Study and Analysis of the Operation of a Cuk Converter for Precise Voltage Regulation

Merabet Hichem *‡ iD , Bahi Tahar ** iD , Boukadoum Aziz *** iD Drici Djalel* iD

* Research Centre In Industrial Technologies (CRTI), Cheraga, Algeria
** Department of Electrical, Badji Mokhtar Mokhtar Univ., LASA Lab., Annaba 23000 Algeria
*** Electrical Department, University of Tebessa , Algeria

(h.merabet@crti.dz, tbahi@hotmail.fr, azizboukadoum@yahoo.fr, d.drici@crti.dz)

‡
 Merabet Hichem; Research Centre In Industrial Technologies (CRTI) P.O Box 64, Cheraga, Algeria, h.merabet@crti.dz

Abstract- This paper focuses on the application of a Cuk converter for voltage regulation in electronic devices. The Cuk converter is a DC-DC voltage converter that uses a unique topology to regulate the output voltage from a DC input voltage source. In this study, we examine the operation of the Cuk converter, model its behavior, analyze its performance, and optimize its design for various applications. The Cuk converter has several advantages, including galvanic isolation, reduced switching losses, and the ability to use low voltage rating components. These advantages make it an ideal choice for powering electronic devices that require precise voltage regulation, such as sensor power supplies, control electronics, and wireless communication systems. Analyzing its performance Analyzing the converter's performance also involves examining its efficiency, output voltage regulation, and stability under varying load conditions. Simulation results with MATLAB/Simulink provide evidence of the performance of the converter's control in photovoltaic systems applications; it is able to make the output voltage stable when rapid changes occur in the input parameters.

Keywords: Cuk converter, Voltage regulation, Control; Stability, Simulation.

1. Introduction

The Cuk Converter is a DC-DC voltage converter that uses a unique topology to regulate the output voltage from a DC input voltage source. This topology offers advantages such as galvanic isolation, reduced switching losses, and the ability to use low voltage rating components. The Cuk Converter is increasingly used in applications that require precise voltage regulation, such as sensor power supplies, control

electronics, and wireless communication systems [1].The study of the Cuk Converter involves understanding its operation, modeling its behavior, analyzing its performance, and optimizing its design. A fundamental understanding of the Cuk Converter's operation requires an examination of its circuit topology, which consists of an inductor, two capacitors, a switch, and a diode. The switch and diode are used to control the flow of energy between the inductor and the capacitors, thereby regulating the output voltage [2].

To model the behavior of the Cuk Converter, a set of mathematical equations is used to describe the voltage and current relationships in the circuit. These equations can be derived from the circuit topology and the principle of conservation of energy. The model allows us to analyze the converter's performance in terms of efficiency, output voltage regulation, and stability [3].

The Cuk Converter is a DC-DC voltage converter that regulates the output voltage from a DC voltage source. Unlike conventional converters such as Buck, Boost or Buck-Boost, the Cuk Converter has an original topology that allows it to supply an output voltage lower or higher than the input voltage, with high efficiency [4].

Analyzing the performance of the Cuk Converter requires a thorough understanding of the converter's characteristics and limitations. Factors such as the value of the inductor, the capacitance of the capacitors, and the duty cycle of the switch affect the converter's performance [5].

Optimizing the design of the Cuk Converter involves selecting the appropriate values for the inductor and capacitors to achieve the desired performance. Optimization also involves selecting the appropriate switching frequency and duty cycle to balance the trade-off between efficiency and output voltage regulation. Furthermore, the design must be optimized to ensure stability under varying load conditions and to minimize electromagnetic interference [6].

2. Structure and Operation Mode

A) Structure and Topology

The Cuk Converter is a DC-DC voltage converter that uses a specific topology to regulate the output voltage from a DC voltage source. Its structure is composed of the following elements [7, 8]:

- DC voltage source (V_{in}): this is the converter's input voltage. It can be powered by a battery, an external power source, or any other gadget that can produce a DC voltage.

- A switch (S): This is an electronic component that controls the current flowing in the circuit. It can be controlled by a control signal to switch between two states: open and closed.

- An inductance (L): this is a passive component that stores electrical energy in the form of a magnetic field. It is used to smooth the current and regulate the output voltage.

- Two capacitors (C_1 and C2): These are also passive components that store electrical energy in the form of electrical charge. They are used to filter voltage variations and reduce oscillations in the circuit.

- A diode (Di): This is an electronic component that allows current to flow in one direction only. It is used to provide a return path for current when the switch is open;. Its circuit is presented in Fig. 1
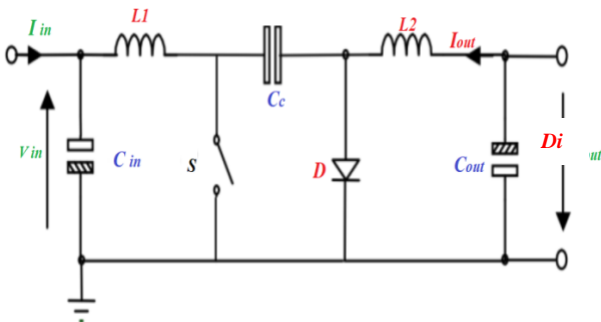

Fig. 1. Cuk converter Circuit

B) Operation Mode

The Cuk Converter operates in two distinct phases: the charging phase and the discharging phase. During the charging phase presented in figure 2, the switch (S) is closed and the current flows through the inductance (L) which stores electrical energy in the form of a magnetic field. Capacitor C1 also charges through the inductor.
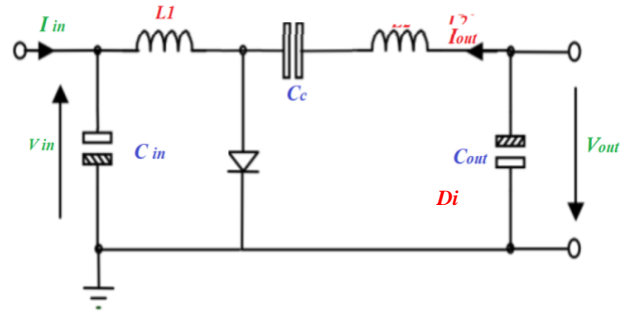
Fig. 2. Operation charging mode

When the switch is open, the discharge phase begins presented in figure 3. Current then flows through the diode (Di) and the output capacitor (C2), which regulates the output voltage (Vout). The inductor releases the stored energy as current, which adds to the discharge current of capacitor C2.
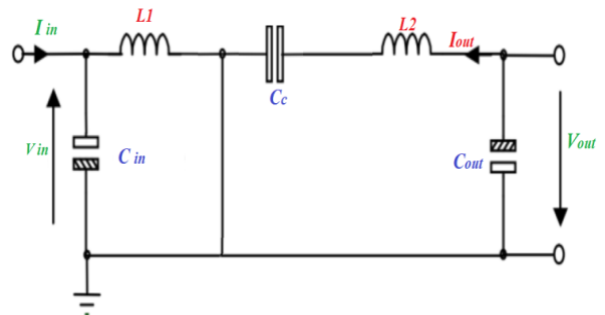
Fig. 3. Operation discharging mode

The structure of the Cuk Converter makes it possible to regulate the output voltage by adjusting the duty cycle of the control signal. When the switch is closed, current flows through the inductor and stores electrical energy. When the switch is open, current flows through the output diode and capacitor, which helps regulate the output voltage.

The Cuk Converter topology provides benefits such as galvanic isolation, reduced switching losses and the ability to use low breakdown voltage components. It is increasingly used in applications requiring precise voltage regulation [8].

C) Converter Control

The Cuk Converter uses Pulse Width Modulation (PWM) techniques to regulate the output voltage. The duty cycle (D) of the control signal is used to control how long the switch is closed. By varying the duty cycle, the output voltage can be regulated.

An important advantage of the Cuk Converter is that it is able to provide an output voltage lower or higher than the input voltage, unlike some other DC-DC converters which can only provide a lower output voltage. Additionally, its unique topology provides galvanic isolation between input and output, which can be useful in some applications.

In summary, the Cuk Converter works by regulating the output voltage from a DC voltage source. Its unique topology allows the output voltage to be lower or higher than the input voltage and provides galvanic isolation between input and output [9].

3. Mathematical Modelling of the Cuk Converter

The mathematical model of the Cuk Converter describes the voltage and current relationships in the circuit. The model is based on the principle of conservation of energy and the circuit topology, which includes an inductor (L), two capacitors (C1 and C2), a switch (S), and a diode (Di) [10].

A) Charging phase

During the phase of charge, the voltage across the inductor is given by:

$$V_L = V_{in} - V_{out} \tag{1}$$

Where Vin is the input voltage and Vout is the output voltage. The current flowing through the inductor is given by:

$$I_L = \frac{1}{L} \int V_L dt \tag{2}$$

Where $\int V_L \, dt$ represents the integral of the voltage across the inductor with respect to time.

B) Discharge Phase

During the phase of discharge, the voltage across the output capacitor is given by:

$$V_{out} = (1-\alpha)V_{in} + \alpha V_c \tag{3}$$

where α is the duty cycle of the switch and V_c is the voltage across capacitor C_1. The current flowing through the output capacitor is given by:

$$I_{C2} = C_2 \frac{dV_{out}}{dt} \tag{4}$$

Where dV_{out}/dt represents the derivative of the output voltage with respect to time.

The voltage across capacitor C1 is given by:

$$V_c = (1-\alpha)V_{out} + \alpha V_{in} \tag{5}$$

The current flowing through the input capacitor is given by:

$$I_{c1} = C_1 \frac{dV}{dt} \tag{6}$$

The model also includes the voltage drop across the switch (V_s) and the diode (V_d), which can be modeled as ideal switches with zero voltage drop or as non-ideal switches with a finite voltage drop. Using these equations, we can analyze the performance of the Cuk converter in terms of efficiency, output voltage regulation, and stability under varying load conditions. The model also allows us to optimize the design of the converter by selecting appropriate values for the inductor and capacitors, switching frequency, and duty cycle.

C) Mathematical Model

The mathematical model of the Cuk converter can be expressed through the following equations. For the switching period T:

Inductance L stores electrical energy:

$$V_g = \frac{Ldi}{dt} + V_{C1} \tag{7}$$

Capacitor C stores electrical energy:

$$C_{C2} = \frac{1}{C} \int i(t) \, dt \tag{8}$$

The output voltage Vs is regulated by the duty cycle α:

$$V_s = \alpha(V_{C2} - Vg) \tag{9}$$

With, V_g: the voltage across the terminals of the inductor; V_{c1}: the voltage across capacitor C_1; V_{c2}: the voltage across capacitor C_2; i: the current flowing in the circuit; α: the duty cycle of the command signal, between 0 and 1.

The efficiency of the Cuk Converter can be expressed as follows:

$$\eta = P_{out} / P_{in} = ((1-\alpha)^2 V_{in})/(V_{in} - V_{out}) \tag{10}$$

With , P_{out}: the output power; P_{in}: the input power; V_{in}: the input voltage and V_{out}: the output voltage.

These equations make it possible to model the behaviour of the Cuk Converter and to optimize its design to obtain the desired performance in terms of voltage regulation and efficiency.

D) Cuk Converter Sizing

The design of a Cuk Converter involves selecting appropriate values for the inductor (L), capacitors (C_1 and C_2), and other components to achieve the desired performance. The following steps can be followed to design a Cuk Converter:

1. Determine the input and output voltage requirements: The input voltage (V_{in}) and output voltage (V_{out}) should be specified based on the requirements of the application.

2. Determine the output current requirements: The output current (Iout) should be specified based on the load requirements.

3. Determine the switching frequency: The switching frequency (fs) should be selected based on the desired trade-off between efficiency and size of the components.

4. Determine the duty cycle: The duty cycle (α) should be selected based on the desired output voltage and the input voltage.

5. Calculate the inductance value: The inductance value can be calculated using the following equation:

$$L = V_{in}.\alpha(1-\alpha)/f_S \Delta I_L \qquad (11)$$

Where, ΔI_L is the maximum allowable change in inductor current.

6. Calculate the capacitor values: The output capacitor (C2) can be calculated using the following equation:

$$C_2 = I_{out}(1-\alpha)/f_S \Delta V_2 \qquad (12)$$

Where, ΔV_2 is the maximum allowable ripple voltage.

The input capacitor (C1) can be calculated using the following equation:

$$C_1 = I_{out}(1-\alpha)/f_S \Delta V_1 \qquad (13)$$

where , ΔV_1 is the maximum allowable ripple voltage.

7. Select the components: once the values of the inductor and capacitors have been calculated, appropriate components can be selected based on their ratings and availability.

8. Verify the design: the design should be verified using simulations or measurements to ensure that it meets the desired performance requirements.

4. Discussion Result

Following the previous sections, this section presents an analysis of the open and closed circuit behavior of the Cuk converter. First, Figure 4 (a) and Figure 4 (b) show the control signal with a fixed duty cycle (α = 30%) and a variable duty cycle from 60% to 40%, respectively. To prove the operation of the converter in both buck and boost modes, we applied a variable duty cycle to the controlled semiconductor of the Cuk converter according to the profile in Figure 5 (a). Here, duty cycle values below 50% and above 50% are observed. However, note that for values of α <50%, (0 ≤ t ≤ 0.1, α = 30%). (0.1 < t ≤ 0.2, gradual decay of α from 30% to 20%);(0.2 α=40%); (0.3 < t≤0.35, α gradually increases from 40% to 50%. According to Fig. 5(b), the output voltage of the converter is lower than the input voltage as it is recorded, it operates in backward mode.

On the other hand, for α = 50% between 0.6 ≤ t ≤ 0.8, the output voltage is equal to the input voltage, and the intervals

(0.35 ≤ t ≤ 0.4 and t ≥ 0.8, respectively) have duty cycles α = 60% and α = 70%, the output voltage is much higher than the input voltage, which results in step-up operation. Therefore, after this analysis, the Cuk converter can operate in reversible mode. Figure 5(c) shows the current drawn by the load.

For closed-loop operation, a variable input voltage profile was applied stepwise and progressively to the input of the system, as shown in Figure 6. From this profile, we can see that the input and output voltages overlap over the analysis period. Also note that the duty cycle varies to provide reference monitoring. Figure 6 below shows the variation in load current. Finally, with respect to zooming in, we show the evolution of the quantities discussed earlier towards zero and towards t=0.5 s.
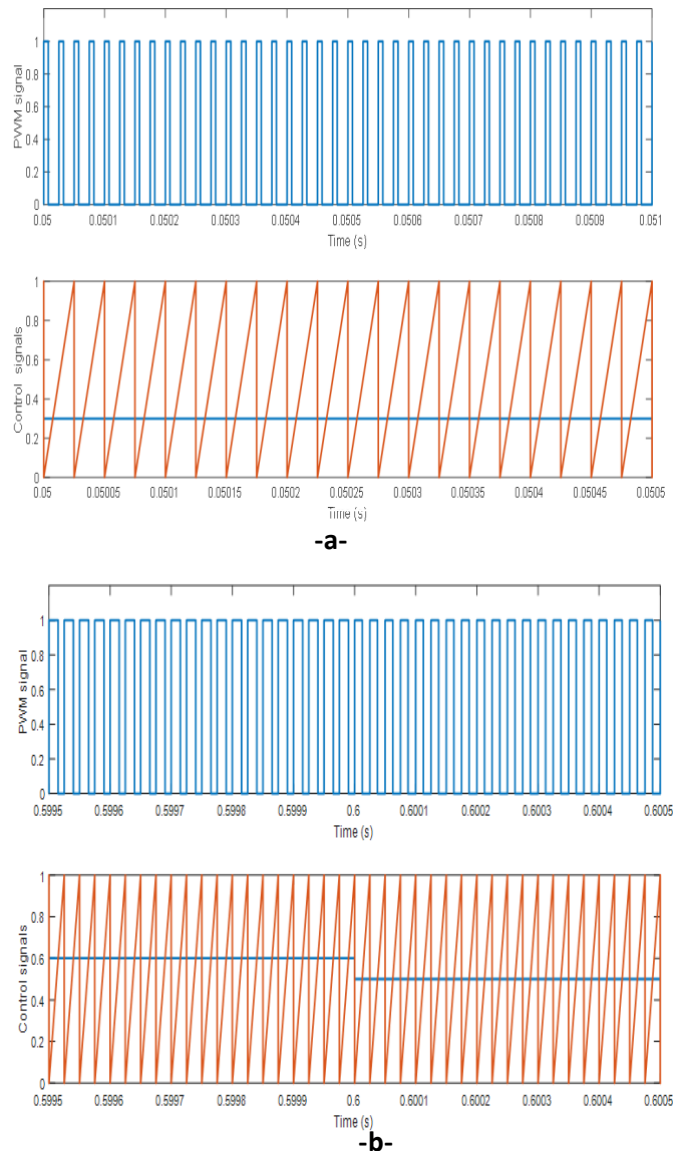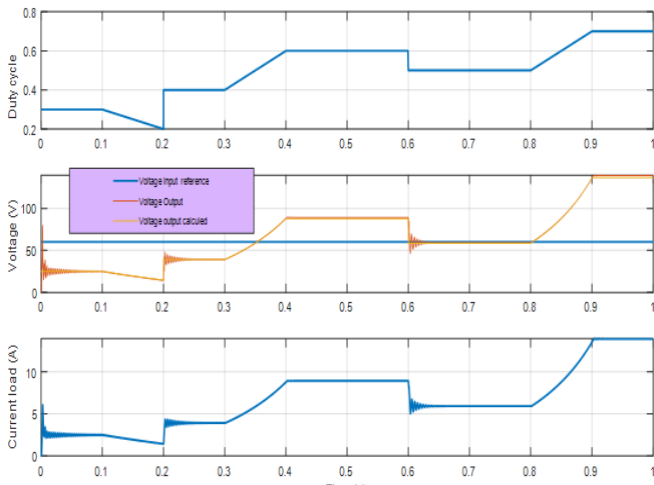

-a-

-b-

Fig. 4. Control Signal
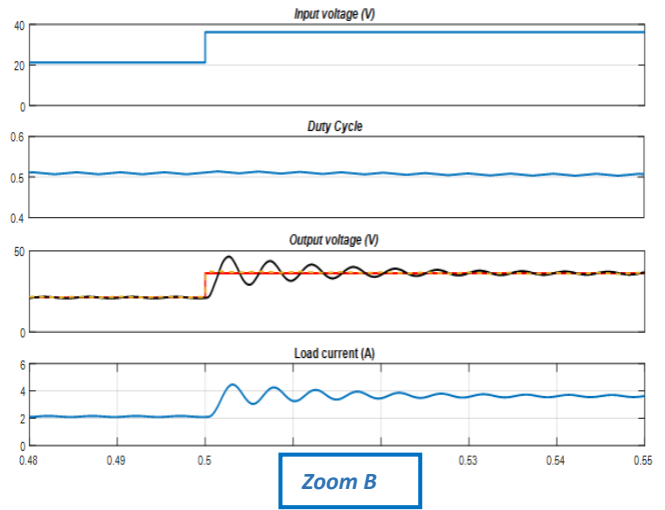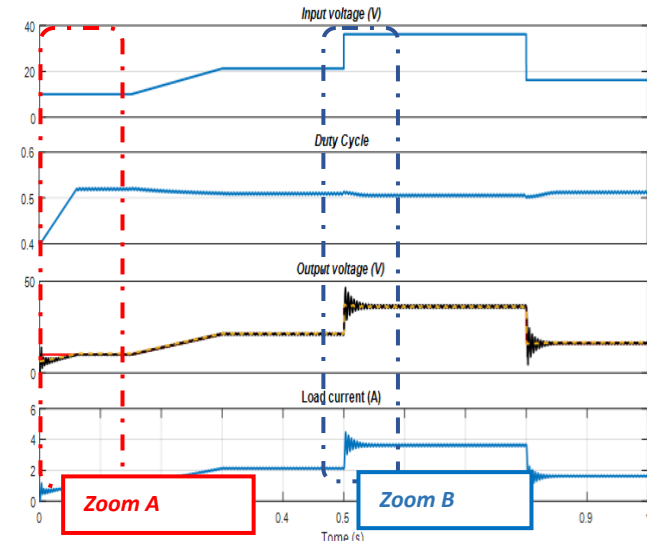
Fig. 5. Operating open loop

**Fig. 6.** Operating closed loop

5. Conclusion

In conclusion, the design of a Cuk converter involves selecting appropriate values for the inductor, capacitors, and other components to achieve the desired performance. The design process involves determining the input and output voltage requirements, the output current requirements, the switching frequency, and the duty cycle. By following these steps, a Cuk converter can be designed to meet the needs of a wide range of applications. The Cuk converter has proven to be a highly efficient and reliable power converter in various applications. It has been successfully implemented in many industrial, demonstrating its practicality and effectiveness. Overall, the Cuk converter is a valuable contribution to the field of power electronics and is likely to continue to play an important role in future designs.

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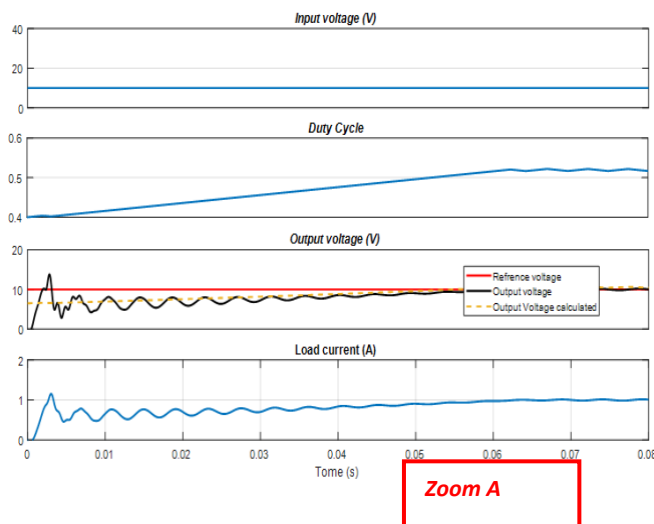
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