Practical Buck DC/DC Converter Theoretical and Experimental Evaluation

Tsveti H. Hranov[1], Nikolay L. Hinov[1] and Adriana L. Lilova[1]

Abstract – **In this paper is presented the study of a buck DC/DC converter via mathematical modelling and then a comparison is made against experimental studies via electronic EVM board. The main goal is to evaluate the feasibility of the model for studies, related to the verification of the design and operating regimes of buck DC/DC converters. The EVM allows for change of the circuit elements, hence the parameters of the DC/DC converter and by studying their influence, it can be concluded how that affects the steady-state operating regimes. By using model-based evaluation one can view the study as a useful tool in design stage for taking decisions about the building blocks and components, which will be used in the design. The study can also be very useful for students and trainees to verify the influence of the passive filters in the converters.**

Keywords – **Buck DC/DC converter, model-based design, mathematical modeling, passive filters, education.**

I. Introduction

The quality of life of modern society is directly related to electrification. This means, on the one hand, ensuring the ever-increasing needs for electrical energy, and on the other, preserving the ecological balance in nature. In this sense, power electronic devices and systems are an important tool for sustainable development. They are applied in cases where it is necessary to manage energy flows or to implement a certain electronic device or system. In this regard, DC-DC converters have established themselves as the most widely used electronic power converters. In recent years, there has been a significant interest in research in this area, and this is related to the significant number of scientific publications devoted to their modeling, design, analysis, optimization and prototyping. On the other hand, guaranteeing the performance of DC-DC converters is also related to improving their performance and reliable operation. Guaranteeing the indicators does not only make technical sense from the point of view of achieving a quality end product, but also has a significant economic and environmental impact. This is due to the strong connection between energy saving and rational use of resources, which is an important requirement in the modern world. Therefore, it is very important to evaluate the influence of the tolerances of the circuit elements and the quality of the individual circuit components on the dynamics and stability of the device in order to make an appropriate decision on what kind of components to choose in the design and prototyping. In addition, such research helps to automate the design process of electronic power converters, which is of great importance to fully satisfy the ever-increasing demands of the modern market.

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The purpose of the present work is to study the impact of changing the parameters of the passive elements on the characteristics of a DC-DC converter. Model-based optimization is used to ensure device performance. To describe the effect caused by the parasitic elements in the power circuit, a specialized mathematical model of the DC-DC converter, implemented using linear ordinary differential equations, has been developed. [1] A simulation analysis of the output voltage of the device was then performed, while varying the parasitic values of the passive components in a manner that was determined to be normal by the manufacturer. The initial values of the circuit elements are obtained by analyzing an existing experimental board design. This experimental board is specially designed to evaluate the influence of passive elements on the operating modes of the converter. Finally, a comparison and analysis of the experimental and simulation results of the output voltage of the converter is made. With the help of this comparison procedure, new studies can be carried out and with the results obtained an evaluation of the behavior of the transducer has been carried out. The comparison of optimized and non-optimized designs demonstrates the benefits of using model-based optimization in the device design and prototyping process.

II. Buck converter model-based evaluation

A DC-DC step-down converter is a power electronic device that converts one DC voltage to another DC voltage of lower value. One of the most commonly used types of output voltage regulation methods in Buck DC-DC converters is a PWM controller. This type of converter uses a controllable switch, an inductance, and a filter capacitor to convert the input voltage.

The principle of operation of the power circuit is as follows: at the beginning of the period, the switch is closed and the current begins to flow through the inductance, charging it with energy. The switch then opens (with the transistor turn-off) and the charged inductance transfers its energy to the output of the converter. Due to the switch-mode operation of semiconductors devices, very high efficiencies are achieved, often over 95%, making them useful for tasks such as: powering LED lighting, home and industrial electronic appliances, and voltage regulation in photovoltaic generator systems.

Buck DC-DC converters typically operate in the switching frequency range of semiconductor devices from 100 kHz to several MHz. The higher switching frequency allows the use of inductors and capacitors with smaller values and correspondingly smaller sizes, but also increases the losses in the circuit due to the more frequent switching of the elements.

A. Design approach

The present study is based on a synchronous step-down converter shown in Figure 1. The power circuit is composed of the following elements: an inductance L with its active loss resistance R_L, a filter capacitor C_0 (its internal resistance is neglected), a load R, T_1 and T_2 are transistors with their switch-on-state active resistance R_{ON}. Anti-phase control pulses are used to control the transistors).

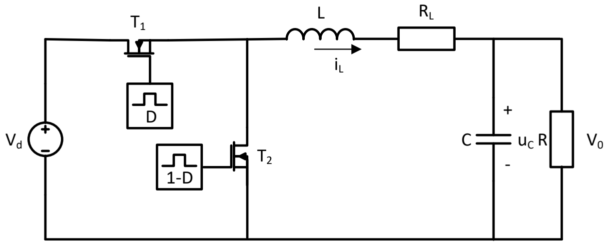

Fig. 1. Classical synchronous Buck DC-DC converter circuit

The Buck converter is mimicked from a integrated solution design, based on the integrated circuit LMR33620 from Texas Instruments. It is an integrated controller with internal synchronous power stage, formed by low- and high-side transistors with R_{DSon} in the range from 90 to 160 mΩ. The control loop is based on regulating the duty cycle of the converter, unlike other simplified solutions, that implement hysteretic control. The nominal rated input voltage is V_d = 12V; the set rated output voltage V_0 = 5V, rated output current up to I_0 = 2A, nominal switching frequency f = 1400 kHz, but is regulated depending on the load parameters. The output resistance is varying with the load, that is evaluated in 100 mA steps from 0 to 2A.

During the analysis and design of the considered converter, the following assumptions were made: an established operating mode is considered (the transient process of device start-up is excluded), the DC power istoner has zero internal resistance, the output capacitor contains no resistance. The design has been verified through computer simulations conducted on LTSpice and a lab bench. In the comparison of the analytical, simulation and experimental results, a very good match was obtained (difference below 5%).

B. Model-based evaluation

The presented research was conducted for continuous current mode (CCM) operation. When operating in this mode, the DC-DC converter is modeled with differential equations regarding the state variables that are constructed by applying Kirchhoff's first and second laws. The conduction states of the transistors are set using the switching function F [2, 8]. In this way, the operation of the DC-DC converter is represented by a single system of linear differential equations. The solution of this system gives the instantaneous values of the currents and voltages of all circuit elements. In this sense, the model of the device is as follows:

$$\left| \begin{array}{l} L\dfrac{di_L}{dt} = F.V_d - i_L(R_{ON} + R_L) - u_C \\ C\dfrac{du_C}{dt} = i_L - \dfrac{u_C}{R} \end{array} \right. \quad (1)$$

Where i_L is the current through the inductor and u_C is the capacitor voltage (output voltage) are the state variables in the studied power scheme.

The system of differential equations (1) is implemented and solved using the MATLAB/Simulink visual programming environment. This is done by building blocks of equations using the Mathematical Modeling palette. In practice, it has been established from numerous studies that visual programming tools provide very good opportunities for implementing the model in mathematical software. This avoids requiring users to be proficient in high-level programming languages. This approach to solving the system of equations was chosen because of its applicability to training interns and students. In addition, it is characterized by productivity and simplicity, relatively high accuracy of calculations, all factors that are very important in mathematical modeling.

C. Mathematical Modelling in MATLAB

The evaluation of the performance of the power circuit can be done by adding or removing parts of the controller or by changing its parameters or setting. In Figure 2 presents the Simulink model of the power electronic device created by mathematical equations.

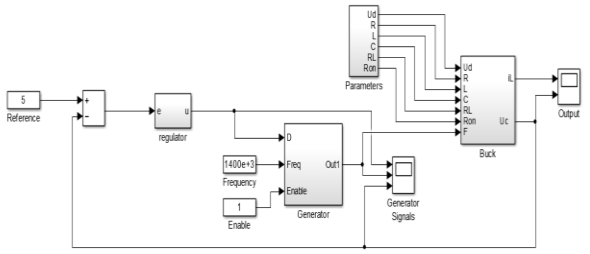

Fig. 2. Mathematical model of linear ODE system, describing the converter

The main advantage of a software product is that it is studied in most curricula of technical universities, and students do not need to study it specifically, but can directly apply it. Of course, in this type of research, it is quite possible to use other software products with similar capabilities and characteristics, such as: LabVIEW, Octave (open source), MathCAD and others. In this sense, the idea presented is to use a research technique that is not tied to a specific software product, and thus each user can use an environment that is well known and available to him..

D. Evaluated hardware

In connection with the modernization and expansion of research in the discipline, evaluation boards were used for the purpose of the study and research with the possibility of evaluating energy efficiency, electromagnetic compatibility, conducting tolerance analysis and automated recording of data from experiments. The evaluation board presented on Figure 3 is based on a DC/DC converter without galvanic isolation, which has the ability to make measurements of the converter efficiency based on the different passive elements used. These could be the capacitors and inductors whether they're taking part in the conversion or filtering the output parameters, such as currents and voltages.

The other possibilities of the layout are as follows. Changing the operating frequency and duty cycle of the control pulses and studying their influence. Study of the ripple coefficient in relation to the different types and constructions of the filter elements, both with the same nominal values and with different ones. Influence of the materials of the inductance used, its construction, as well as the various parameters such as magnetizing current, shielding and applied voltage on the coil. Measurement of the attenuations and anti-jamming effects of the used input and output filters.

III. Experimental Results

The practical study begins with the evaluation of the presented above mathematical model. In the model have been loaded absolutely the same passive elements' parameters such as series DC resistance, saturation currents, non-linearity curve and capacitance parasitic properties found on the datasheet from the manufacturer. The derived results will be summarized in a table and then they will be compared against the results from the evaluation board. Additionally a graphical representation for better comparison will be presented.

A. Model-based evaluation

The model is loaded with the following parameters: rated input voltage V_d = 12V; rated output voltage V_0 = 5V, rated output current I_0 = 2A, fixed operating frequency f = 1400 kHz is selected. The design was carried out according to the datasheets in [5, 7, 9], and the following values of the circuit elements R_L = 0.022 mΩ were obtained; C_{out} = 22µF; Output load R = varying from 2.5 Ω to 50 Ω; the transistor switching resistance is set to a mean of R_{ON} = 120 mΩ.

In Table 1 the results from the model-based evaluation have been summarized. The columns are as follows: I_{in} is the input current, U_0 is the output voltage, I_0 is the output current, P_{in} is the input power, P_0 is the output power and η is the converter efficiency. The input voltage as already states is assumed to be 12V constant.

TABLE I:
MODEL-BASED CONVERTER EFFICIENCY STUDIES

I_{in} [A]	U_0 [V]	I_0 [A]	P_{in} [W]	P_0 [W]	η [%]
0.0001	5.56	0.0001	0.0012	0.0006	46.33
0.07	5.018	0.1	0.84	0.5018	59.71
0.12	5.014	0.2	1.44	1.0028	69.35
0.16	5.011	0.3	1.92	1.5033	78.3
0.21	5.073	0.4	2.52	2.0292	80.52
0.26	5.032	0.5	3.12	2.516	80.64
0.3	5.002	0.6	3.6	3.0012	83.37
0.35	4.976	0.7	4.2	3.4832	82.93
0.39	4.943	0.8	4.68	3.9544	84.49
0.44	4.897	0.9	5.28	4.4073	83.35
0.48	4.884	1	5.76	4.884	84.79
0.53	4.871	1.1	6.36	5.3581	84.25
0.58	4.857	1.2	6.96	5.8284	83.74
0.63	4.844	1.3	7.56	6.2972	83.3
0.67	4.83	1.4	8.04	6.762	84.1
0.72	4.818	1.5	8.64	7.227	83.65
0.77	4.804	1.6	9.24	7.6864	83.19
0.82	4.791	1.7	9.84	8.1447	82.77
0.87	4.777	1.8	10.44	8.5986	82.36
0.92	4.764	1.9	11.04	9.0516	81.99
0.975	4.75	2	11.7	9.5	81.2

The results presented on the table are plotted graphically on Figure 4. It can be seen that the graph represents steadily and smoothly the converter efficiency depending on the load current.

The same experiment will be carried out with the evaluation board using and will be compared to the graph and table presented above.

F. Hardware based evaluation

The hardware design kit is shown on figure 3. It is developed jointly by Wuerth-elektronik and the Wroclaw University of Science and Technology, Poland. It contains a power stage based on the LMR33620 buck "SIMPLE SWITCHER®" power stage, with the ability to interchange the inductors and the output filters. This allows for a comprehensive study on the influence of the passive elements on the operating regimes of the device. This interchangeability allows also for the evaluation of the tolerances of the building elements of the converter, given the ability to acquire enough measurements of a series of same models of a product and concluding via statistical methods how their tolerances will influence the range of change of parameters of the converter.

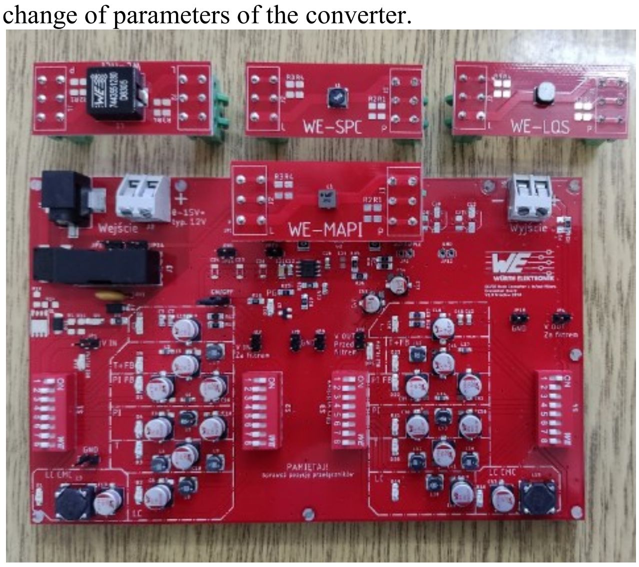

Fig. 3. DC/DC converter without galvanic isolation for the purpose to study the influence of passive elements on its energy parameters

The hardware test bench is based on the evaluation board, connected to a power supply unit GwINSTEK PSW30-36 and an electronic-load TENMA 72-13210 test bench instruments. The power supply allows setting the output voltage from 0 to 30 Volts and the output current protection to 36 A. This is more than enough for the current test-bench measurement. The electronic load allows for precise stepping of the output current in 0.1 mA steps.

The results are summarized in Table 2 from the hardware-based evaluation. Again the columns are as follows: I_{in} is the input current, U_0 is the output voltage, I_0 is the output current, P_{in} is the input power, P_0 is the output power and η is the converter efficiency.

TABLE II:
HARDWARE CONVERTER EFFICIENCY MEASUREMENTS

I_{in} [A]	U_0 [V]	I_0 [A]	P_{in} [W]	P_0 [W]	η [%]
0.0001	5.05	0.0001	0.0012	0.0005	42.083
0.07	5.016	0.1	0.84	0.5016	59.71
0.12	4.993	0.2	1.44	0.9986	69.35
0.16	4.977	0.3	1.92	1.4931	77.77
0.21	4.963	0.4	2.52	1.9852	78.78
0.26	4.9498	0.5	3.12	2.4749	79.32
0.3	4.937	0.6	3.6	2.9622	82.28
0.35	4.923	0.7	4.2	3.4461	82.05
0.39	4.91	0.8	4.68	3.928	83.93
0.44	4.897	0.9	5.28	4.4073	83.35
0.48	4.884	1	5.76	4.884	84.79
0.53	4.871	1.1	6.36	5.3581	84.25
0.58	4.857	1.2	6.96	5.8284	83.74
0.63	4.844	1.3	7.56	6.2972	83.3
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0.77	4.804	1.6	9.24	7.6864	83.19
0.82	4.791	1.7	9.84	8.1447	82.77
0.87	4.777	1.8	10.44	8.5986	82.36
0.92	4.764	1.9	11.04	9.0516	81.99
0.975	4.75	2	11.7	9.5	81.2

The results are presented graphically on figure 4. Comparing both the table 1 and 2, and figures 4 and 5, it can be observed that the accuracy of the model is worse on light loads, but it improves with loads greater than 1 A. Also the graph is smoother on the model-based evaluation, given the fact, that after all additional (complex) factors such as board layout take part in the efficiency equations.

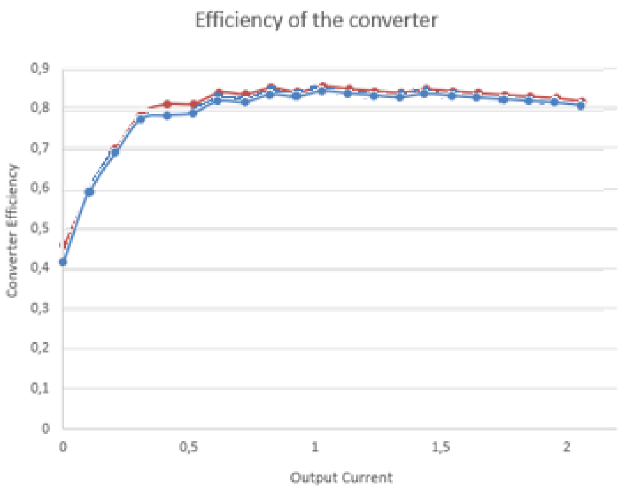

Fig. 4. Comparison between model-based (red) and hardware (blue) evaluation of the DC/DC converter efficiency

However the good match between model-based and hardware-based evaluation give the right to conclude, that the model-based evaluation can be successfully used to carry design study of the influence of the passive elements on the converter efficiency with sufficient applicable accuracy for the power stage development.

IV. Conclusion

The reviewed mathematical model along with the presented evaluation board have been evaluated. The mathematical model is loaded with the absolutely same passive elements' parameters such as series DC resistance, saturation currents and other parasitic properties found on the datasheet from the manufacturer. The evaluation board has been evaluated according the manufacturer's instructions, and the presented results have been summarized in a table and presented graphically.

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