Minimization of Transients in Buck Converter Using Cascade Control Techniques

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Abstract: Power converters are broadly utilized for different modern applications because of their high efficiency, fast switching actions and low cost. It is hard to draw the limits for uses of electronic topologies due to latest advancement in semiconductor devices. The dc-dc conversion technology has been developing very rapidly because of its high efficiency, fast dynamic response and compactness. There is lot of ongoing research on this convertor and it has great attention in the field of power electronics convertors. This should effortlessly be possible with the assistance of state conditions and MATLAB/SIMULINK as an apparatus for reproduction of those state conditions. In this paper, a cascade controller model has been intended for the control of dc-dc Buck converters. In this research work cascade loop and single loop model have been outlined.

Keywords: Single loop control system, Cascade loop control system, Single loop, Cascade loop, Pulse Width Modulation.

1. Introduction

Buck converters are found in various applications such as home personal computers, instrumentation, and control devices, modern alternating current and direct current drives, aircraft, and many more vast applications. The DC-DC conversion technology is developing very rapidly because of its high efficiency, fast dynamic response, and compactness [1]. Buck converter is consisting of three basic components and they are inductors, solid state switch, and diode. Inductor normally stores magnetic energy when the diode is reverse biased and release energy when the diode is forward biased shown in figure 1.

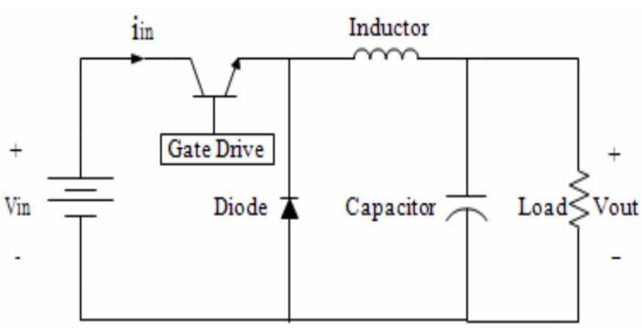

Fig. 1: Buck converter [2][3]

Buck converter operations are based on two different modes. In continuous conduction mode inductor current never ever approaches to zero value it is both continuously increasing or decreasing but never comes to zero and this is known as continuous conduction mode as shown in Fig 2. In this mode inductor, current becomes fall to zero for brief time and then either increase or decrease and this is called as discontinuous conduction mode as shown in Fig 3

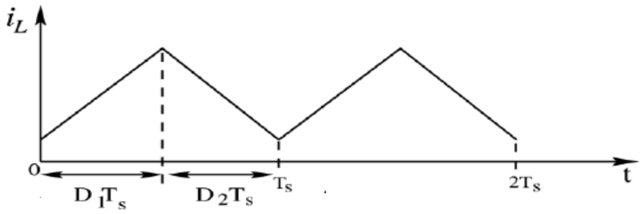

Fig. 2: Continuous conduction mode [4]

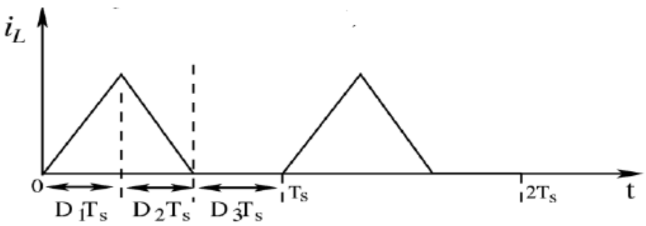

Fig.3: Discontinuous conduction mode [4]

Initially, we have focused on the background for that purpose we have gathered different researcher works related to this research paper. In [5] authors describe that constant variation in input supply voltage cause malfunctioning of the DC-DC converter. Two control methods are described one is continuous or analog and another is discrete or digital.

These methods are widely used in industrial applications. Since loads are very sensitive they require the constant value of voltage for its proper functioning so to avoid this problem and enhance the efficiency of converters various voltage regulators are utilized. Due to various problems stated above, there is great need of performance enhancement in the design of a controller for dc-dc converters. Different control methods are utilized for the controlling the dynamics of the buck converter.

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Conventional controlling methods have produced unsatisfactory results and are limited to perform under precise conditions [6]. Authors in [7] mentioned that in case of constant load good performance is obtained when single loop technique is used. Further, it is pointed out that the main disadvantage of the single loop is that it gives poor performance when input supply voltage is constantly changing. Scientists in [8] have described in their research work that lower instability is observed in the single loop due to the absence of current feedback. In this work, there is only voltage single loop is used. Similarly, there is the absence of protection against short circuit faults due to which there is need of additional circuitry. Constant frequency clock device is used in case of peak current mode whose function is to turn on and off by focusing the inductor current amount which approaches to threshold value mentioned by the voltage loop. In case, when duty cycle exceeds the 50%, different problems are generated such as noise, distortion, harmonic oscillation [9].

Authors in [10] mentioned that the DC-DC conversion technology is developing very rapidly because of its high efficiency, fast dynamic response, and compactness. Power electronic converters not only changes the electricity one form to another form such as from ac to dc or dc to ac but also variation in value either higher or lower can be done. The main purpose of using these converters is to achieve the target of higher efficiency and minimum losses, reduction in the size of device and saving in cost is also achieved. The Demand for good controllers is increasing continuously to meet different source and load criteria, single-loop voltage-mode control technique is largely utilized by the most of converters, in that voltage at output is taken for the feedback purpose and most PID (proportional integral derivative) type of controller uses that method also although their results are not satisfactory under load disruption, bulk supply, nonlinearity and parameter variants [11].

Problem*:* When the dynamics of buck converter are controlled with single loop control scheme high transients are developed during its operation also gain and system dynamic behaviors is influenced by variation in input main supply voltage, similarly delayed in response is also observed [12] [15]. In single loop voltage mode control greater the chance of risk instability [9] because there is no current feedback involved, voltage mode control converter has no inherent short circuit protection. Additional circuitry is required for detection and protection of the converter from the short circuit [8] and lower value of reliability due to the expanding demand of load and line voltage changes in dc-dc converter. [16].

For the need of step- down switching mode dc power con verters are used. A higher value of efficiency and smart size can be achieved, and they have replaced completely linear voltage regulators and the similarly higher output voltage can be obtained with the help of buck converter. In our proposed method a cascade loop buck converter is used in which current loop is added that is justified with the help of mathematical and Simulink models along comparison with a single loop in further sections.

2. Mathematical Modeling

This section has following subsections in which we discussed mathematical models of buck converters analyzed with single loop and cascade loop according to our proposed method.

2.1. Mathematical Modelling of Buck Converter with SLCS

In Constant load gives good performance when single loop technique is used. When in single loop technique load is continuously varying then delayed response and poor performance will be observed.[12]. Voltage and current dynamics which describe the state space are given by equation (1) and (2) and further equations are derived for getting damping ratio through analyzing figure 4 that shows a block diagram of single loop control system.

$$C\dot{V}_0(t) = i_L(t) - \frac{V_0(t)}{R} \tag{1}$$

$$L\dot{i}_L(t) + V_0(t) = V_i(t) \tag{2}$$

$$G_v(s) = \frac{V_O(s)}{i_L(s)} = \frac{R}{RCs+1} \tag{3}$$

$$G_{PI_1}(s) = \frac{K_1(R_1Cs+1)}{R_1 s} \tag{4}$$

When the K1 and R1 are constants then closed loop

$$\frac{V_0(s)}{V_r(s)} = \frac{G_{PI_1}(s)G_V(s)}{1+G_{PI_1}(s)G_V(s)} \tag{5}$$

$$\frac{V_0(s)}{Vr(s)} = \frac{K_1RR_1Cs + K_1R}{RR_1Cs^2 + (R_1 + K_1RR_1C)s + K_1R} \tag{6}$$

$$\Delta(s) = RR_1Cs^2 + (R_1 + K_1RR_1C)s + K_1R \tag{7}$$

$$G(s) = \frac{w_n^{\ 2}}{\delta^2 + 2\delta w_n + w_n^{\ 2}} \tag{8}$$

$$\frac{V_0(s)}{V_r(s)} = \frac{K_1RR_1Cs + K_1R}{RR_1Cs^2 + (R_1 + K_1RR_1C)s + K_1R} = \frac{K_1 s + \frac{K_1}{R_1C}}{s^2 + \left(\frac{1}{RC} + K_1\right)s + \frac{K_1}{R_1C}} \tag{9}$$

$$\omega_n = \sqrt{\frac{K_1}{R_1 C}} \tag{10}$$

$$2\delta\omega_n = \frac{1}{R_1 C} + K_1 \tag{11}$$

$$\delta = 1$$

$$K_1 = \frac{1}{R_1 C}$$

$$w_n = \sqrt{\frac{1}{R_1^2 C^2}} \tag{12}$$

Un-damped natural frequency

$$w_n = \frac{1}{R_1 C} \tag{13}$$

$$2\delta\omega_n = \frac{1}{RC} + K_1 \tag{14}$$

If the loading resistor approaches zero (R=0) in Eq.14 then

then we got $2\delta\omega n = \alpha$

If the loading resistor approaches infinity (R=∞) Applying on Eq.14 so we get

$$2\delta\omega n = K_1 \tag{15}$$

Putting ω_n and *K1* value in Eq.15 so we get damping ratio

$$2\delta \times \frac{1}{R_1 C} = \frac{1}{R_1 C}$$

$$\delta = \frac{1}{2} = 0.5$$

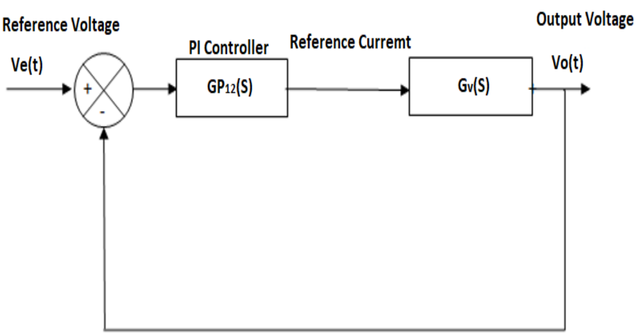

Fig. 4: Block diagram of Single loop controller [11]

Voltage controller feedback is output voltage in case of a single loop. Voltage controller controls the output voltage. Voltage controller output tries to get *Vo(t)* is equal to *Vref*. Primary voltage controller generates *Iref* for the inner loop.

2.2. Mathematical Modelling of Buck Converter with CLCS

There are two loops in cascade controller one is inner loop is shown in figure 5 (it is also known as current loop, it is faster than the outsider loop) and the second one is outer loop (this loop is also known as voltage loop) hence cascade controller is sometimes also known as multi-loop controller shown in figure 6. Inductor current is considered to be the reference value for the output command of the PI controller in case of voltage control loop.

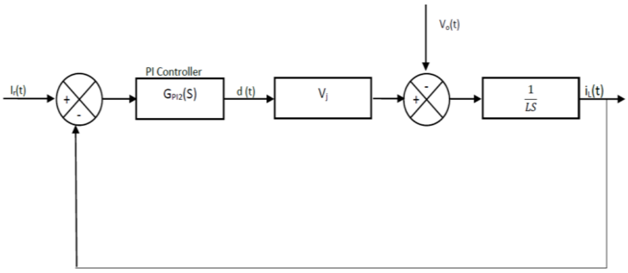

Fig. 5: Block diagram of Current loop controller [11]

Current dynamics are considered to in current control. Where i_L *(t)* & *ir (t)* are the current of inductor and the reference value of current. The closed loop T_F [13] [14] becomes

$$\frac{i_L(t)}{i_r(t)} = \frac{\dfrac{G_{PI_2}(s)\times V_i}{Ls}}{1+\dfrac{G_{PI_2}(s)\times V_i}{Ls}} \tag{16}$$

When $V_0(t) = 0$ (2.45)

$$G_{PI_2}(s) = \frac{K_2(Ts+1)}{s}$$

$$= \frac{\dfrac{K_2(Ts+1)}{s}\times\dfrac{V_i}{Ls}}{1+\dfrac{K_2(Ts+1)}{s}\times\dfrac{V_i}{Ls}} \tag{17}$$

$$\frac{i_L(t)}{i_r(t)} = \frac{K_2(Ts+1)\times Vi}{Ls^2 + K_2 TsVi + K_2 V_i} \tag{18}$$

$$\frac{i_L(s)}{V_0(s)} = \frac{-\dfrac{1}{LS}}{1+\dfrac{1}{LS}\times G_{PI_2}(s)\times V_i}$$

$$= \frac{-\dfrac{1}{Ls}}{1+\dfrac{1}{Ls}\times\dfrac{K_2(Ts+1)}{s}\times V_i}$$

$$\frac{i_L(s)}{V_0(s)} = \frac{-s}{Ls^2 + K_2 Ts\,V_i + K_2\,V_i} \quad (19)$$

$$i_L(s) = \frac{-s}{Ls^2 + K_2 T\,V_i\,s + K_2\,V_i} \times V_0(s) + \frac{K_2(Ts+1)\times Vi}{Ls^2 + K_2 TVis + K_2 V_i} \times I_r(s)$$

$$wn_2 = \sqrt{\frac{K_2 V_i}{L}} \quad (20)$$

$$\omega n_2 = N\omega n_1$$

$$N\omega n_1 = \sqrt{\frac{K_2 Vi}{L}} \quad (21)$$

Squaring on both Sides on equation (21) we get

$$N^2 \omega_{n_1}{}^2 = \frac{K_2 V_i}{L}$$

$$K_2 = \frac{N^2 \omega n_1{}^2 \times L}{Vi}$$

$$2\delta\omega_2 = \frac{K_2 T V_i}{L}$$

When

$$\delta = 1$$

$$2\omega_{n_2} = \frac{K_2 Ts V_i}{L}$$

$$2N\omega_{n1} = \frac{N^2 \omega_{n_1}{}^2 L \times Ts V_i}{V_i L}$$

$$T = \frac{2}{N\omega n_1} \quad (22)$$

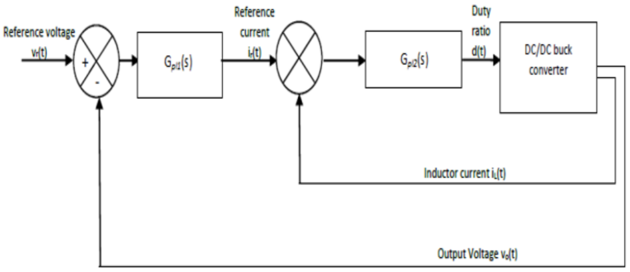

Fig. 6: Cascade loop buck convertor [11]

2.3. *Mathematical Modelling of Buck Converter*

A step-down switching mode dc power converter as shown in Fig 7 is commonly known as a buck converter and it has a higher value of efficiency and very robust design. Diode becomes the reverse biased when the switch is in conducting state. The inductor current $I_{L(t)}$, capacitor voltage *Vc(t)* and the output voltage *V0(t)*. So according to our proposed model shown in figure 11 so are final equation becomes

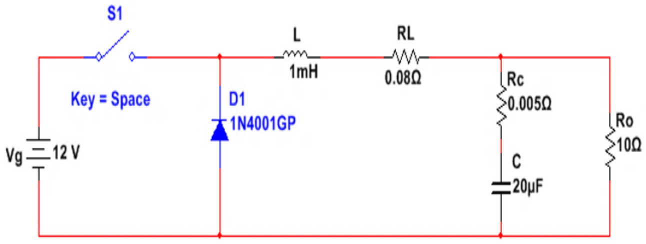

Fig. 7: Modeling of Buck converter

$$V_{in} - V_L - V_{RL} - V_0 = 0 \quad (23)$$

$$\frac{di_L}{dt} = \frac{V_{in} - V_0 - i_L R_L}{L} \quad (2.69) \quad (24)$$

$$i_L(s) = \left[\frac{V_{in}(s) - V_o(s) - i_L(s) R_L}{Ls}\right] \quad (2.70) \quad (25)$$

$$V_0(s) = (i_L(s) - i_o(s)) R_C + \frac{1}{Cs}(i_L(s) - i_o(s)) \quad (2.71) \quad (26)$$

3. Results and Discussion

In this part, we will discuss the simulations performed in MATLAB according to our proposed model and further the dynamics of the buck converter is analyzed by considering transient, line and load variation. Further, their simulation and bar graphs are shown for detailed discussion.

3.1. *Simulation Model of Buck Converter*

This Simulink model has a multiplier, summing blocks and gain blocks and subsequently fed into two integrators, the subsystem obtainable calculation to obtain the output voltage and current of inductor shown in figure 8.

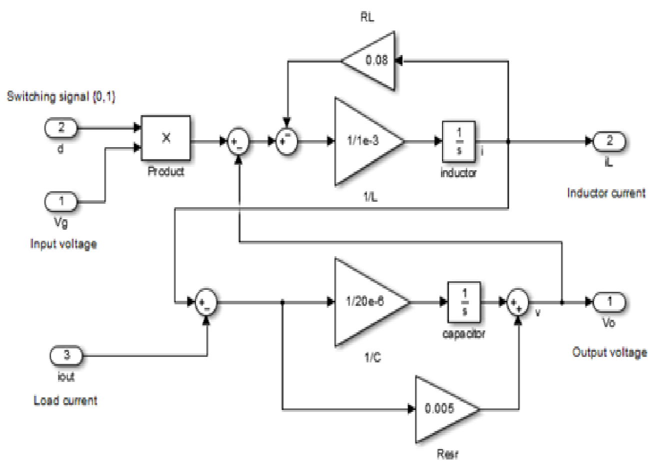

Fig. 8: Simulink modeling of Buck converter subsystem [11]

3.2. *PWM Generator for Buck Converter*

Varying duty cycles can be produced with the help of PWM pulses as displayed in Fig 9. There are two conditions of working one is duty interval (T_{ON}) when chopper switch is closed, and another is one is freewheeling mode (T_{OFF}) when the switch is open. The two inputs of the subsystem are (i) current controller duty cycle and (ii) frequency of switching. The resulting output waveform in 1 in Fig 10

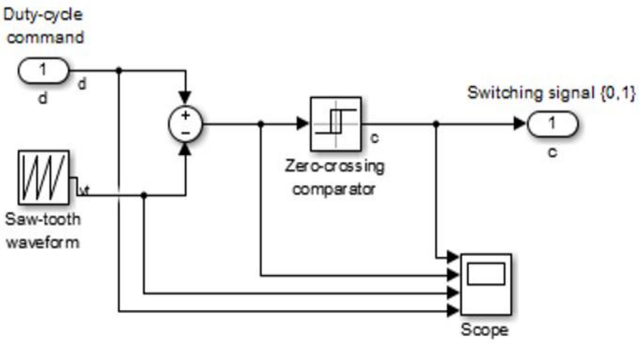

Fig 9: PWM subsystem [1]

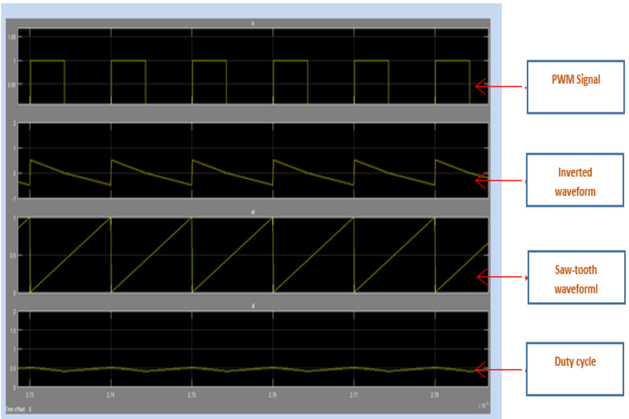

Fig 10: Pulse width modulation waveform

3.3. Buck Converter with S.L &C. L

Figure 11 shows Buck Converter Simulink model with Single loop and Cascade Loop Scheme. In this figure, we have combined both control system together.

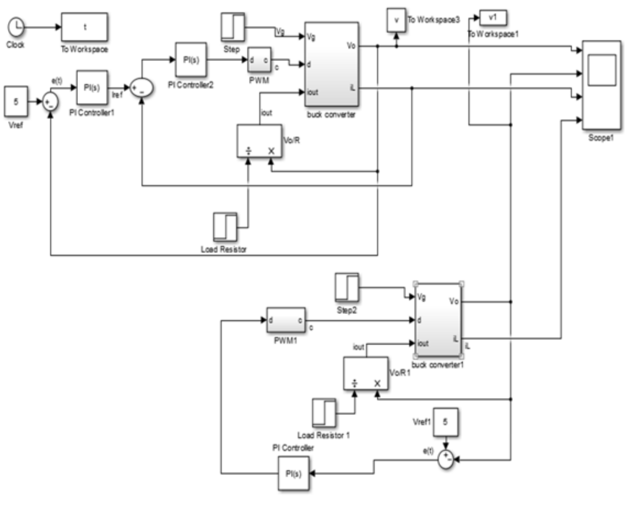

Fig. 11: Simulink model of a buck converter with S.L & C.L

3.4. Transient output voltage analysis with single loop and cascade loop

Fig 12 shows the single loop and cascade loop output voltage transient analysis. The red waveform shows the response of cascade loop and blue waveform shows the response of single loop.

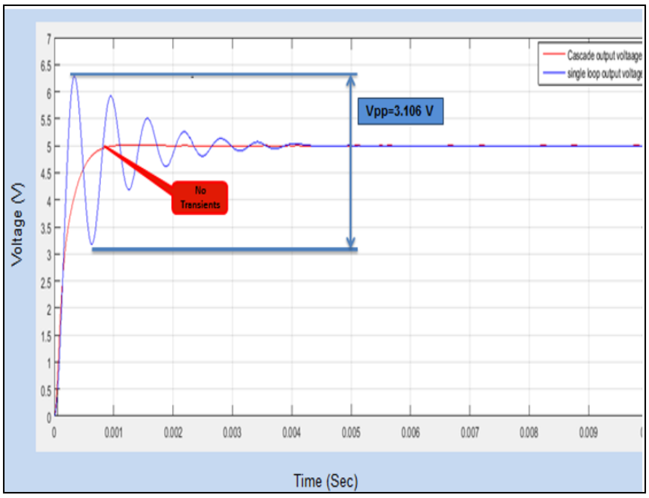

Fig. 12: Transient output voltage with S.L and C.L

In cascade loop, there is no transient in the output voltage of buck converter. From Fig 12, it is observed that maximum overshoot in output voltage is 3.106V when buck converter is controlled with a single loop. Fig 13 represents both controllers settling time, it is observed that cascade loop having less settling time as compare to a single loop. Cascade loop takes 1.004ms to settle down and single loop takes 3.87ms to settle down.

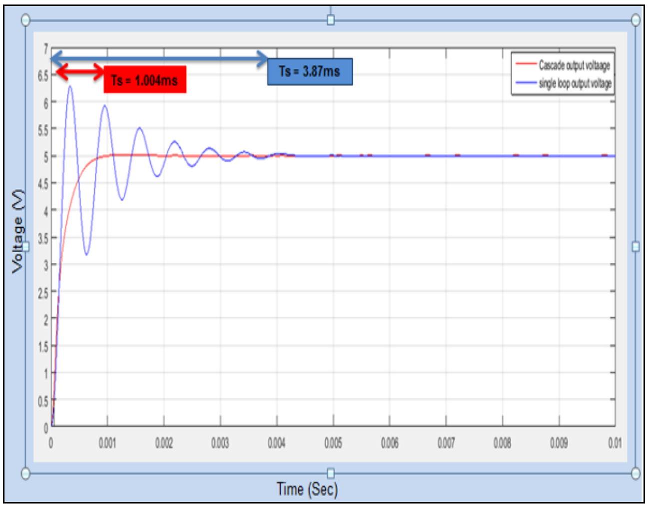

Fig. 13: Single & Cascade loop settling time

3.5. Transient inductor current analysis with single loop and cascade loop

Fig 14 shows the comparison of transient analysis in inductor current of single loop and cascade loop. In a single loop, the maximum transient is present and maximum current is 0.871A. In Cascade loop, minimum transients are present and maximum current is 0.1323A.

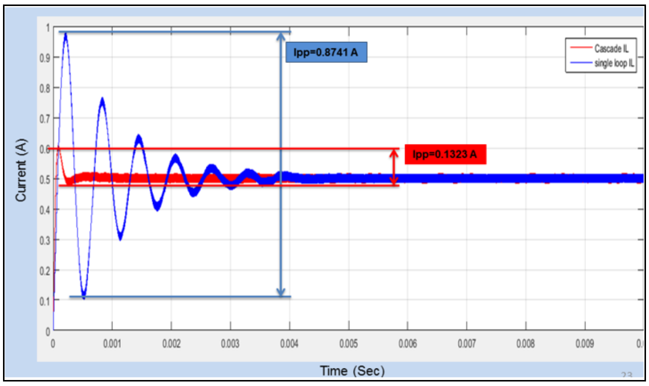

Fig. 14: Transient inductor current analysis with S.L and C.L

The Fig 15 represents both controllers settling time, it is observed that cascade loop having less settling time as compare to a single loop. Cascade loop takes 0.362ms to settle down and single loop takes 3.93ms to settle down.

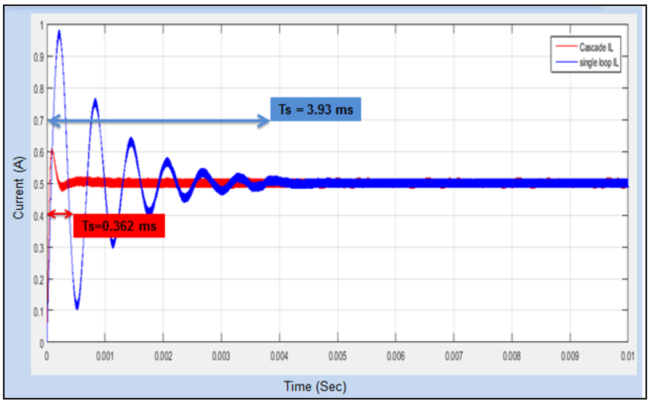

Fig. 15: Transient inductor current settling time with S.L and C. L

3.6. Buck Converter with Line Voltage Variation and Load Variation

The dynamics of the buck converter is analyzed by considering the line voltage variations from 12V to 14V. Fig 16 represents the single loop and cascade loop line voltage variation. The line voltage is not constant it increases or decreases. From the Fig 16 during the line voltage variation is observed that the maximum overshoot in line voltage is 0.536V when buck converter is controlled with a single loop. In cascade loop, the minimum transient is present, and the maximum voltage is 0.03V.

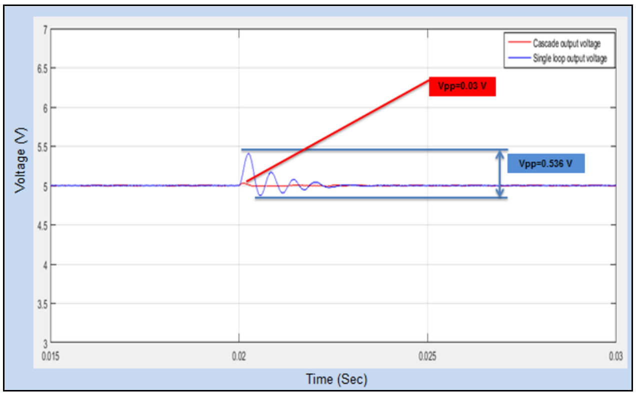

Fig. 16: Line voltage variation with single loop and cascade loop

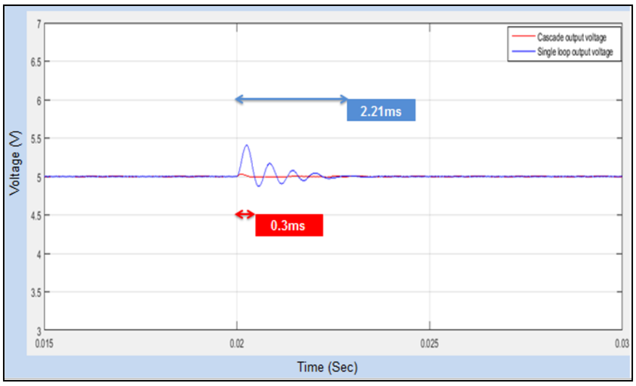

Fig. 17: Line voltage settling time with single loop and cascade loop

Fig 17 represents both controllers settling time, it is observed that cascade loop having less settling time as compare to a single loop. Cascade loop takes 0.3ms to settle down and single loop takes 2.21ms to settle down.

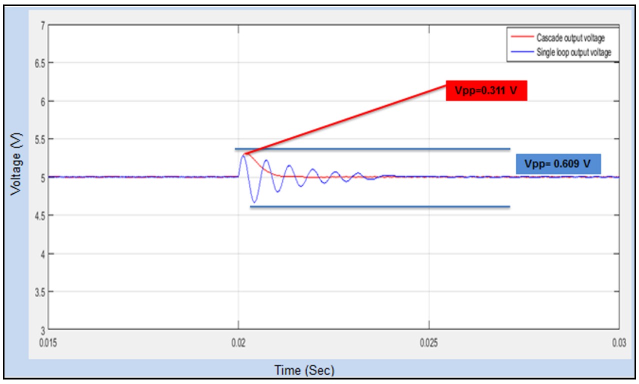

Fig. 18: Load variation with single loop and cascade loop

Fig 18 represents both controller load regulation, it is observed that cascade loop peak-to-peak voltage is 0.311V and single loop peak-to-peak voltage is 0.609V. From Fig 18 it is observed that the maximum overshoot in during load regulation when dynamic of buck is controlled with a single loop.

The Fig 19 shows the single and cascade loop settling time has been observed that single loop more settling time as compare to cascade loop. Cascade loop takes 1.3ms to settle down and single loop takes 3.69ms to settle down. In case of load variation, cascade loop is better than a single loop in term of settling time.

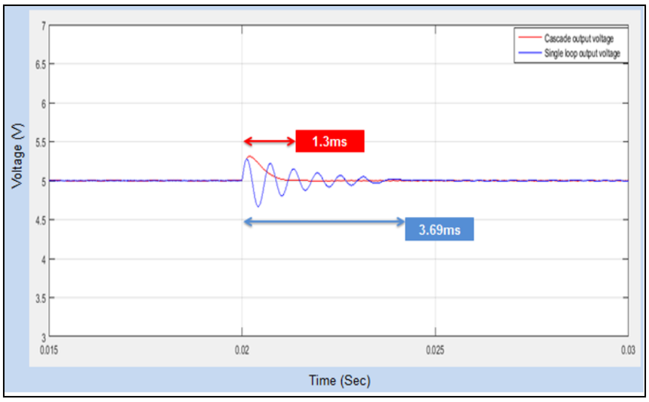

Fig. 19: Load variation settling time with single loop and cascade loop

3.7. Graphical Representation of Buck Converter Transient Voltage and Transient Current

The Fig 20 represents the transient voltages and shows the clear values of single loop and cascade loop transient's voltages. The blue bar shows the single loop transient and red bar shows the cascade loop transient. From Fig 20, it is observed that maximum numbers of transients in a single loop and a minimum number of transient in buck converter controlled with cascade loop. Fig 21 represents the both controller's transient current. It is observed that maximum numbers of transient's current in a single loop and a minimum number of the transient when buck converter is controlled with cascade loop.

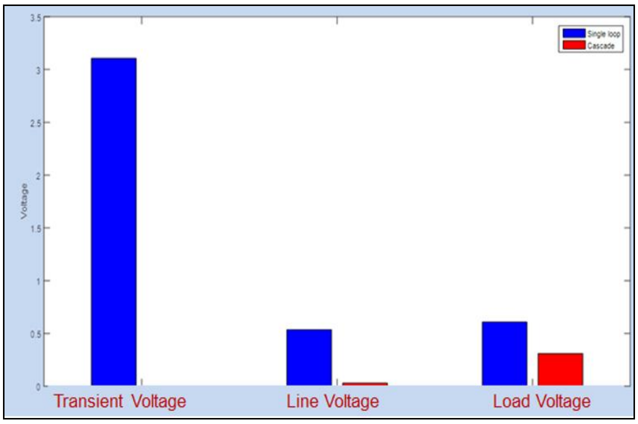

Fig. 20: Graphical representation of transient voltages with S.L and C. L

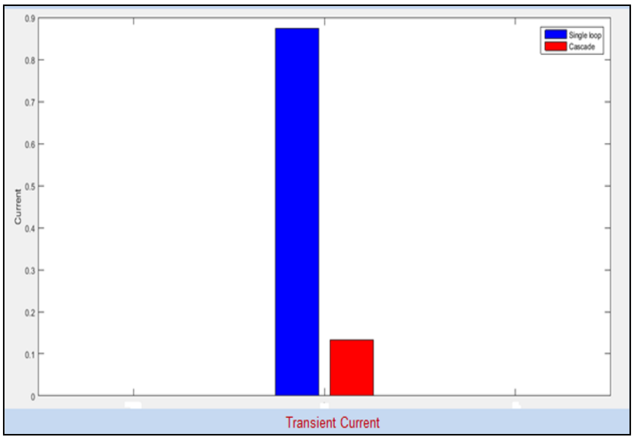

Fig. 21: Graphical representation of transient current with S.L and C. L

In single loop maximum, transient current as compared to cascade loop. Cascade loop is better than a single loop in term of transient current.

4. Conclusion

By comparing transient responses of both controllers, the single loop has more transients as compare to cascade controller. From the results, it is observed that there is no any overshoot in the output voltage of buck converter controlled with cascade controller. The maximum overshoot in inductor current of a buck converter with cascade controller is approximately 85% less than the single loop controller. During line voltage variation of a buck converter with cascade, controller has 94.4% is reduced than a single loop. During load regulation of buck converter with cascade, the controller is approximately 48.9% less than single loop controller. The cascade controller has overall good performance, better disturbance rejection and faster speed of response. The controller has been shown to be robust against load changes and supply changes. The simulation model of a buck converter with a single loop as well as cascade loop is successfully developed in Mat lab/Simulink software.

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