



Design and Development of Frequency Domain-Based Lead and Lag-Lead Controller-Based DC-DC CUK Converter for Electric Vehicle Applications



Bandan Kumar Panigrahi, Ranjan Kumar Jena, Durgesh Prasad Bagarty

Abstract: DC-DC high-power electronic converter plays an important role in the domain of fast charging of electric vehicles. Compared to other basic DC-DC converters, the Cuk converter offers advantages such as high-power extraction capability and low ripple DC output voltage, making it more suitable for electric vehicle applications. This paper aims to design a robust, novel controller for the Cuk converter to improve its reliability and efficiency compared with existing controllers. This paper presents a complete proof-of-concept frequency-domain-based design of the Lead and Lag-Lead controllers for a DC-DC Cuk converter. The proposed control scheme is being implemented in MATLAB Simulink to verify the theoretical concepts. Lastly, a comparison has been made between the open-loop and closed-loop responses of the Cuk converter to validate the proposed controller.

Keywords: Lead Controller, Lag-Lead Controller, MATLAB

Nomenclature:

DCMs: Discontinuous Conduction Mode

EMI: Electromagnetic Interference

I. INTRODUCTION

One of the best meaningful solutions to the ever-increasing energy demand is to improve energy utilization efficiency. Power electronics makes a strong contribution towards making the energy conversion from renewable energy sources more efficient and easier. Global warming is caused by pollution, including air, land, and water pollution. The evolution of electric vehicle technology and solar cell technology has reduced the effects of global warming. Power electronics play a vital role in the design and implementation of hybrid electric vehicles and solar power plants. Power electronics include various types of converters, inverters, and multilevel inverters. High power quality and high voltage are required in HEVs and smart grids. Power electronics plays a vital role in the modern world.

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It has vast applications across different fields, e.g., adjustable-speed drive control, induction heating, switched-mode power supplies, FACTS controllers, and energy conversion for renewable energy sources. The power electronic circuit is assumed to operate at a supply voltage that is usually constant. A voltage regulator is a power electronic circuit that maintains a constant output voltage regardless of changes in load current or line voltage. A variety of voltage regulators with different control schemes are used. As circuit complexity increases, a more stringent requirement for accurate, fast regulation is needed. Switch-mode power supply topologies follow a set of rules. Many consider the basic group to consist of the three converters: BUCK, BOOST, and BUCK-BOOST. The CUK, essentially a BOOST-BUCK converter, may not be considered as a basic converter along with its variations: the SEPIC and the zeta converters.

The Canonical Cell forms the basis of analysing switching circuits, but the energy transport mechanism forms the foundation of the building blocks of such converters. The Buck converter may consequently be seen as a Voltage-to-Current converter, the Boost as a Current-to-Voltage converter, the Buck-Boost as a Voltage-Current-Voltage converter, and the CUK as a Current-Voltage-Current converter. All other switching converters MUST fall into one of these configurations if they do not increase the number of switching stages further, for example, into a V-I-V-I converter, which is difficult to realise with a single controlled switch. It does not require explanation that a current source must be connected to deliver its energy into a voltage sink, and vice versa. A voltage source cannot discharge into a voltage sink, and neither can a current source discharge into a current sink. The first would cause current stresses, while the latter would result in voltage surges. This rule is analogous to the energy exchange between a source of Potential Energy (the Voltage of a Capacitor) and a sink of Kinetic Energy (the Current in an Inductor), and vice versa. Both can, however, discharge into a dissipative load without causing any voltage or current amplification.

Schemes and small-signal analysis of the system are necessary for designing a stable compensation circuit. State-space analysis is typically used to develop a small-signal model of a converter, and, depending on the control scheme, the small-signal model is modified to facilitate the design of the



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compensation network. In contrast to a state-space approach, PWM switch modelling focuses on the small-signal modelling of the switching components of the converter. Behavioural modelling of the IC system represents the functionality of an IC using macro models rather than the actual circuit implementation, thereby enabling more efficient modelling. MATLAB Simulink and Verilog-A are powerful tools for developing behavioural models of electronic systems. Simulink offers the advantage of its graphical user interface and block diagram implementation of any system. It also supports writing your own functions and integrating C program code.

The DC-DC converter takes an unregulated DC input and outputs a constant or regulated DC voltage. Regulators can be classified as linear or switching. All regulators have a power transfer stage and a control circuitry to sense the output voltage and adjust the power transfer stage to maintain the constant output voltage. Since a feedback loop is necessary to maintain regulation, some compensation is required to maintain loop stability. Compensation techniques vary for different controls. Conventional DC-DC power electronic converters, such as buck, boost, and buck-boost, use an inductive medium to transfer energy from the source to the load. The proposed Cook converter uses a capacitive medium to transfer energy from the source to the load with an inventive polarity.

II. LITERATURE SURVEY

The solution prescribed in [1] exhibits precision as well as reflects the continuous character of the converter waveform. The key of this approach is the extraction of the switching elements (transistors, or transistor and diode, operated as synchronous switches) in a time-varying two-port, called an alternator. The constitutive equations of the alternator are added, obtaining the global model of the cyclically switching circuit in the s-domain. In this way, the converter analysis is performed using the tool familiar to engineers, the Laplace transform. The method is applied to the coupled-inductor Cuk converter operating in continuous conduction mode, in which the transient state is due to a step in the line input voltage. The concept of a dual-transistor base-drive circuit using the Cuk switching regulator topology enables low-volume construction [2]. The unit provides two base drive outputs using a single switching converter. It can be used to control two individual power transistors in different inverter configurations, e.g., common-emitter or bridge configurations.

A new concept for modelling PWM-controlled converters, the low-frequency behaviour models of hysteretic current-mode controlled CUK converters, including those with coupled inductors, are developed [3] [9]. These models are simple, accurate and easy to use. Computer simulations based on such models are carried out to analyse transfer characteristics and transient responses. Based on these models, the characteristics of hysteretic current-controlled cuk converters under various operating conditions were simulated and experimentally verified. The study of the characteristics of Cuk converters in discontinuous-capacitor-voltage mode operation is being done [4]. A Cuk converter in this mode of operation is an

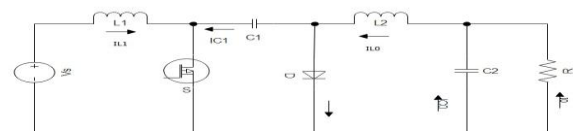
inherent power-factor corrector and features soft turn-off switching. Simulation and experimental results are reported to verify the theoretical analysis. The undesired load variation in a DC-DC converter must be accounted for when designing a controller for stable operation [5]. This paper presents a state feedback control design in which feedback is taken from the load state and compared with the desired value. Errors in each operation are computed, and the average is taken over the number of iterations to determine the control parameter. Despite the various advantages of the CUK converter, it is a major challenge to analyse and control it to meet design specifications [6]. Controller design of the CUK converter is done very carefully because it has four state variables and can operate in two continuous conduction mode CCMs and two discontinuous conduction mode (DCMs) as well. Sliding-mode and hysteresis control are generally used to design controllers for the CUK converter.

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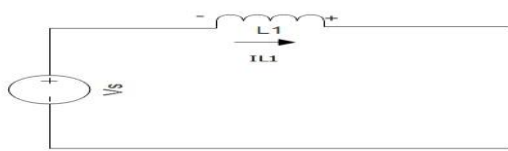
III. CUK CONVERTER

The Cuk converter is a DC-DC converter that is essentially a cascade connection of a conventional boost converter and a buck converter, with a capacitor to couple energy. It has two inductors and two capacitors. Here, the input capacitor is the primary means of transferring energy from the input to the output. It has low switching losses and the highest efficiency among all non-isolated DC-DC converters. The output capacitor and the inductor eliminate the need for an additional filter circuit. Cuk converters generate low noise and electromagnetic interference [EMI] and have better dynamic response compared to conventional DC-DC converters.

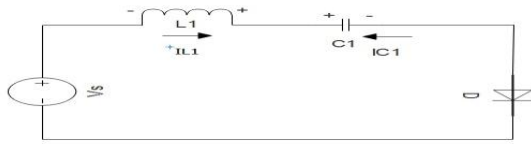
A. Working Principle



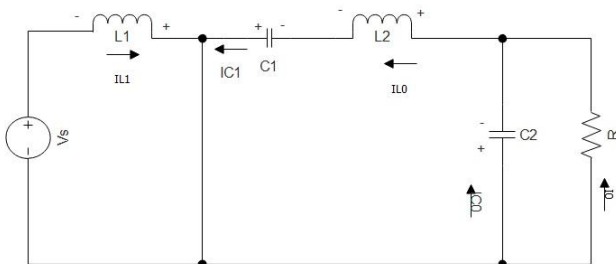
[Fig.1: Schematic Circuit Diagram of DC-DC Cuk Converter]



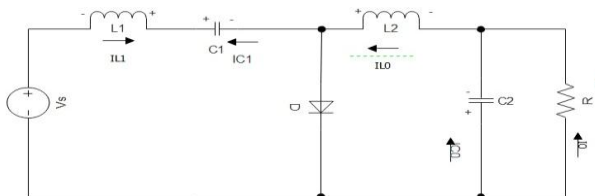
[Fig.2: Equivalent Circuit Diagram of DC-DC Cuk Converter in Mode-1]



[Fig.3: Equivalent Circuit Diagram of DC-DC Cuk Converter in Mode-2]



[Fig.4: Equivalent Circuit Diagram of DC-DC Cuk Converter in Mode-3]



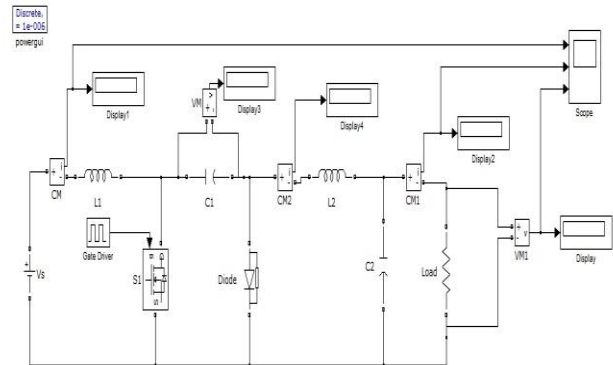
[Fig.5: Equivalent Circuit Diagram of DC-DC Cuk Converter in Mode-4]

B. Operation

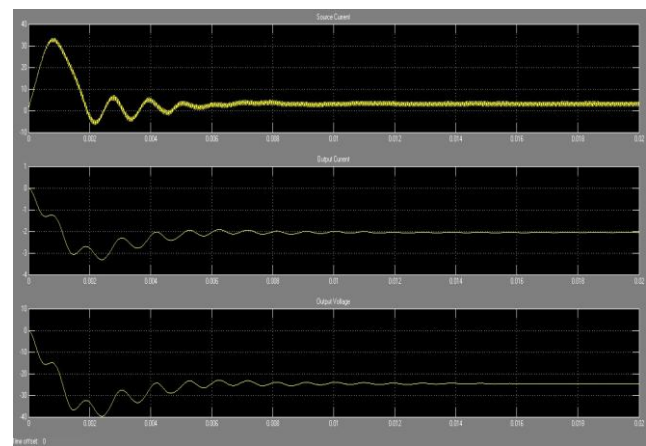
The Cuk converter provides an output voltage that is either less than or greater than the input voltage, but the output voltage polarity is opposite to that of the input voltage. When the input voltage is turned on, and the switch is turned off, then the diode D_1 is forward-biased, and the capacitor C_1 is charged through L_1 , D_1 and supply E or V_g . The proposed converter operates in two modes. Mode 1 begins when the switch is Q_1 is turned ON at $t=0$ [refer to fig.2]. The current through the input inductor L_1 rises, and at the same time, the voltage of the input capacitor C_1 reverse biases the diode D_1 and turns it off. The capacitor C_1 discharges its stored energy to the circuit formed by C_1 , output capacitor C_2 , load and output inductor L_2 .

Mode 2 begins when it is turned off at time $t =$ [refer to fig. 3]. The capacitor is charged from the supply, and the energy stored in the inductor is transferred to the load. The diode and the switch provide synchronous switching action. The capacitor provides the medium for transferring energy from the source to the load.

IV. SIMULATION AND RESULT



[Fig.6: Simulation Diagram of the Cuk Converter]



[Fig.7: Simulated Waveform of the Cuk Converter]

From the simulated waveform above, the output voltage and current have negative magnitudes, as predicted theoretically. The output voltage shows some oscillations and settles in 0.014 seconds, which is very small. The output voltage and output current have magnitudes of 25 V and 2 A, respectively.

V. STATE SPACE ANALYSIS OF CUK CONVERTER

Let x be the matrix that defines the state variables to be analysed. The Cuk converter has four energy storage components, namely two inductors and two capacitors [both on the input and output sides], therefore four state variables need to be considered. So

$$x = \begin{bmatrix} i_1 \\ i_2 \\ v_1 \\ v_2 \end{bmatrix} \quad (1)$$

where
 i_1 = inductor current of input inductor L_1
 i_2 = inductor current of output inductor L_2

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v_1 = capacitor voltage of input capacitor C_1

v_2 = capacitor voltage of input capacitor C_2

Let u be the input, which is equal to the supply voltage. V_s

And y is the output matrix, which is the same as V_o .

The governing equation for the state space analysis is as follows.

$$\frac{dx}{dt} = Ax + Bu \quad (2)$$

$$y = Cx + Eu \quad (3)$$

During switch ON (i.e., DT_s)

$$\frac{di_1}{dt} = \frac{V_s}{L_1} \quad (4)$$

$$\frac{di_2}{dt} = \frac{v_1 - v_2}{L_2} \quad (5)$$

$$\frac{dv_1}{dt} = \frac{-i_2}{C_1} \quad (6)$$

$$\frac{dv_2}{dt} = \frac{i_2}{C_2} - \frac{v_2}{RC_2} \quad (7)$$

During switch OFF [ie. $(1-D)T_s$]

$$\frac{di_1}{dt} = \frac{-v_1 + V_s}{L_1} \quad (8)$$

$$\frac{di_2}{dt} = \frac{-v_2}{L_2} \quad (9)$$

$$\frac{dv_1}{dt} = \frac{i_1}{C_1} \quad (10)$$

$$\frac{dv_2}{dt} = \frac{i_2}{C_2} - \frac{v_2}{RC_2} \quad (11)$$

Table I: Parameters for Controller Design

1	Source Voltage	10 V
2	duty cycle	.6
3	input inductor	.4e-3 H
4	input capacitor	1e-6 Farad
5	Output Capacitor	1e-6 Farad
6	Output Inductor	.6e-3 H
7	load(resistive)	100
1	Source Voltage	10 V

Putting the values of the parameters in the equation of the open-loop transfer function of the proposed DC-DC converter, we have,

$$G_{v_d}(s) = \frac{V_g}{(D)^2} \left[\frac{s^2 \left(\frac{L_1 C_1}{D} \right) + s \left(\frac{D^2 L_1}{(D)^2 R} \right) + 1}{s^4 \left(\frac{L_1 C_1 L_2 C_2}{(D)^2} \right) + s^3 \left(\frac{L_1 C_1 L_2}{(D)^2 R} \right) + s^2 \left(\frac{L_1 C_1 L_2}{(D)^2} + L_2 C_2 + \frac{D^2}{(D)^2} L_1 C_2 \right) + s \left(\frac{L_2}{R} + \frac{D^2 L_1}{(D)^2 R} \right) + 1} \right]$$

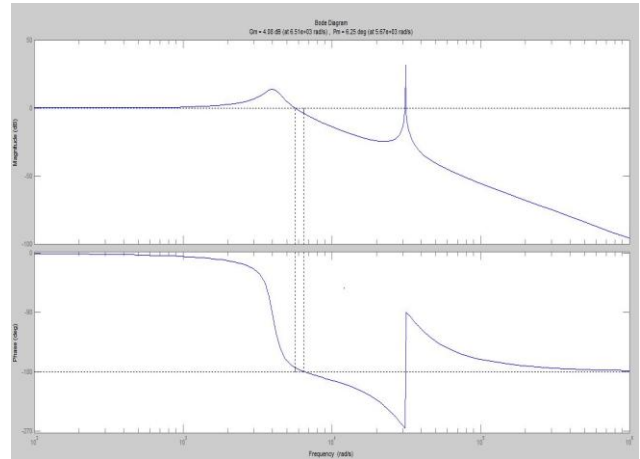
$$G_p(s) = 125 \left[\frac{s^2 (10^{-9}) - s (3 \times 10^{-5}) + 1}{s^4 (62.4 \times 10^{-18}) + s^3 (0.05 \times 10^{-12}) + s^2 (62.4 \times 10^{-9}) + s (0.05 \times 10^{-3}) + 1} \right]$$

VI. PROPOSED CONTROLLER DESIGN

A. Design of the Lead Controller for the Cuk Converter

In accordance with the design specification and frequency-domain constraints, for the system to be robust, the phase margin should be between 30° and 45° . By plotting

the Bode plot of the uncompensated CUK converter, we have,



[Fig.8: Bode Plot of an Uncompensated Cuk Converter]

The phase margin of the uncompensated cuk converter is found to be 6.25° . So, an additional 48.75° phase margin must be added to the system, with an error constant of 10° , to achieve the desired 45° .

The next step is to determine the value of α , given by the following relation.

$$\alpha = \frac{1 - \sin \phi_{ex}}{1 + \sin \phi_{ex}}$$

So, the value of α is found to be .141. To find the gain crossover frequency for an extra 48.75° phase margin, we have:

$$G_p(s) \Big|_{s=j\omega} \Big|_{\omega=\omega_{gcf}} = -10 \log \left(\frac{1}{\alpha} \right)$$

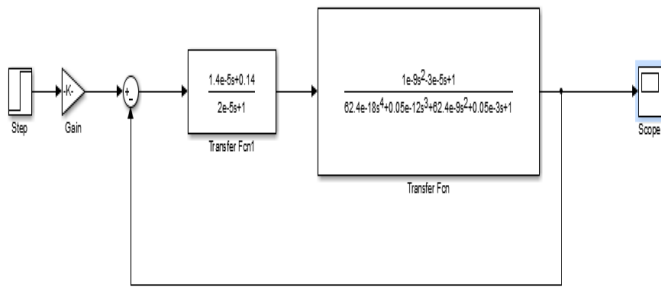
Since the plant has a fourth-order characteristic equation, we have four distinct values of the gain crossover frequency (i.e., all the roots are complex). Considering both the real and imaginary parts positive, the value is 15363.70. After entering all required values, we obtain $Z_c = 5761.38$ and $P_c = 40969.86$. Now, the transfer function of the lead controller is given by:

$$G_c(s) = \frac{1.4e - 05s + 0.14}{2e - 05s + 1}$$

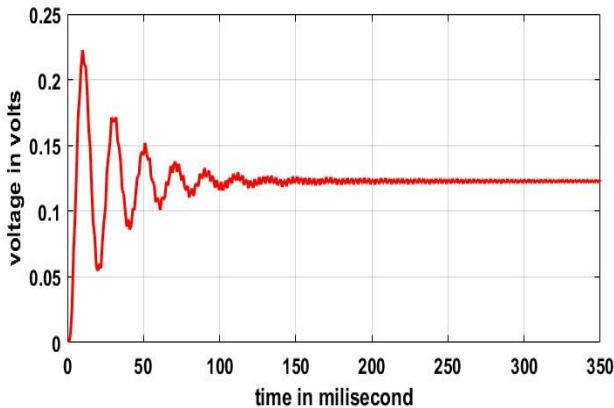
The closed-loop transfer function of the cuk converter with lead compensator is given by:

$$G(s) = \frac{1.4e - 14s^3 - 2.8e - 10s^2 + 9.8e - 06s + 0.14}{1.248e - 21s^5 + 6.34e - 17s^4 + 1.312e - 12s^3 + 6.312e - 08s^2 + 7.98e - 05s + 1.14}$$

So, the closed-loop simulation of the cuk converter with the proposed lead controller is given by:



[Fig.9: Schematic Block Diagram of the Cuk Converter with Lead Controller]



[Fig.10: Output Voltage Waveform of the Cuk Converter with Lead Controller]

B. Design of proposed Lag-Lead Controller for Cuk Converter:

A lag-lead compensator is a combination of a lag compensator and a lead compensator. The lag section consists of a real pole and a real zero, with the pole to the right of the zero. The lead section consists of a real pole and one real zero, but the zero lies to the right of the pole. So, for the lag section

$$180^\circ + \text{angle of } G_p|_{s=j\omega} = 55^\circ$$

Solving the above expression, we have the gain crossover frequency as 2.7831×10^4 . Now, to find the constant term β , we have to equate the following expression

$$20 \log G_p(s)|_{s=j\omega} = 20 \log \beta$$

So, by solving the above equation, the values of β are 13.48. Next, we have to find out the value of τ , which is the upper cut-off frequency, and the corresponding transfer function is given by

$$G_1 = \frac{0.074 + 1.066e - 05}{s + 1.07e - 05}$$

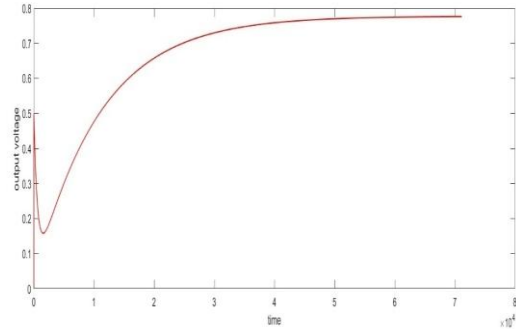
Similarly, when we plot the root locus of the Cuk converter with the Lag compensator, we can find out the gain crossover frequency for the Lead compensator at the phase line as 1.36×10^4 . So, the value of τ in this case will be determined by a similar procedure to that used in 3.4×10^4 .

The final transfer function of the Lag-Lead compensator is given by

$$G_c = \frac{139.0s^2 + 0.09414s + 1.066e - 05}{140.2s^2 + 1.002s + 1.07e - 05}$$

Therefore, the transfer function of the Cuk converter with Lag-Lead compensator is given by

$$G(s) = \frac{1.399e - 07s^4 - 0.004196s^3 + 139.9s^2 + 0.09414s + 1.066e - 05}{8.748e - 15s^6 + 7.01e - 12s^5 + 8.888e - 06s^4 + 0.002814s^3 + 280.1s^2 + 1.096s + 2.136e - 05}$$



[Fig. 11: Output Voltage Waveform of the Cuk Converter with Lag-Lead Controller]

VII. CONCLUSION

In this paper, the concept of frequency-domain analysis of a DC-DC CUK converter is presented in detail. The state-space analysis of the DC-DC Cuk converter is being performed mathematically, and it has been found to have a fourth-order pole in the s-plane. Simulation of the cuk converter with the proposed lag and lag-lead controllers is being successfully performed. The simulation results show the effectiveness of the proposed control scheme compared to time-domain-based controllers. Figure 10 shows that with the lag controller, the plant takes only 0.15 sec to return to steady state from the transient caused by load variations. In contrast, the lag-lead controller has a value of 0.04 sec. The mathematical analysis and closed-loop control simulation with the proposed control scheme demonstrate the effectiveness and reliability of the frequency-domain-based control algorithms.

DECLARATION STATEMENT

As the article's author, I must verify the accuracy of the following information after aggregating input from all authors.

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adequate resources of this article are publicly accessible.

- **Author's Contributions:** The authorship of this article is contributed equally to all participating individuals.

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