# Design and Analysis of Feedback Control for DC-DC Buck Converter

Sajad Ahmad Tali, Faroze Ahmad, Inayat Hussain Wani
Islamic University of Science and Technology, Awantipora, J & K, India
Corresponding author: Inayat Hussain Wani, Email: inayathussain9018@gmail.com

The DC-DC buck converters have wide range of emerging applications such as in photovoltaic systems and linear drives which have the requirement of high efficiency and optimum transient response over dynamic changes in line voltage and load. The purpose of this manuscript is to make a DC-DC buck converter robust against the deviations in the input voltage, load current and to reduce the steady state error. In this paper averaging and linearization of buck converter has been done and then applying K-Factor method controller has been designed in such a way that stabilizes the output voltage of buck converter irrespective of the line voltage and load disturbances. Mathematical analysis and MATLAB simulation waveforms of proposed method validate that output voltage is maintained irrespective of the disturbance in line voltage and load variations while retaining acceptable phase margin.

**Keywords**: DC-DC buck converter, PWM converter, Compensator, Phase margin, Bode plot.

2021. In Rahul Srivastava & Aditya Kumar Singh Pundir (eds.), *New Frontiers in Communication and Intelligent Systems*, 319–328. Computing & Intelligent Systems, SCRS, India. https://doi.org/10.52458/978-81-95502-00-4-33

# 1 Introduction

Modern Switching converters are an essential part of many electronic systems. They are mainly used to regulate the input voltage and to transfer the power efficiently. Switching converters have applications in Wind Energy Conversion Systems [1], Photovoltaic Systems (PV), high Voltage DC transmission system [2], communication equipment's, Universal Serial Bus (USB) chargers to step down the input voltage [3], battery powered devices and in many other applications. The output of a switching converter is sensitive to perturbations in line voltage, load resistance and non-ideal behavior of components therefore compensators (Feedback network) are required to mitigate this problem of unstable output under different perturbations in line voltage ($V_L$) and load resistance ($R_L$).There are many methods of designing a compensator for a switching converter such as Voltage Control Mode (VCM), Current Control Mode (CCM) and Constant On-Time Control[4] etc, each of these converters have their own limitations such as requirement of sensors for feedback signals, complex control schemes which increases cost[5]. In addition to that output voltage and efficiency is reduced due to parasitic capacitance of the circuit components and voltage drop across diode. To overcome these issues, the performance analysis of buck converter under both varying line voltage and load conditions has been done. In this paper the small signal model of the buck converter and pulse width modulator (PWM) converter is obtained and then the analysis and design of the feedback loop for DC-DC buck converter has been done in the frequency domain with the aid of bode plot. For proper functioning of the converter phase margin should be between 45°- 60°. The open loop buck converter has usually low phase margin. In this paper K-factor method is used to improve the phase margin of DC-DC buck converter. An improved feedback control for DC-DC buck converter is designed for the phase margin of 55°and crossover frequency of 10 KHz further mathematical analysis for the same is done using Matlab Simulink. Waveform results carried out shows the improved performance of the buck converter over wide range of $V_L$ and $R_L$.

# 2 Design of open loop Buck converter

The DC-DC buck converter is designed to convert 15V input to 5V output at 2A load current. The designed buck converter is subjected to wide range of input voltage and load to examine its performance. The specifications of the buck converter are given in the table 1.

**Table 1** Specifications of Buck Converter

| **Quantity** | **Name of Unit** | **Symbol** |
|---|---|---|
| Capacitor | 12.5µF | C |
| Inductor | 83.25µH | L |
| Resistor | R=2.5Ω | R |
| Load current | 2A | $I_L$ |
| Input voltage | 15V | $V_{in}$ |
| Output voltage | 5V | $V_{out}$ |
| Frequency | 200 KHz | F |
| Duty cycle | D=33.33% | D |
| Capacitor resistance | 0.15Ω | $R_C$ |
| Inductor Ripple current | 20% of $I_L$ | $I_r$ |

# 3 Implementation and analysis of Buck converter in MATLAB Simulink

The designed buck converter is implemented in Matlab Simulink and results carried out under dynamic changes in line voltage and load shows the performance of buck converter as depicted in fig.2, fig.3 and fig.4.

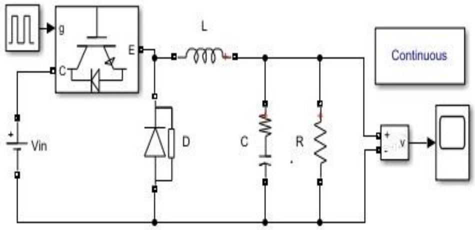


**Fig. 1.** Open loop Buck converter

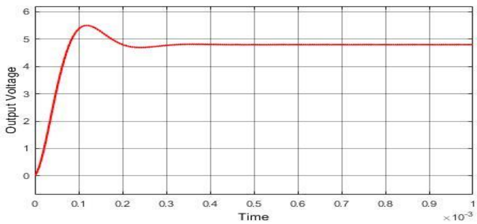


**Fig. 2.** The output waveform of the converter under constant voltage and constant load current

From fig.2 It can be noticed that when the open loop buck converter is supplied with constant voltage of 15V and constant load of 2.5$\Omega$ the output is stable. However, upon subjecting DC-DC buck converter to dynamically changing load the output of the buck converter is unstable as depicted in fig.3.

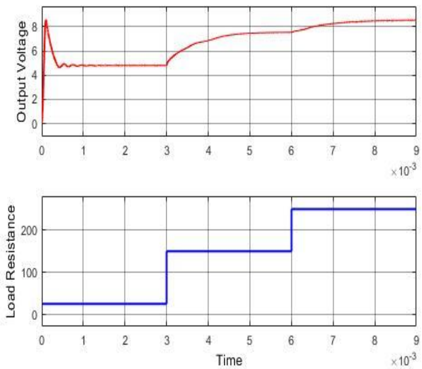


**Fig. 3.** Response under varying Load

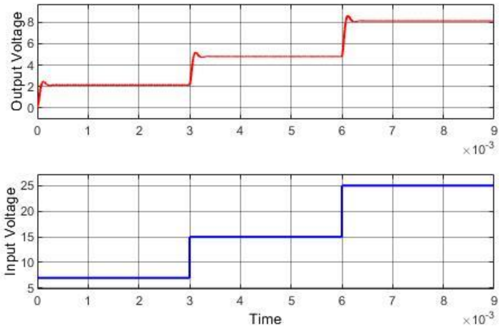


**Fig. 4.** Output Response under varying Input voltage

From fig.4 it can be examine that when the input voltage changes the output follows the input voltage which is undesirable because when the input voltage increases output voltage also increases as $V_O= DV_{in.}$, where D is duty cycle.

### 3.1 Modelling of buck converter

The schematic for the buck converter when the switch is open and closed are shown in fig.5(a) and fig.5(b) respectively.

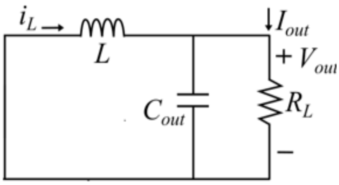


**Fig.5** (a) buck converter when switch is open

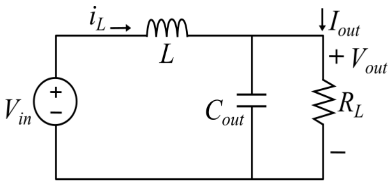


**Fig.5** (b) buck converter when switch is closed

From fig.1 (a)

$$\frac{di_L}{dt} = \frac{V_{in} - V_{out}}{L} - \frac{V_{out}}{L}(1-d) \tag{1}$$

$$\frac{di_L}{dt} = \frac{V_{in}}{L}d - \frac{V_{out}}{L} \tag{2}$$

From fig. 1 (b)

$$\frac{dV_{out}}{dt} = \frac{i_L - V_{out}/R}{C} d - \frac{i_L - \frac{V_{out}}{R}}{C}(1-d) \quad (3)$$

$$\frac{dV_{out}}{dt} = \frac{i_L}{C} - \frac{V_{out}}{RC} \quad (4)$$

Therefore, the control to output transfer function can be obtained from (1) and (2) as

$$G_p(s) = \frac{V_{out}}{d} = \frac{\frac{V_{in}}{LC}}{s^2 + \frac{s}{RC} + \frac{1}{LC}} \quad (5)$$

Output control transfer function by taking (ESR) of capacitor into account

$$G_p(s) = \frac{\frac{V_{in}}{LC}(1+sCr)}{s^2 + s(\frac{1}{RC} + \frac{r}{L}) + \frac{1}{LC}} \quad (6)$$

### 3.2 Modeling of Pulse width modulator (PWM ) converter

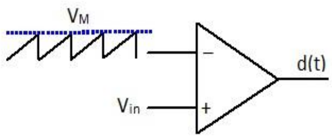


**Fig. 6** PWM converter

The duty cycle of the PWM is given by

$$d(t) = \frac{v_{in}(t)}{V_M} \quad (7)$$

By taking Laplace transform of equation 7 the transfer function $G_{PWM}(s)$ of PWM is given by

$$G_{PWM}(s) = \frac{D(s)}{V_{in}(s)} = \frac{1}{V_M} \quad (8)$$

where $V_M$ is peak voltage of reference signal.

### 3.3 Modeling of compensator

The transfer function of the compensator being used in this paper is given by

$$G_c(s) = \frac{k}{s}\frac{(1+\frac{s}{\omega_Z})^2}{(1+\frac{s}{\omega_p})^2} \quad (9)$$

Therefore, loop transfer function is given by

$$L(s) = G_{PWM}(s)G_C(s)G_P(s) \quad (10)$$

In this work and $V_M = 1$ therefore

$$L(s) = G_C(s)G_P(s) \quad (11)$$

In order to design compensator the value of DC gain (k) and the location of poles($\omega_p$) and zeros ($\omega_Z$) required are calculated using the equations 12-16.

$$\emptyset_b = -90° - \angle G_p + \emptyset_{PM} \quad (12)$$

$$K_b = \tan(45° + \frac{\emptyset_b}{4}) \quad (13)$$

$$\omega_Z = \frac{2\pi f_C}{K_b} \quad (14)$$

$$\omega_p = 2\pi f_C K_b \quad (15)$$

$$k = \frac{1}{|G_p G_C|_{f_C}} \quad (16)$$

where ($\phi_b$) is the phase required to add the open loop converter and ($\phi_{PM}$) is the phase margin required to achieve the stability.

# 4 Design and analysis of feedback loop

The transfer function of the open loop buck converter is given by equation 6 using the values of components listed in table.1

$$G_p(s) = \frac{2.703 \times 10^4 s + 1.441 \times 10^{10}}{s^2 + 3.38 \times 10^4 s + 9.61 \times 10^8}$$

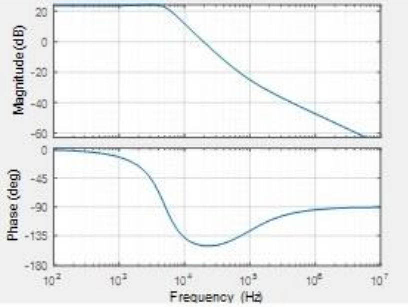


**Fig. 7.** Bode plot of open loop buck converter transfer

From the fig.7 it can be noticed that phase margin is not $55°$. The feedback loop is designed for crossover frequency of 10 KHz and phase margin of 55°. Therefore, from equations 12-15

$$\emptyset_b = 102.86°, K_b = 2.858, \omega_P = 1.80 \times 10^5 \frac{rad}{s}$$

$$\omega_Z = 2.20 \times 10^4 \frac{rad}{s}$$

The controller transfer function is

$$G_C = k \frac{3.22 \times 10^{10} s^2 + 1.42 \times 10^{15} s + 1.56 \times 10^{19}}{4.83 \times 10^8 s^3 + 1.74 \times 10^{14} s^2 + 1.56 \times 10^{19} s}$$

The bode plots of controller and loop transfer function for k=1 are shown in figure 8 and figure 9.

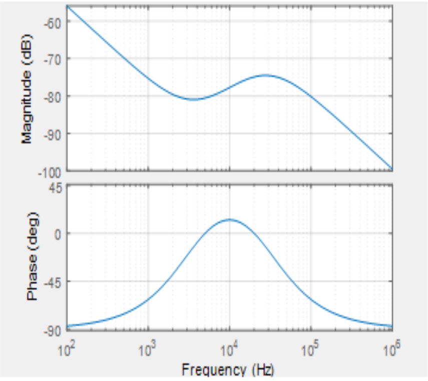


**Fig. 8.** Bode plot proposed controller

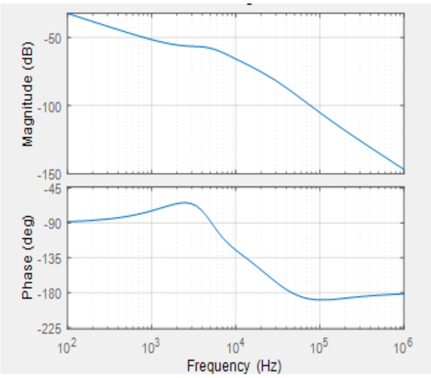


**Fig.9.** Bode plot of closed loop system (k=1)

Fig.9 shows at the desired crossover frequency ($10^4$Hz) the phase margin is 55° but the magnitude is not zero dB.Therefore, the value of k can be calculated so that magnitude becomes 1 or zero dB. The gain at crossover frequency calculated with the help of bode plot is $5.15 \times 10^{-4}$ therefore

$$k = \frac{1}{5.15 \times 10^{-4}} = 1.94 \times 10^3$$

The bode plot of loop transfer function for $k = 1.94 \times 10^3$is shown in figure 11.

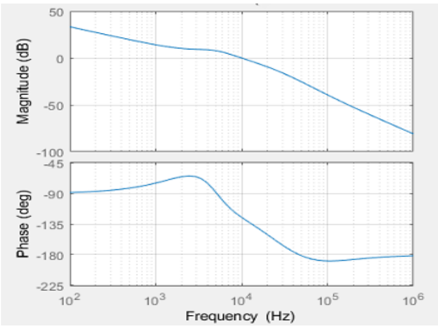


**Fig. 10.** Bode plot of closed loop system ($k = 1.94 \times 10^3$)

From the fig .10 it is clear that crossover frequency is $10^4$Hz.

# 5 Results

The MATLAB simulation results of closed loop DC-DC buck converter having crossover frequency of 10 KHz and phase margin of 55° under dynamic changes in line voltage and load are given in the fig.13 and 14 respectively.

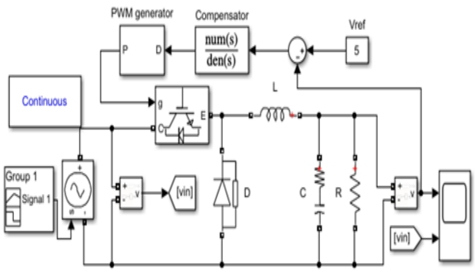


**Fig.11.** Closed loop buck converter

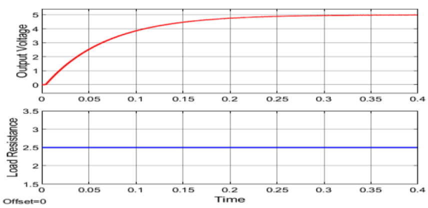


**Fig. 12.** Simulation waveform under constant input voltage and constant load current

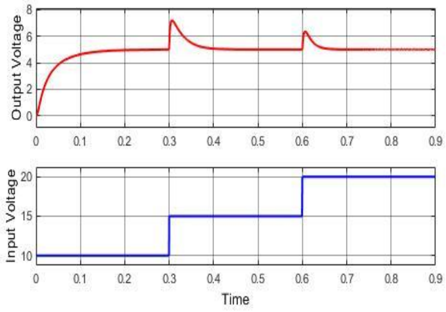


**Fig. 13.** Simulation waveform of closed loop buck converter under varying input voltage

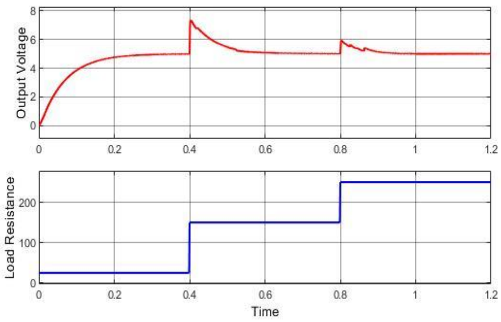


**Fig. 14.** Simulation waveform of buck converter under varying load

It can be noticed from the fig.13 and fig.14 that output follows the supply voltage irrespective of the dynamic changes in supply voltage and load.

**Table 2.** Performance comparison of open loop buck converter (OLBC) and closed loop buck converter (CLBC) at constant load

| Input Voltage | Output of OLBC | Output of CLBC |
|---|---|---|
| 10 V | 3.2 V | 5 V |
| 15 V | 4.7 V | 5 V |
| 20 V | 6.2 V | 5 V |

**Table 3.** Performance comparison of (OLBC) and (CLBC) at constant line voltage

| Load Resistance | Output of OLBC | Output of CLBC |
|---|---|---|
| 5 Ω | 4.8 V | 5 V |
| 15 Ω | 7.8 V | 5 V |
| 25 Ω | 8.2 V | 5 V |

## 6 Conclusion

The output of a buck converter is dependent on variations in supply voltage, load and non-ideal behavior of components. Averaging and linearization method is used to obtain transfer function for the DC-DC buck converter furthermore by K-method the compensator is designed to improve the phase margin of closed loop buck converter. Mathematical analysis and simulation results verify the output voltage is stable and reaches steady state quite fast over dynamic changes in line voltage and load. With the aid of complex control theory, a proper controller can be designed by analyzing the frequency response of the DC-DC converter to make the DC-DC converter robust against disturbance in load and supply voltage. The future scope of this work is to validate the simulation results on hardware and to improve the transient response of the converter.

## References

[1] Hussain, J. and Mishra, M. K. (2015). Design of current mode controlled SEPIC DC-DC converter for MPPT control of wind energy conversion systems. In *International Conference on Computation of Power, Energy, Information and Communication*, 0177-0182.

[2] El-Menshawy. M. and Massoud, A. (2019). Multimodule DC-DC Converters for High-Voltage High-Power Renewable Energy Sources. In *2nd International Conference on Smart Grid and Renewable Energy*, 1-6.

[3] Ahmad, I. and Fernandes, B. G. (2020). Concept of Universal USB Charger. *IEEE Industry Applications Society Annual Meeting*, 1-5.

[4] Ridley. R. B. (1990). A new continuous-time model for current-mode control with constant frequency, constant on-time, and constant off-time, in CCM and DCM. In *21st Annual IEEE Conference on Power Electronics Specialists*, 382-389.

[5] Sajad A. T, and Faroze, A. (2021). Comparative Analysis of PID Controller and Current Mode Controller in Matlab Simulink for DC-DC Buck Converter. *JCR*, 12.