Journal of Information & Optimization Sciences
ISSN 0252-2667 (Print), ISSN 2169-0103 (Online)
Vol. 45 (2024), No. 2, pp. 595–603
DOI : 10.47974/JIOS-1597

Implementation of unidirectional control mechanism for DC-DC converters

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Abstract

In the ongoing global transition from non-renewable energy sources to renewables such as solar, wind, and tidal power, solar energy plays a predominant role. Take, for instance, the widespread use of solar-powered e-rickshaws. These vehicles require a consistent and low-harmonics DC supply to charge their batteries. However, during overcast days, the solar panels on the e-rickshaws may struggle to provide the necessary power for battery charging, leading to potential interruptions. One effective solution to address this challenge involves implementing a DC-DC converter to maintain a stable voltage supply to the load. Three types of DC converters have been designed and their input-output voltage relations are calculated

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and compared. All three converters are simulated using MATLAB with an open-loop control approach.

Subject Classification: *93-XX, 94-XX.*

Keywords: *Duty cycle, Output voltage, Input voltage, Frequency, Load resistance.*

1. Introduction

Electric vehicles (EVs) are experiencing rapid growth, driven by concerns about sustainability and energy efficiency. Efficient battery management is crucial for maximizing EV range and lifespan. DC-DC converters play a vital role in regulating voltage and current flow between the battery and various electrical components. Various types of DC-DC converters, such as buck, boost, and buck-boost converters, are employed in EVs to accommodate the varying voltage requirements of different loads.

2. Literature Review

Research on open-loop converters for EVs is limited but growing. Research by Chen et al. (2019) [1] investigated the application of open-loop control techniques in DC-DC converters for EVs, emphasizing the importance of accurate modeling and parameter selection for optimal performance. Research by Li et al. (2020) [2] delved into efficiency optimization strategies for open-loop controlled DC-DC converters, emphasizing the importance of considering real-world operating conditions. Research by Kim et al. (2018) [3] explored the impact of open-loop control on voltage regulation and transient response in DC-DC converters. Recent research by Wang et al. (2021) [4] proposed a comprehensive approach to integrate open-loop controlled DC-DC converters with advanced battery management algorithms, enhancing overall system performance and reliability.

3. System Modeling

There are two methods to step-up and step-down the DC voltage.

i. Employing an inverter to transform the DC input [5] into AC output, can be a time-consuming and expensive procedure.

ii. Instead of this opt for a more streamlined approach by utilizing DC-to-DC converters, which come in three types.

(a) Buck converter can be employed [6] to step down the dc voltage. (b) Boost converter can be used to step-up the dc voltage. (c) The Buck-Boost converter has the capability to both step up and step down the DC voltage.

Consider a basic circuit of a buck converter as depicted in Figure 1. The relation between input and output voltage is given by the equation (1).

$$v_0 = Dv_s \tag{1}$$

This is given by

$$D = \frac{T_{oN}}{T} \tag{2}$$

The adjustment of the duty cycle [7, 8] allows for the variation of the output voltage. Ripples in the inductor current are shown in Figure 2, and this ripple is denoted by ΔI_L.

$$\Delta I_L = \frac{D[1-D]v_s}{fL} \tag{3}$$

Ripple in output voltage Δv_c

$$\Delta v_c = \frac{\Delta I_L}{8cf} \tag{4}$$

Critical inductance (*Lc*) is minimum value of inductance required for stable and efficient operation, which is given by:

$$L_C = \frac{R[1-D]}{2f} \tag{5}$$

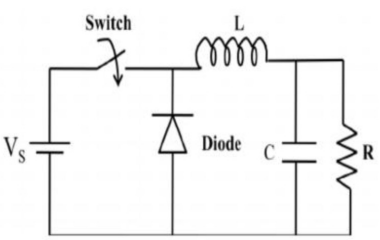


Figure 1

Diagram of Buck Converter

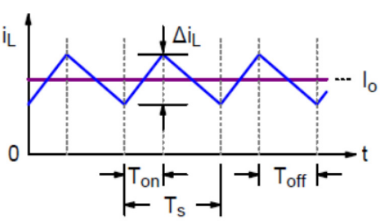


Figure 2

Ripple in Inductor current

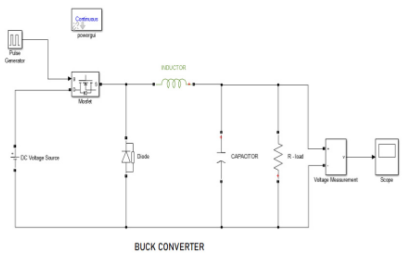


Figure 3

MATLAB model of Buck Converter

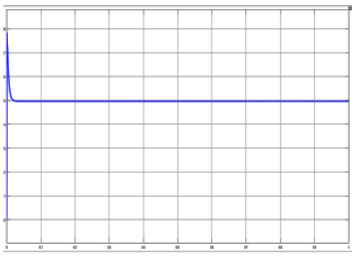


Figure 4

Output Voltage

Duty cycle in case of critical inductance.

$$D = 1 - \frac{2L}{RT} \tag{6}$$

The critical capacitance (c_c) is essential for filtering and smoothing the output voltage, reducing ripple and maintaining a relatively constant voltage level shown in Figure 3.

$$C_C = \frac{1}{8fR} \tag{7}$$

The open-loop buck converter is simulated using MATLAB Simulink, and the corresponding output voltage is depicted in Figure 4.

Despite anticipating an output of 4.8V for the given input, the obtained result remains a consistent DC voltage of 4.969V, as illustrated in Figure 4.

A Boost converter shown in Figure 5 is a type of DC-DC converter that increases (boosts) the input voltage to a higher output voltage.

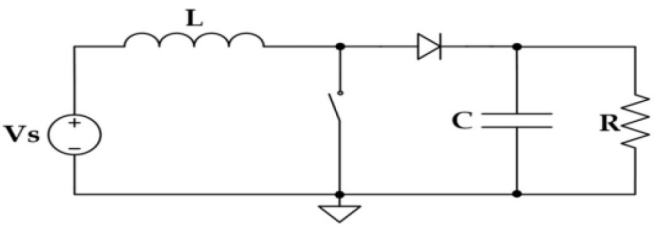


Figure 5

Diagram of a boost converter circuit

The relation between the output and input voltage is given by the equation.

$$v_0 = \frac{v_s}{1-D} \tag{8}$$

where D is the duty cycle and $[1-D]<1$

$v_0 > v_s$, mean output voltage is more than the input voltage.

Ripple in inductor current is represented as

$$\Delta I_L = \frac{DV_s}{fL} \tag{9}$$

$$\Delta v_0 = \frac{DI_0}{fC} \tag{10}$$

Critical inductance (L_c):

$$L_C = \frac{D[1-D]^2 R}{2f} \tag{11}$$

Critical capacitance (c_c):

$$C_C = \frac{D}{2fR} \tag{12}$$

The simulation of the open-loop boost converter model in MATLAB Simulink is illustrated in Figure 6.

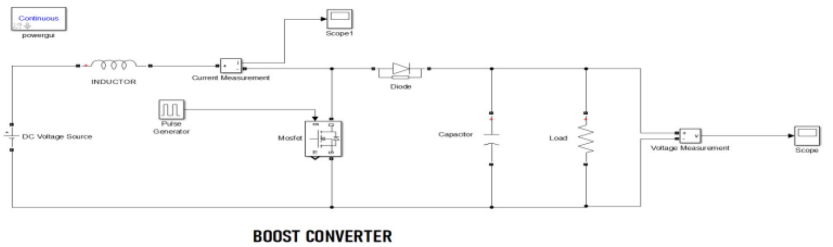


Figure 6

MATLAB model of Boost Converter

Despite anticipating a 20V output with the specified input, the observed output voltage in Figure 8 is recorded at 18.92V.

Ripple in inductor current is which is shown in Figure 7.

Effect of inductor resistance on boost converter.

Including the inductor resistance, the output voltage is:

$$v_0 = \frac{v_s}{[1-D]+\frac{r}{R[1-D]}} \tag{13}$$

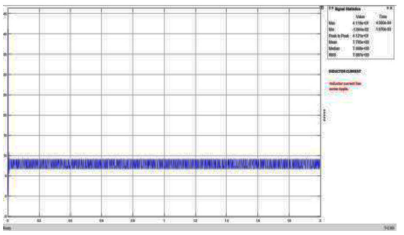


Figure 7
Inductor current

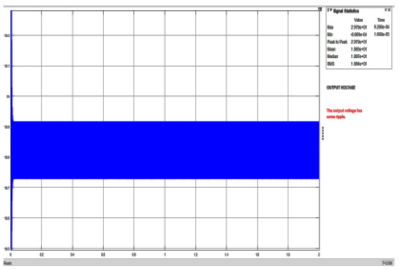


Figure 8
Inductor current output voltage

At D = 0,

$$v_0 = \frac{v_s}{1+\frac{r}{R}} \tag{14}$$

which means output voltage is less than input voltage.

$$v_0 < v_s$$

At D = 1, $v_0 = 0$

$$v_0 = \frac{v_s}{[1-D]+\frac{r}{R[1-D]}} \tag{15}$$

The denominator value should be low for the maximum output voltage. The value of D for maximum output voltage can be calculated using:

$$D(\max) = 1 - \sqrt{\frac{r}{R}} \tag{16}$$

The maximum output voltage of the boost converter with inductor resistance is given by:

$$v_{O(\max)} = \frac{v_s}{2}\sqrt{\frac{R}{r}} \tag{17}$$

The Buck–boost converter is a type of DC-to-DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude and is shown in Figure 9.

The output voltage can be represented by the equation.

$$v_0 = \frac{D}{1-D} \cdot v_S \tag{18}$$

The inductor current can be expressed by the equation.

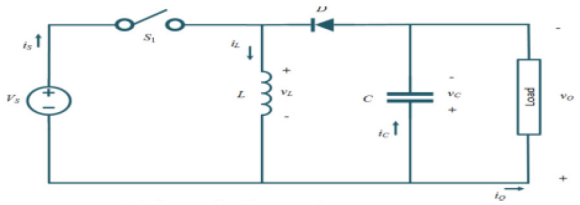


Figure 9

Buck Boost Converter

$$I_L = \frac{I_0}{1-D} \tag{19}$$

Ripple in output voltage can be derived from capacitor current i_c and the same is represented as:

$$\Delta v_0 = \frac{DI_0}{fC} \tag{20}$$

Critical Inductance:

$$L_C = \frac{R[1-D]^2}{2f} \tag{21}$$

Critical capacitance:

$$C_C = \frac{D}{2fR} \tag{22}$$

The range of duty cycle to operate as a buck converter is:

$$0.1 \le D \le 0.5$$

The range of duty cycle to operate it as a boost converter is:

$$0.6 \le D \le 0.9$$

The simulation of the buck boost converter model in MATLAB Simulink is illustrated in Figure 10.

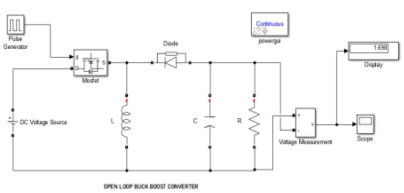


Figure 10

Open Loop buck boost

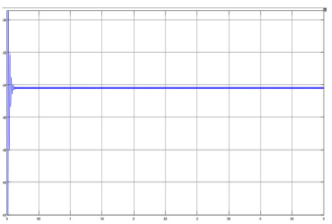


Figure 11

Buck Boost Converter output voltage

With this input, the output voltage should be 36v. But the simulated output voltage obtained is 34.23v which is shown in Figure 11.

4. Conclusion

In this paper the advantages of open-loop control of DC-DC converters were highlighted, while acknowledging the limitations in terms of output regulation and robustness compared to closed-loop counterparts. These include simplicity, low cost, faster response times, and radiation tolerance. Open-loop control is suitable for applications with minimal load variations and well-defined input voltages. Careful component selection and design are crucial for achieving desired output characteristics within an open-loop system.

5. Future scope

The future scope of open-loop DC-DC converters in electric vehicle applications holds significant promise for enhanced efficiency [9, 10] and simplicity. With ongoing advancements in technology, the integration of open-loop converters in electric vehicles can contribute to improved power management and overall performance, addressing the evolving needs of the electric mobility sector.

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