DESIGN OF AN EFFICIENT AND LOW-COST BUCK-CONVERTER BY OPTIMIZING FREQUENCY AND INDUCTANCE VALUES

FREKANS VE ENDÜKTANS DEĞERLERİ OPTİMİZE EDİLEREK VERİMLİ VE DÜŞÜK MALİYETLİ BİR BUCK DÖNÜŞTÜRÜCÜ TASARIMI

Abdullah ALSERAJI
Yıldız Teknik Üniversitesi, Elektrik-Elektronik Fakültesi, Elektrik Mühendisliği Bölümü, Esenler, İstanbul.

Ress. Assist. Musa TERKEŞ
Yıldız Teknik Üniversitesi, Elektrik-Elektronik Fakültesi, Elektrik Mühendisliği Bölümü, Esenler, İstanbul.
ORCID NO: 0000-0002-4411-411X

Assist. Prof. Dr. Alpaslan DEMİRCİ
Yıldız Teknik Üniversitesi, Elektrik-Elektronik Fakültesi, Elektrik Mühendisliği Bölümü, Esenler, İstanbul.
ORCID NO: 0000-0002-1038-7224

ÖZET

Düşük maliyetli ve verimli DC-DC dönüştürücülerin tasarımı, dikkate alınması gereken değişkenlerin çokluğu nedeniyle bazı durumlarda zor olabilmektedir. Bu çalışmada, tasarım sürecini hızlandırmak için Mosfet'in anahtarlama frekansının ve buna bağlı değişkenlerin değiştirilerek istenen çıkışın bulunduğu bir yöntem tanıtılmıştır. Önerilen yöntemin performansı, Python programı kullanılarak oluşturulan izole olmayan bir buck dönüştürücü modeli kullanılarak analiz edilmiştir. Ayrıca, dönüştürücünün temel elemanlarından kaynaklanan bazı kayıplar da incelenmiştir. Sonuçlar, devre tasarımcısına anahtarlama frekansını değiştirmenin etkileri hakkında daha fazla fikir vererek, tasarımcının verimlilik ve bütçe hedeflerine bağlı olarak devre değerlerini seçmesini sağlar.

Anahtar kelimeler: Python, DC-DC dönüştürücü, düşürücü dönüştürücü, anahtarlama frekansı, iletim ve anahtarlama kayıpları.

ABSTRACT

Designing low-cost and efficient DC-DC converters can be difficult in some cases due to the amount of variables that need to be considered. This study, to speed up the design process, a method is introduced where the Mosfet's switching frequency and, subsequently the variables depending on it are changed to find the desired output. The performance of the proposed method is analyzed using a non-isolated buck converter model created using a Python program. Some losses due to the essential elements of the converter were also investigated. The results give the circuit designer more insight into the effects of changing the switching frequency, enabling the designer to choose the circuit values depending on the efficiency and budget goals.

Keywords: Python, DC-DC converter, buck converter, switching frequency, conduction and switching losses.

INTRODUCTION

For each use case, DC-DC converters are designed to meet specific criteria determined by the load and the environment in which it will work. Depending on the load and power source, the needed topology and control method can change drastically (Dagal & Akın, 2023; Hossain et al., 2018). Many topologies have been developed to meet certain design requirements, increasing the conditions a designer needs to evaluate (Bubovich, 2017) the characteristics of design converters. A good demonstration of difficulties encountered while designing buck converter is to design converters for battery-powered electronics (Zhao & Qian, 2006). Applications like battery powered IoT devices require unique voltage and current values. While standard designs might work in these situations, many use circuit elements with higher values than needed, leading many companies to cut costs by choosing lower-quality parts. Situations like this lead to products with shorter lifespans creating unnecessary e-waste (Gupta & Quamara, 2020; Kim et al., 2022; Richelli et al., 2021). Electrolytic capacitors are widely used in DC-DC converters for their higher capacitance value at the same price point. These have two problematic disadvantages that lead to the early malfunctioning of the circuit. Firstly, they have a low resistance to heat. Secondly, with every increase in environmental temperature over the rated temperature, the capacitor's lifetime decreases rapidly (Torki et al., 2023). The other disadvantage is its low lifetime compared to the other components in the circuit. This means that a product that uses electrolytic capacitors is not used to its full extent and has a shorter life span. With the option of using ceramic capacitors, a designer can increase the product's life span without an increase in the price (Joubert et al., 2007). LED flashlights are a notable case of increasing the life span of a product. Generally, LEDs can last up to 100000 hours if operated optimally. However, many products that utilize them die much faster than expected. The main culprit in most cases is the early death of the converter (Casamayor et al., 2015). This paper proposes a design process that can find the most efficient values for the circuit parts in a wide range of use cases. These values are achieved by looking at the power losses at each frequency step in a predetermined range. It's considered that while choosing the best parts for the circuit will provide better results, these parts can also cost a lot more than the planned budget for the circuit. Because of this, the proposed design process chooses the least value of capacitance and inductance needed to achieve a certain efficiency goal. The mosfet and diode types are left to the design process user to choose based on their budget and the results of the desired or selected operational frequency.

CIRCUIT AND LOSSES ANALYZED

Non-isolated Switch-mode DC-DC Converters

These converters utilize the characteristics of inductors, capacitors, and semi-conductors to change the voltage level of the DC power at a high-efficiency level. They offer high efficiency, and with high enough frequency, the output voltage can have a little noise. However, as frequency increases, the power losses also increase due to the values of capacitors and inductors. For this reason, the most efficient middle ground needs to be decided based on desired parameters (Mumtaz et al., 2021).

Buck Converter

Buck converters are non-isolated switch-mode dc-dc converters that lower the input voltage to a desired value. The block diagram in **Hata! Başvuru kaynağı bulunamadı.** shows the basic principle of the circuit analyzed. The main switch is an n-channel mosfet controlled by a PWM signal. It's assumed that a duty cycle controlling method like a PI controller is used to lessen the input voltage change on the output. Power losses and power needed by the controller circuit are not considered. The buck converter was chosen as an application example of the method introduced because of the different types of losses involved in the circuit and the simplicity of comparing it with real-life experiments (Altintas et al., 2021; Bauwelz Gonzatti et al., 2022; Yilmaz et al., 2021).

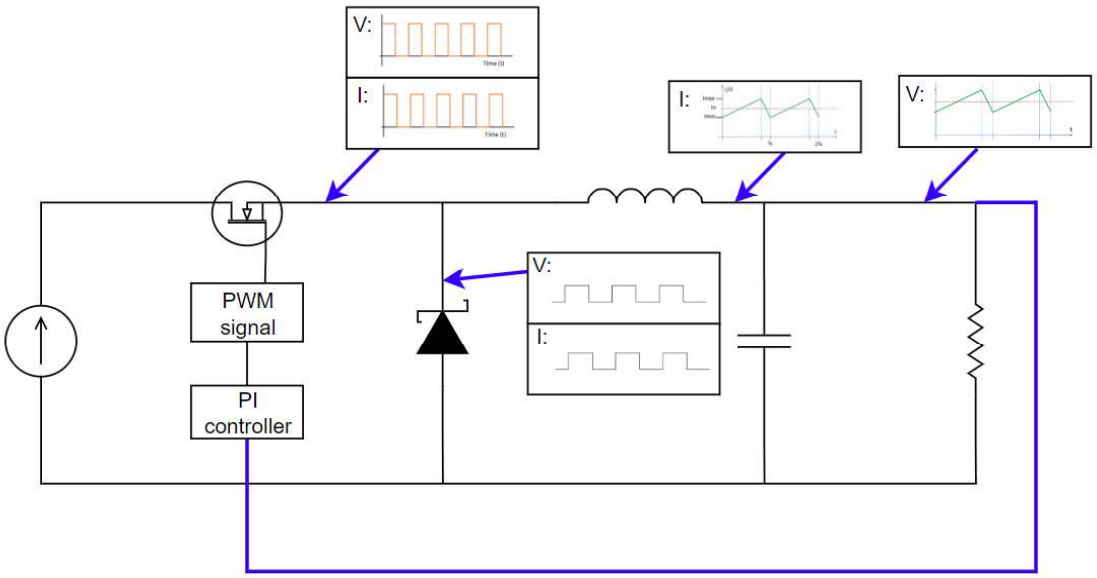


Figure 1. Buck converter circuit

Losses

The main losses considered in choosing the optimum frequency are the ones that change depending on the duty cycle and the switching frequency. Constant losses are also considered when evaluating the total efficiency of the circuit. While it's possible to assess the losses theoretically precisely, many variables and characteristics of the parts used need to be considered. Unfortunately, some of these characteristics are not generally mentioned in the datasheet of the parts. For this reason, only characteristics easily obtainable from part datasheets are considered here (Luo & Ye, 2007; Rajakumari & Deshpande, 2019).

Capacitor Losses

Most manufacturers provide the internal resistance of the capacitance as a single ohmic value without considering the internal inductance. Therefore, approximate values for the internal inductance (L_C) depending on the capacitor type and capacitance will be considered. To be able to find the capacitor power loss, the capacitor`s reluctance (Z_C) is first found using the Equation (1).

$$Z_C = \sqrt{ESR^2 + \left(\frac{1}{2\times\pi\times C\times F} - (2\times\pi\times L_C\times F)\right)^2} \quad (1)$$

With the capacitor`s reluctance found, the capacitor power loss (P_C) can easily be calculated using the Equation (2).

$$P_C = I_{rms}^2 \times Z_C \quad (2)$$

This equation combines both the constant and frequency-dependent parts of the power loss.

Transistor Losses

The losses considered here can be described as switching losses and conduction losses. Switching losses occur in the short time it needs to fully close and open the circuit. Therefore, the faster the mosfet is switched, the better. The switching power losses (P_S) for the relevant goal are calculated using Equation (3).

$$P_S = \frac{V_{in}}{2} \times I_P \times \left(t_{on} + t_{off}\right) \times F \quad (3)$$

Input voltage (V_{in}), peak input current (I_P), turn-on time (t_{on}), turn-off time (t_{off}) and switching frequency (F) are used in this equation. Conduction power losses (P_C) on the other hand, occur when the mosfet is in its conducting state. As it happens because of the internal resistance of the mosfet (R_S) it can be found using the Equation (4) with the help of RMS current (I_{rms}) and duty cycle (DC).

$$P_c = I_{rms}^2 \times R_S \times DC \quad (4)$$

After the values of different types of losses are found, the total mosfet power losses (P_m) are calculated using Equation (5).

$$P_m = P_S + P_C \quad (5)$$

Inductor Losses

Unfortunately looking at the current state of the market for power inductors, many manufacturers don't give detailed loss characteristics of the inductor and only provide experimental results. For this reason, only the constant internal resistance generally given in inductor datasheets is considered in this paper. For calculating inductor conduction losses (P_L) using the inductor`s internal resistance (R_L), the Equation (6) can be used.

$$P_L = I_{rms}^2 \times R_L \quad (6)$$

Diode Losses

For diodes, the main power loss causes are due to the internal resistance and forward voltage drop. Generally, for semi-conductors, their internal resistance increases with their temperature. To find the total diode power loss (P_d), the Equation (7) can be used.

$$P_d = (1 - DC) \times I_{rms} \times (V_d + (I_{rms} \times R_d)) \quad (7)$$

In addition to the previously discussed parameters, diode forward voltage (V_d) and diode internal resistance (R_d) are used in this above equation.

METHODOLOGY

Python

Python is a beginner-friendly high-level programming language, which makes it easy to cooperate in a design process with little programming knowledge. At the same time, it offers various libraries that can help visualize data and results. In a circuit design process, Python can help with solving a series of equations for many iterations while changing any desired variable. Then, by graphing the simulation results, the effect of the chosen variable can be understood better. As it can be seen in **Hata! Başvuru kaynağı bulunamadı.**, the code starts by asking the user to enter some initial values. After that, it enters the optimum frequency-finding function. With the initial values and the optimum frequency, the code finds the optimum capacitance and inductance values needed for the converter.

Initial Values

For the simulation of a buck converter's power losses the initial parameters are the rated max power (P), the desired output voltage (V_O), input voltage (V_{in}), and output current ripple (ΔI) and voltage ripple (ΔV). Using these parameters load resistance for the rated max power (R_{load}), average input current (I_{in}), peak current (I_P), and RMS current (I_{rms}) can be calculated using the following Equations (8)-(12).

$$R_{load} = \frac{V_o^2}{P} \tag{8}$$

$$I_o = \frac{P}{V_O} \tag{9}$$

$$I_{in} = \frac{P}{V_{in}} \tag{10}$$

$$I_P = 1.41 \times I_{in} \tag{11}$$

$$I_{rms} = 1.11 \times I_{in} \tag{12}$$

Optimum Frequency

For finding the optimum frequency, the code calculates the optimum capacitance and inductance values and the losses associated with them for a frequency range the user decides. With the values needed to find the power losses involved, the start frequency, frequency step, and end frequency will be asked from the user. Then, the fixed power loss values are calculated as they will not change depending on frequency. After that, the code enters while loop calculating the optimum capacitance and inductance values and losses until the frequency value reaches the end frequency. To show the results in details, the function plots all the losses, capacitance, and inductance values in y-axis with frequency in x-axis. At the end of this function, an optimum frequency is found. This value can yield the best efficiency for the conditions the user presented.

SIMULATION RESULTS

This section applies the proposed design process using the values in Table 1. It should be mentioned that the capacitor`s ESR, parasitic inductance, and inductor`s resistance are approximate values based on typical values. These values are based on an electrolytic capacitor.

The optimum frequency, capacitance, and inductance values found by the program will be first presented to the user. Then as can be seen in Figure 3 the program will present the result of total mosfet power losses, inductor power losses, and capacitance power losses calculated at every frequency step. In addition, the program will also show the optimum inductance and capacitance values for every frequency step. These can, for example, help the user to compromise on efficiency and have cheaper inductors and capacitors used. The program will also generate a pie chart like the one in Figure 4, which shows the user a detailed breakdown of all the losses that are occurring in the circuit. In the big ring, a breakdown of how much each component contributes to the total loss percentage. This can help choose the part to focus on changing if further optimization is needed. Furthermore, with the help of the detailed breakdown of the loss types in the small ring, a better understanding of the properties of the new parts needs to be made. Figure 4 shows that the conduction losses of the mosfet have a major impact in this case. A mosfet with similar characteristics but smaller internal resistance can be chosen to reduce its effects. After the user acquires the graph in Figure 3, they can increase the inductance or the frequency depending on their goal, and the program will generate the pie chart and the losses depending on the values chosen by the user.

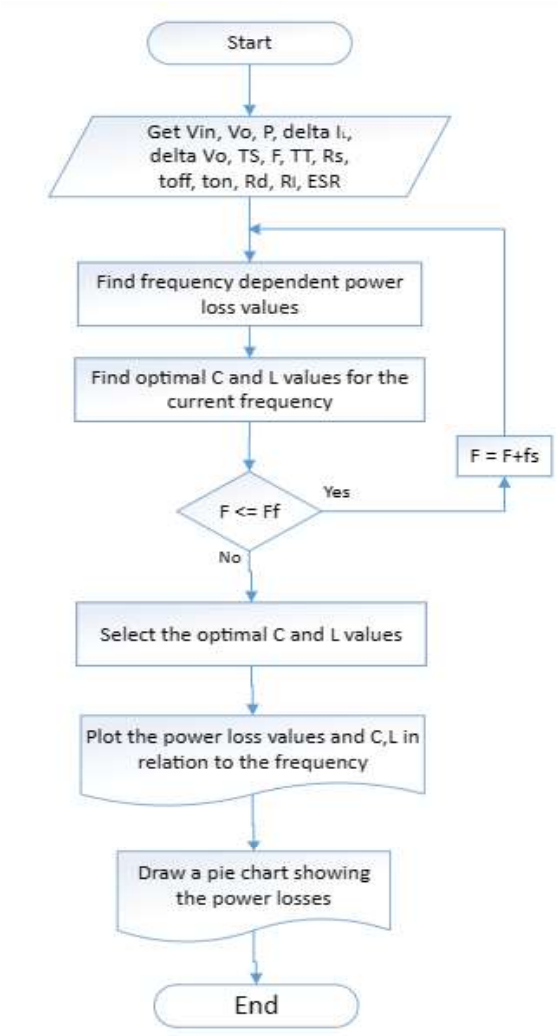


Figure 2. Flow chart describing the general code structure

Table 1. Initial values used in the experiment

Input voltage (V_{in})	12 V
Rated max power (P)	15 W
Desired output voltage (V_O)	5 V
Output current ripple (ΔI)	30% output current
Output voltage ripple (ΔV)	1% output voltage
Used mosfet model	PJA3404_R1_00001
Mosfet internal resistance	40 mΩ
Mosfet switch on time	40 ns
Mosfet switch off time	39 ns
Used diode model	241-SX33L_R1_00001
Diode forward voltage drop	0.35 V
Capacitor ESR	2 Ω
Capacitor`s parasitic inductance	10 nH
Inductor`s resistance	2 Ω

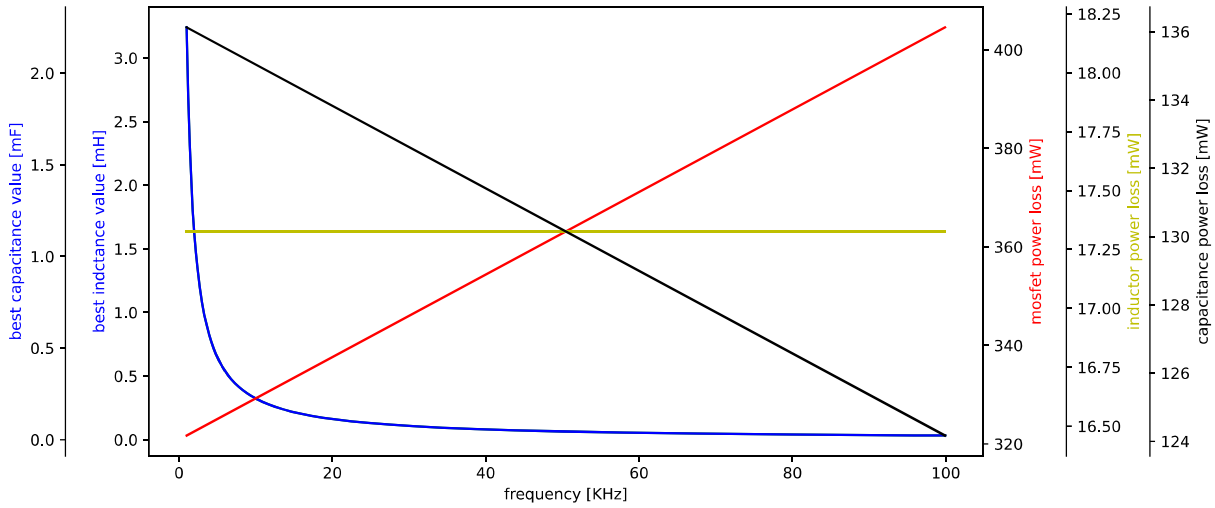


Figure 3. Inductance, capacitance, and power losses calculated at a frequency band

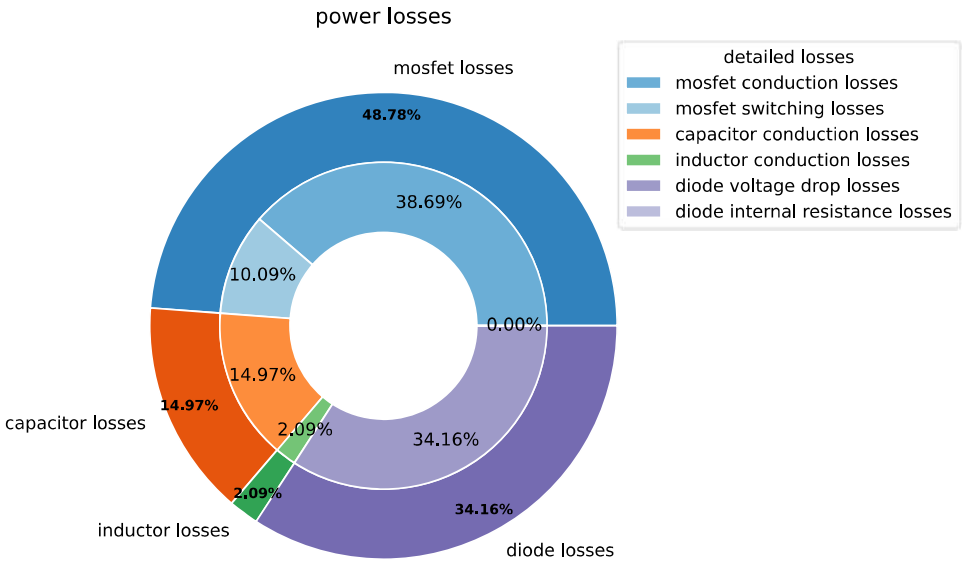


Figure 4. Power loss breakdown

CONCLUSION

With the increasing complexity of DC-DC converters, the considerations involved in their design process get more difficult. The proposed optimization method provides the converter designer with additional information to help understand the relation between the switching frequency and inductance value. The proposed method parameters used, and the simulation results revealed that the proposed design process is optimum for the selected buck converter and other DC-DC non-isolated converter types. Besides, the results of the illustrative code show the method's feasibility and its potential to work with different topologies of converters. Our future work will apply the same design process to evaluate another type of power electronics converters based on their components and feature characteristics.

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