Performance assessment of buck converter using single and cascade control loops

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Abstract

Switch mode power supplies play a vital role in the applications of computers, telecommunications and mobile chargers due to their fast-dynamic response and less power consumption. These power supplies require sophisticated and powerful solid state devices to withstand greater variations of input line voltage and load. The performance analysis of buck converter against these changes is presented in this research work. These changes are controlled with single and cascaded control schemes. Initially, the buck converter is implemented with a single output voltage loop and then a cascade control scheme. Both control schemes are designed with Proportional, Integral and derivative (PID) controllers. The cascade control scheme consists of two loops that are current and voltage loops. The buck converter is decomposed into two first-order systems and its dynamics are controlled with a cascade control scheme. These control schemes are developed and simulated in Simulink toolbox of MATLAB software. The simulated results of the buck converter with a single loop are compared to the cascaded loop. The analysis shows that with the addition of an inner current loop in cascade control scheme, the inductor current of buck converter is reduced.

Keywords
Buck converter, single loop, cascade loop, PID controllers

1. Introduction

The new development of semiconductor devices and converters increases the use of power electronics in various industrial applications. These converters have high efficiency, fast response to certain changes and low cost. Among these converters, DC converters are very popular due to their high efficiency, fast dynamic response and compactness. Buck converters are non-isolated DC converters. They are most commonly used in battery and renewable energy powered applications due to attractive features like fast switching actions, high efficiency and compact size (Shenoy et al. 2016), (Ge et al. 2018), (Mirzaei and Afzalian 2009), (Abro et al. 2009) and (Mahar et al. 2009). Buck converters are inherently non-linear due to their switching operation that produces switching transients, oscillations in output voltage and generation of harmonics when they are connected to the power system. To handle these disturbances of buck converter, various researchers (Abro et al. 2009) and (Mahar et al. 2009), (Tsang and Chan 2005), (Diaz and Soriano 2007), (Suntio et al. 2007), (Silva et al. 2015) (Kumar et al. 2008), (Ling et al. 2016) and (Wang et al. 2019) have also workout with different controller techniques. In this research paper, the buck converter is initially simulated with a single voltage loop controller. This voltage loop is designed with PID controller. Then, the cascade controller is used to control the dynamics of the buck converter. To design the cascade controller, the converter is decomposed into two systems of first-order (Abro et al. 2009) and (Mahar et al. 2009). The Cascade controller has two loops which are current loop and voltage loop. Both loops are designed with PI controllers. Finally, the results of both control schemes are compared.

2. Buck converter

It is also referred as a step down converter. The output voltage of this converter is regulated by changing the duty ratio (D) of the semiconductor switch. The circuit of topology shown in Fig.1 consists of a solid state switch, diode, input voltage, capacitor and inductor.

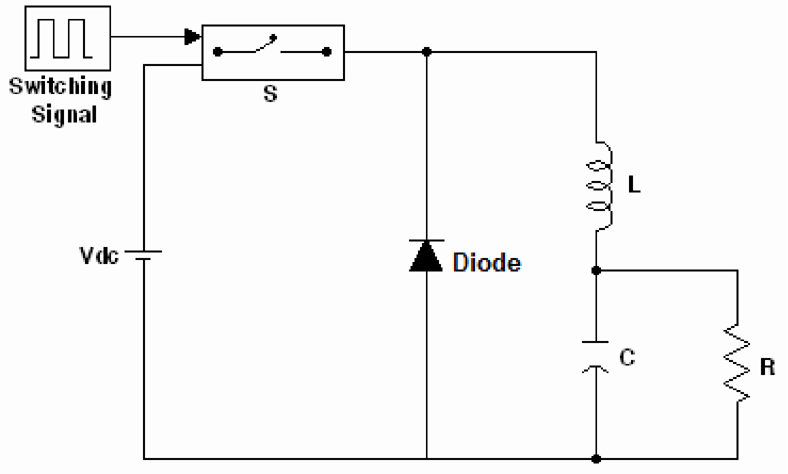

Figure 1. Buck converter

The buck converter has continuous conduction mode (CCM) and discontinuous conduction mode (DCM). The state space average model in CCM is used in this paper. Eq.1 shows the state space model of converter (Abro et al. 2009), (Mahar et al. 2009), (Tsang and Chan 2005).

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = \begin{bmatrix}0 & -\frac{1}{\mathrm{L}}\\ \frac{1}{C} & -\frac{1}{\mathrm{RC}}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix} + \begin{bmatrix}\frac{D}{L}\\ 0\end{bmatrix}V_{dc} \qquad (1)$$

3. Buck converter with single loop

The single loop controller is designed and simulated using SIMULINK toolboxes from the MATLAB software. By using Eq.1, the buck converter is implemented in the MATLAB software. The simulation model of buck converter with single voltage loop is shown in Fig. 2. In this model, the feedback signal is taken from the output voltage (V_o) and compared with reference voltage (V_{ref}). The voltage difference is then used as input of PID controller. The output of the controller is compared to the sawtooth signal of the pulse width modulator (PWM). Finally, the PWM output is used as a switching signal for solid state switch of the buck converter.

4. Buck converter with cascade loop

In this paper, the cascade control scheme is also used for control the dynamics of buck converter. This control scheme composed of two control loops, as shown in Fig. 3. The output voltage is controlled by external loop while the current is by inner loop. The basic requirement of this scheme is that the current loop is faster than outer voltage loop (Abro et al. 2009) and (Mahar et al. 2009). In this work, the current dynamics of cascade controller is 20 times faster than the voltage loop. Both control loops are implemented by Proportional Integral (PI) controllers. The detail of the design equations are documented in (Mahar et al. 2009). The PI values for voltage control loop can be obtained by using transfer function of Eq. 2 and the current-loop PI controller is obtained from the transfer function of Eq. 3.

$$G_{PI}(s)=\frac{K_1(R_1Cs+1)}{R_1s} \tag{2}$$

$$G_{PI}(s)=\frac{K_2(Ts+1)}{s} \tag{3}$$

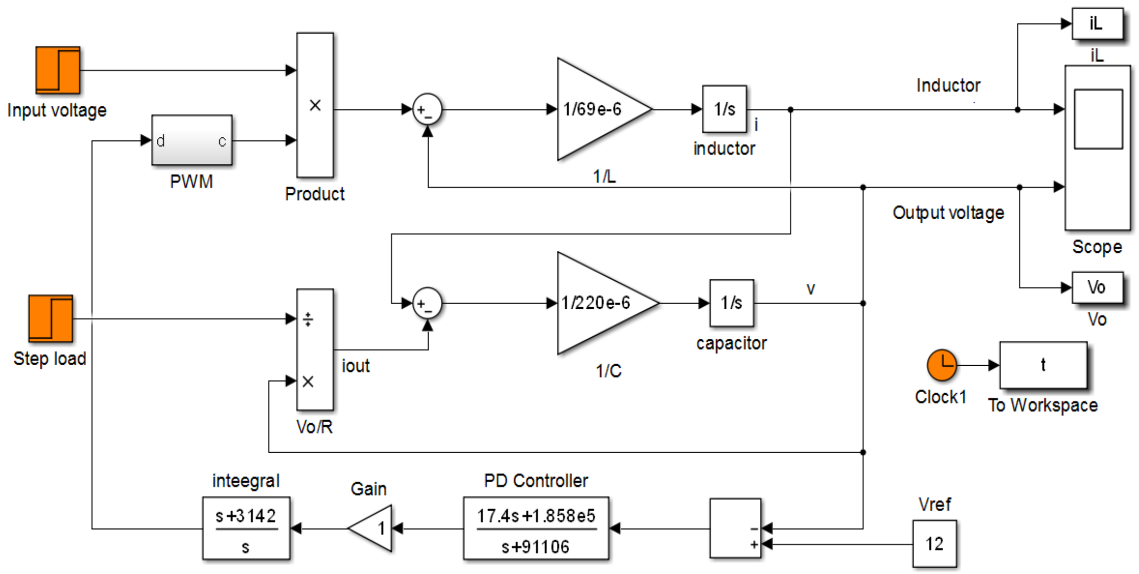

Figure 2. Buck converter with single loop

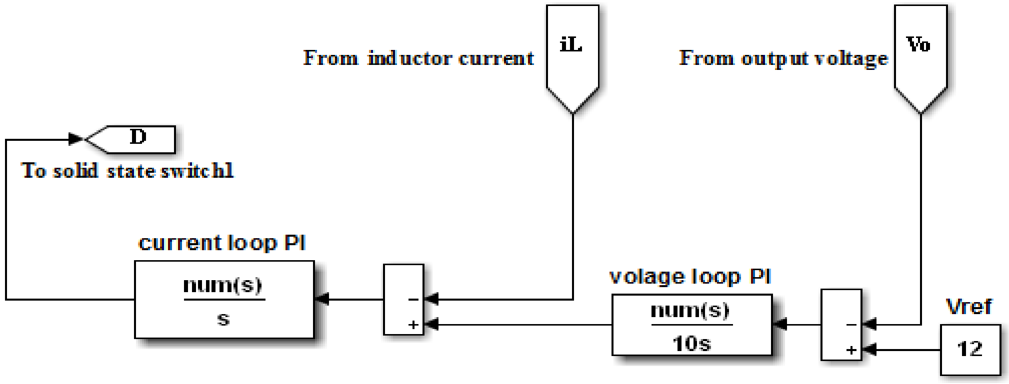

Figure 3. Cascade controller scheme

5. Results and comparison

The performance of the buck converter with single and cascade loops is assessed in transient, load variation and line variation. The voltage and current response of the converter under transient state is shown in Fig. 4 and Fig. 5 respectively. From both figures it is clear that there is an overshoot in the voltage and the current when the buck converter only operated with single voltage loop. This overshoot is reduced by the cascade controller, but at the cost of increase in settling time. The reduction in the inductor current due to the addition of current loop in cascade controller. The values of both controllers are compared with Table 1.

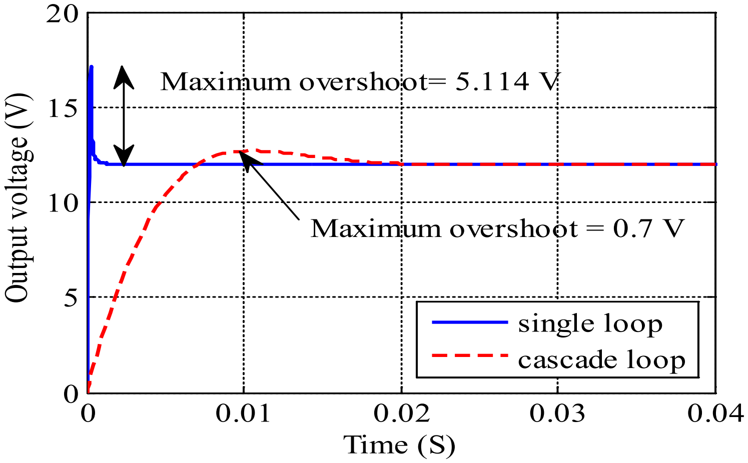

Figure 4. Buck converter performance under transient region

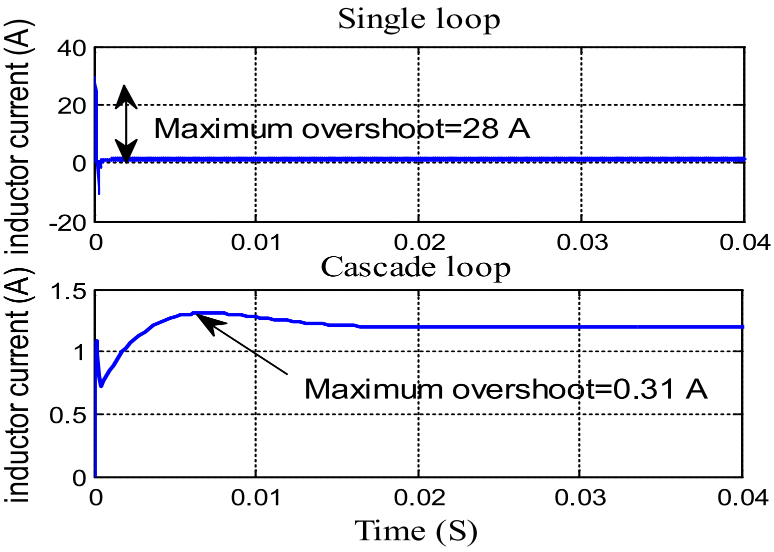

Figure 5. Inductor current response of buck converter under transient region

Table 1. Results of Buck converter in transient region

Parameters	Single loop PID Control		Cascade loop PI control	
Output voltage	Overshoot	Settling time	Overshoot	Settling time
	5.114 V	0.45 ms	0.7 V	22 ms
Inductor current	28 A	0.45 ms	0.31 A	15 ms

The performance of the buck converter is also investigated in line variations. The step change of the input voltage from 20 to 28 V is given to the converter. As a result, oscillations of buck converter increase with cascade controller. Fig. 6 shows the comparison of output voltage of the buck converter during line variation. The results are tabulated in Table 2.

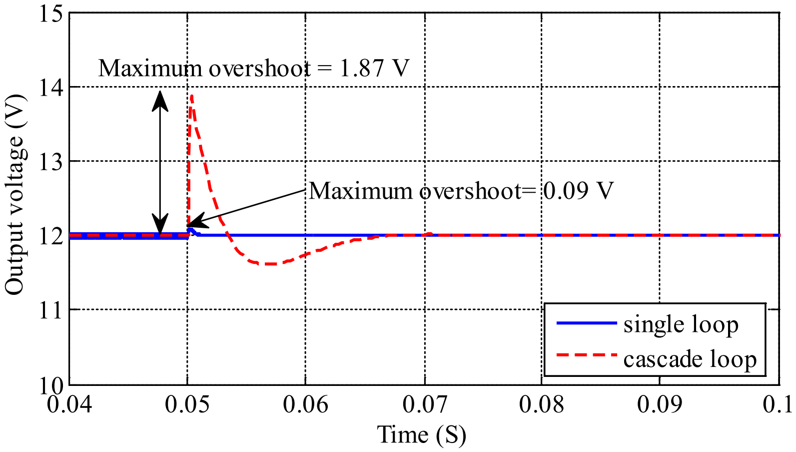

Figure 6. Buck converter performance during line variations

Table 2. Results of buck converter line variation

Parameters	Single loop PID Control		Cascade loop PI control	
Output voltage	Overshoot	Settling time	Overshoot	Settling time
	0.09 V	2 ms	1.87 V	18 ms

The performance of the buck converter with single and cascaded loops is also analyzed during load variations. With step change of load, no any oscillation of buck converter is observed with single loop. But oscillations increase with the cascade controller. The waveforms of both controllers under load variations are shown in Fig. 7. The results are recorded in the Table 3.

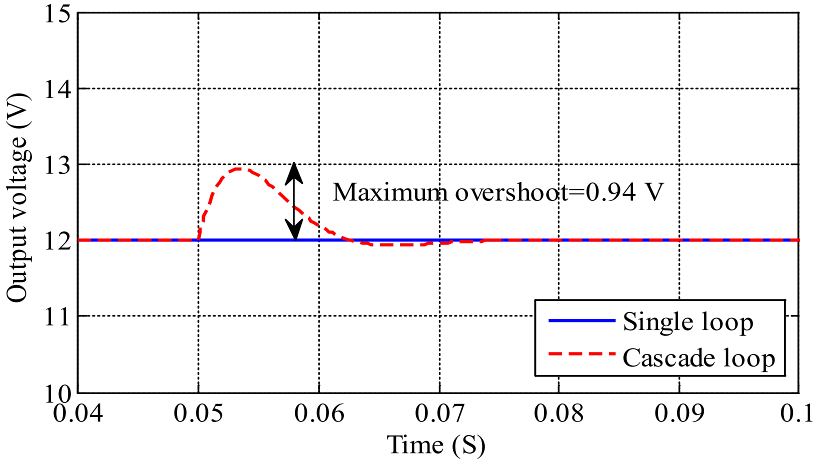

Figure 7. Buck converter performance during load variations

Table 3 Results of buck converter under load variation

Parameter	Single loop PID Control		Cascade loop PI control	
Output voltage	overshoot	Settling time	overshoot	Settling time
	No overshoot	----	0.94 V	25 ms

6. Conclusion

In this research work, the performance of the buck converter is simulated with single voltage loop and cascade control loop schemes. Simulation results confirm that the inductor current of buck converter has been reduced five times due to addition of inner current loop in cascade controller. Moreover, it is also clear from results of cascade control scheme that this reduced overshoot comes to normal current with larger settling time compared to single loop. The oscillations in output voltage of buck converter with cascaded controller is increased during line and load variations.

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Biographies

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