of the control system during runtime of the hardware. Furthermore we can see measured values from the micro-controller with Simulink's Data Inspector live. In practice this gives us the possibility, to adjust the values of the PID controller live and evaluating the results immediately.

Summarizing the previous points, we see that the use of MATLAB Simulink holds some deficits. It still gives the possibility to test circuits and control systems before the implementation of hardware.

Using the Embedded Coder's features speeds up development and tuning of our control system, without the need of additional measuring equipment.

Acknowledgement

This work was carried out at the Science Center for eMobility, Power Electronics, and Decentralized Energy Supply (Wissenschaftszentrum für Elektromobilität, Leistungselektronik und Dezentrale Energieversorgung (EMLE)), within the Department of Electrical Engineering and Information Technology at Technische Hochschule Lübeck (University of Applied Sciences Lübeck).

This paper was originally written as part of the 'Scientific Project' master's course in the Applied Information Technology program in February 2024. It was revised in February 2025.

Author's Statement

Authors state no conflict of interest.

6 References

- [1] KM Sudharshan and BP Divakar, "Design and Simulation of Error Amplifier used in Power Management chips", in *[International Journal of Recent Technology and Engineering (IJRTE) ISSN: 2277-3878 (Online), Volume-8 Issue-4]*, [2019], pp. [2123-2124].
- [2] MathWorks Embedded Coder Team, "Embedded Coder Support Package for STMicroelectronics STM32 Processors", in *[https://de.mathworks.com/matlabcentral/fileexchange/43093-embedded-coder-support-package-for-stmicroelectronics-stm32-processors]*, [2023].
- [3] YJ Zhao, QX Qiu, Zhao1, "PID Parameter Tuning for Buck Controllers Based on an Improved Differential Evolution Algorithm" in *[Journal of Physics: Conference Series]*, [2021], p. [5].
- [4] W. Belloumi, A. Bréard, J. B. H. Slama, and C. Voltaire, "Impact of Layout on the Conducted Emissions of a DC-DC Converter Using Numerical Approach", in *[15th International Multi-Conference on Systems, Signals & Devices (SSD)]*, [2018], pp. [287-291].