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Performance Improvement of Buck Converter with Sliding Mode Controller

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Abstract

This paper proposes a Sliding Mode Controller to improve the dynamic performance of buck converter. Proposed controller comprises of a linear part and a nonlinear part. Linear and non-linear parts of the controller consist of PID and hysteresis control respectively. PID controller is applied to the output voltage loop of buck converter and hysteresis control is implemented through inductor current ripple, which is used to select ON and OFF points of the hysteresis control. Proposed controller for buck converter is simulated using MATLAB®/SIMULINK® software. Simulation analysis shows improved response with proposed SMC. Little and no overshoot in output voltage and inductor current is observed respectively for initial transient, however settling time is drastically improved and there is negligible overshoot in output voltage during line and load variation.

Keywords: Buck Converter, Line and Load Variation, Sliding Mode Controller, Transient Response

1. Introduction

DC-DC converters are analogous to AC transformers and perform the function of stepping up or down dc voltage level. They have added advantage of being highly efficient, compact sized, low-priced converters. Their fast-dynamic response lead to their increasing use in modern power systems[1]. Their applications include High Voltage Direct Current (HVDC) transmission, Flexible Alternating Current Transmission (FACTS), computers, laptops, Light Emitting Diode (LED) televisions, LED lights, telecommunication, electric vehicles and motor drives etc.[2] Based on circuit configurations and operations DC-DC converters have many topologies[3] from which two major classifications are isolated and non-isolated. In isolated topology converter and supply are isolated from each other. On the other hand, in non-isolated topologies there is no isolation present between the two. There are different DC DC converter topologies such as Boost, buck, buck boost, cuk and zeta on the basis of their operation. Buck converters are the most widely used DC DC converters which always give the lesser output regulated voltage than the input voltage[4].

Switched mode controllers usually have high frequency switching operations of semiconductor power electronic switches, which leads to reduced size of inductors and capacitors. Use of semiconductor switches introduce non-linearities in the system making converter a non-linear device. These nonlinearities are considered while designing a proper controller. The DC-DC converter when operated in an open loop configuration i.e. without a feedback controller the output voltage is unregulated[5]. Moreover, line and

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load variations, high overshoot and longer settling time are observed. Hence there is a need of designing a suitable controller for DC-DC converters. In[6] a Second Order Sliding mode controller is designed for Synchronous Buck converter. The proposed controller was simulated, and results showed good start up transient response and robustness, but this initial transient increased with increase in load current. Sahito in[7] used SMC comprising of PI and hysteresis control scheme. Parameters of PI controller used in voltage loop was designed through mathematical modelling based on critically damped system. Simulation analysis showed robust operation during supply, line and load variations but settling time is 17 ms, which is quite high. Various researchers have employed different control techniques to control dynamics of buck converter. PI controller was commonly employed to control dynamics of the converter but fails to control satisfactorily the nonlinear behavior of the buck converter under line and load variations.

Sliding Mode Controller (SMC) is a type of nonlinear controller having variable structure system. Because of which it is a suitable controller for DC-DC converters. It is easy to implement and have a quick dynamic response. SMC can be suitably used to control the performance of buck converter because it satisfies the required condition that is "the system is controllable if every state variable can be affected by an input signal"[8] and therefore they used it in their research. Integral control and hysteresis control were used for voltage and current control loop respectively. Overshoot and high settling time were observed because of using Integral. Hussaini in[9] have used similar control strategy with different integral gain and parameters.

2. Dynamics of Buck Converter

The circuit diagram of simple open loop buck converter is shown in Figure 1.

By taking the switch on and switch off conditions of buck converter the transfer function can be calculated which is:

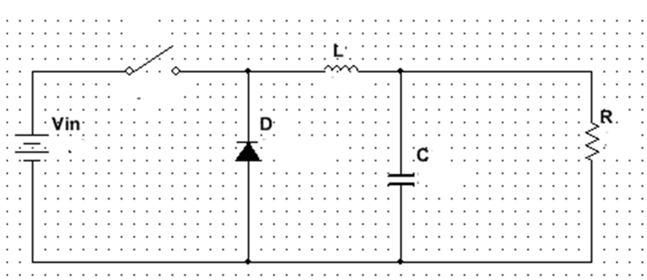

Figure 1. Buck converter.

$$\frac{v_o}{v_{in}} = \frac{1}{LCs^2 + \frac{L}{R}s + 1} \tag{1}$$

From Figure 1 the DC-DC buck converter has two state variables i.e. Inductor current (i_L) and capacitor voltage (v_c).

$$V_L = V_{in} - V_o \tag{2}$$

where, V_L = Voltage across inductor.
V_{in} = Input voltage.
V_o = Output voltage.

$$L\frac{di_L}{dt} = V_{in} - V_o \tag{3}$$

Integrating both sides

$$i_L = \frac{1}{L}\int\left(V_{in} - V_o\right) \tag{4}$$

From the circuit in figure, it can be seen that;

$$V_{in} = D_x V_{in} \tag{5}$$

where, D_x = switching signal.

$$\therefore i_L = \frac{1}{L}\int\left(D_x V_{in} - V_o\right)dt \tag{6}$$

Similarly, for capacitive voltage.

$$V_c = \frac{1}{C}\int\left(i_l - i_o\right) \tag{7}$$

These equations can be written in matrix form as follows:

$$\begin{bmatrix} i_L \\ V_c \end{bmatrix} = \begin{bmatrix} 0 & -1/L \\ 1/C & -1/RC \end{bmatrix}\begin{bmatrix} i_L \\ V_C \end{bmatrix} + \begin{bmatrix} D_x/L \\ 0 \end{bmatrix}\begin{bmatrix} V_{in} \end{bmatrix} \tag{8}$$

The Simulink model developed for the open loop buck converter based on the above state space modelling is shown in Figure 2.

SMC represents the nonlinear nature similar to that of Switch-Mode Power supply, derived from VSCS theory and has numerous advantages over other control methods. An alternative way of implementation of control action is provided by SMC for Variable Structure Systems. To force the system trajectory to remain on the selected surface, the converter switches are considered as the function of state variables (instantaneous values), and that selected surface is known as sliding surface in state space[10].

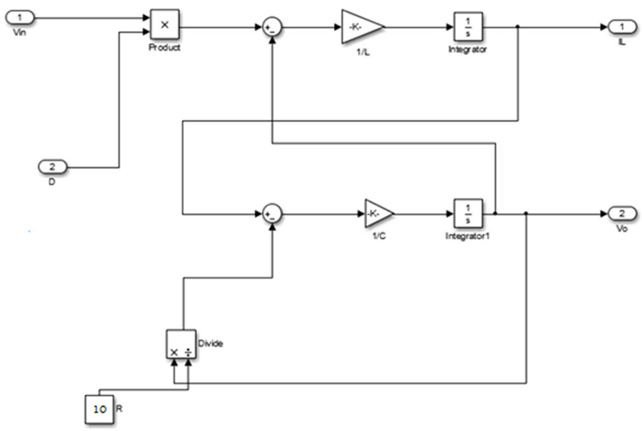

Figure 2. Simulink model for state space model for buck converter.

Whenever formulating any control design the problem may arise sue to the difference between the values of actual plant and the mathematical modeling developed for its design. The difference can be because of the approximation of behavior of complex plant or because of the variation in the parameters of the system. The controller must be able to give required values irrespective of the mismatches. SMC has replaced many linear controllers like PID because of its several advantages including fast speed and efficient response towards the line and load variations. Comparing the SMC with the conventional linear controllers it is easy to implement, and it is used in various applications[11]. The SMC can be characterized as a type of VSCS, such that it is again divided into decision rule and control laws.

3. Design of Sliding Mode Controller for Buck Converter

Sliding mode deals with the motion of system trajectories to slide within the selected boundaries known as sliding surface. Designing a sliding mode controller has two parts, first part is to select the sliding surface along which the system trajectories are to be confined and second is to select the control law which keeps the system trajectories on sliding surface. In SMC, the systems input state is decided by using sliding surface. In case of Sliding Mode Controller, the switching states *u* are chosen by the sliding line. The elaboration of sliding surface. Thus, the switching function can be given as:

$$\sigma = c_1 x_1 + c_2 x_2 = C^T x = 0 \tag{9}$$

where,

$C^T = \left[c_1, c_2\right]$ is the vector of sliding surface coefficients and

$x = \left[x_1 x_2\right]^T$ are the state variables.

Now

$$\sigma = c_1 x_1 + c_2 \dot{x}_1 = 0 \tag{10}$$

This equation shows the sliding mode according to system dynamics.

The control law in this case can be defined as,

$$u = \begin{Bmatrix} 1 = ON, when\, \sigma > k \\ 0 = OFF, when\, \sigma < k \end{Bmatrix}$$

The parameters used to analyze the performance of buck converter in this research work are given in Table 1. It is used to step down 24V to 12V. Proposed SMC for buck converter is divided in two parts; voltage control implemented with PI and PD controllers and current loop implemented through hysteresis. For voltage control loop values of Proportional and integral gains that are used in PI controller are calculated as Kp=1 and Ki=3142 and gains of PD controller are calculated as kp=2.03 and Kd=0.0002 Switching point for hysteresis control is selected as 0.3 and -0.3 as half of the inductor ripple current (0.6A). Figure 3 shows complete simulation diagram of the buck converter with proposed SMC. Buck block contains simulation model of the Figure 2.

4. Results and Discussions

Buck converter with proposed SMC is simulated using MATLAB® SIMULINK® for performance analysis. Output voltage and inductor current for initial startup condition of the SMC controlled buck converter are shown in Figures 4 and 5 respectively. It is evident that overshoot of 0.9V is present in output voltage but

Table 1. Parameters selected for Buck converter

Parameter	Value
Supply Voltage (Vin)	24 V
Output Voltage (Vo)	12 V
Inductor (L)	69 µH
Capacitor (C)	220 µF
Load Resistance (R)	10 Ω

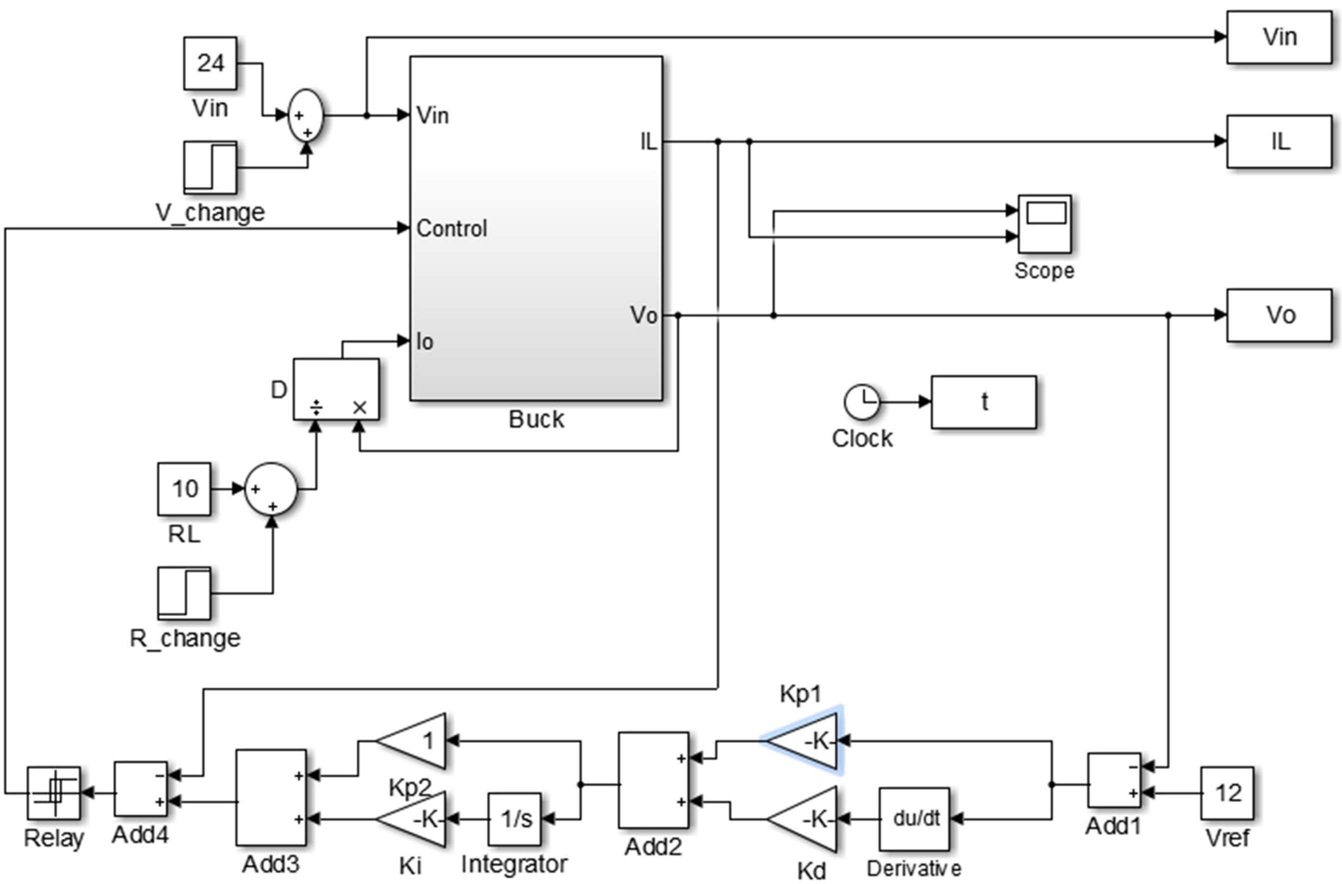

Figure 3. Buck converter with proposed SMC.

settling time is 2 ms which is considerably improved. No overshoot and settling time of 2 ms in transient response for inductor current is observed from Figure 2. Figure 6 shows steady state ripple of output voltage, which is 0.6 mV, from 11.9997 to 12.0003. Small ripple indicates that output is almost constant.

A step change is applied in supply voltage to check the performance of buck converter against line variations. The supply voltage is first increased from 24V to 28V and then decreased from 24V to 20V, as shown in Figures 7 and 8 respectively, it is clear that in both the cases the output voltage is unaffected

The results for the load variation are shown for output voltage and inductor current in Figures 9 and 10 respectively. Load variation results are analyzed by applying a step change in load resistance to increase load from 10Ω to 5 Ω (40%). An undershoot of 0.8V is observed with a settling time of 2 ms. Figure 10 show that inductor current has an overshoot of 0.05 and settles during in 2 ms.

5. Conclusion

Linear Integral and PI controllers failed to satisfactorily control dynamics of buck converter under line and load variations. SMC is considered effective nonlinear controller for buck converter due to its response speed, easy implementation and robustness. In this paper, SMC is proposed to control dynamics of the buck converter. Proposed SMC has two parts; linear part implemented by PI and PD controller collectively used as (PID control) and nonlinear part implemented by hysteresis. Simulation of buck converter with proposed SMC show an overshoot of 0.9V in voltage and inductor current for initial transient and line variations. For 40% decrease in load, overshoot in output voltage is 0.8V and inductor current has 0.05A overshoot. Negligible overshoot in output voltage is observed for initial start. Settling time for all the cases is observed as 2 ms. Supply variation has no effect on output of the converter with proposed SMC. Simulation results confirm the improvement in performance of buck converter with proposed SMC.

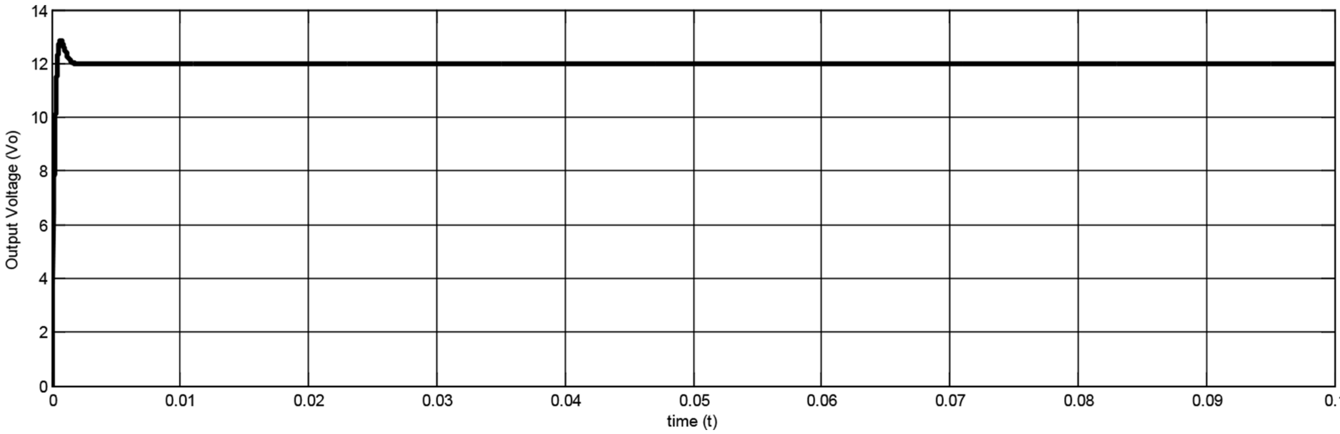

Figure 4. Initial response of output voltage.

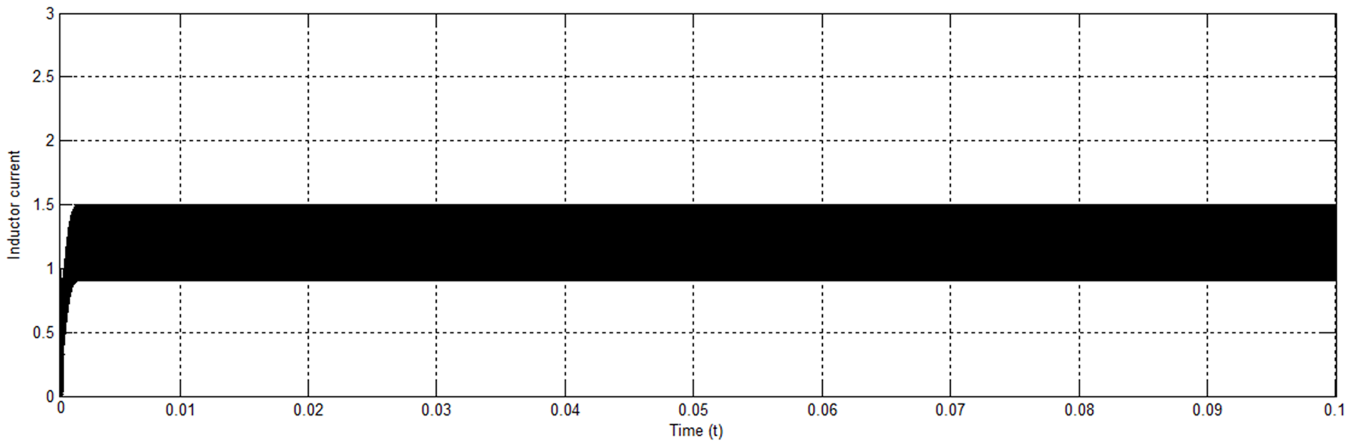

Figure 5. Initial response of inductor current.

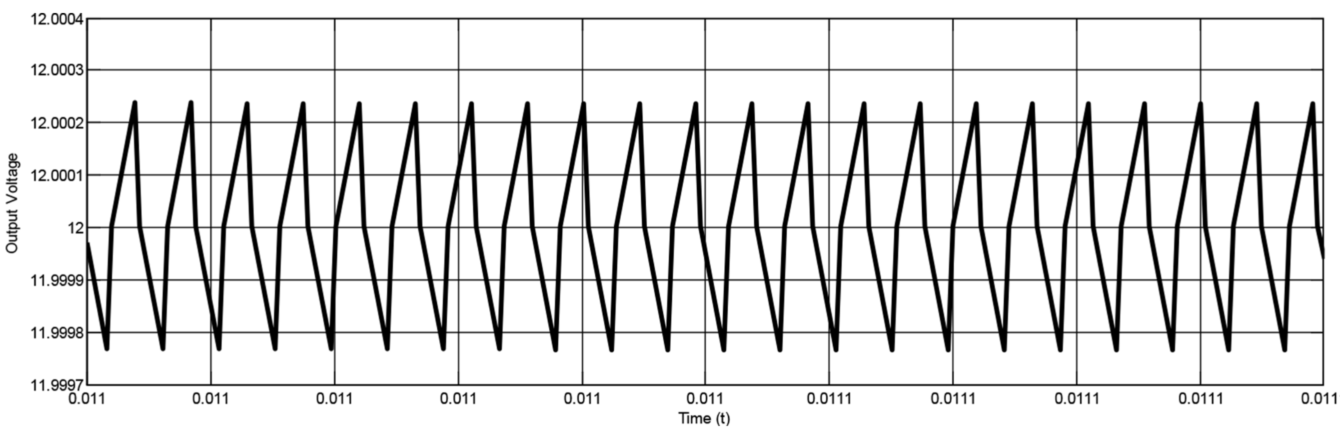

Figure 6. Output voltage ripple of buck converter with proposed SMC.

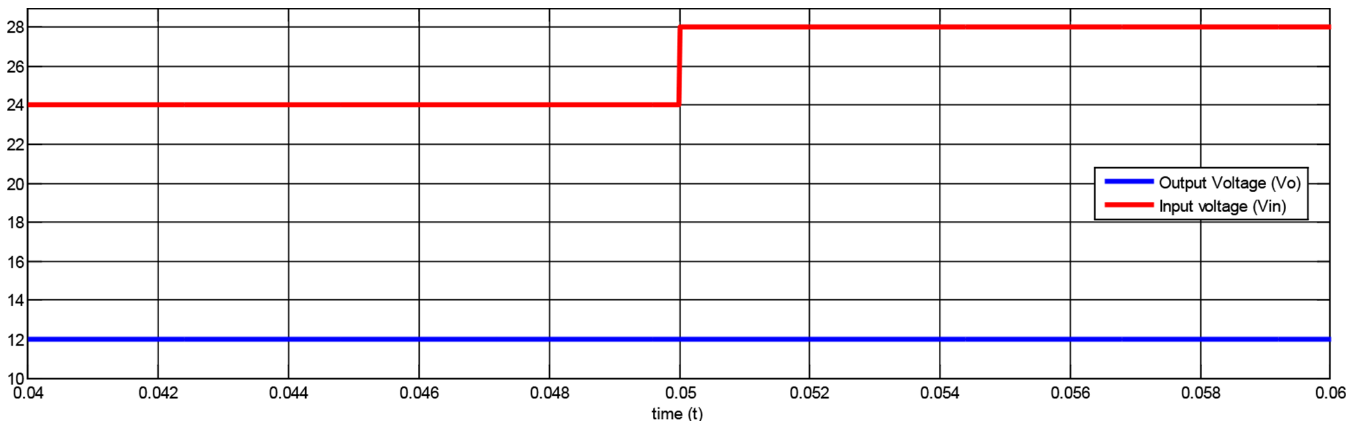

Figure 7. Voltage response of buck converter with proposed SMC when input voltage is changed from 24V to 28V.

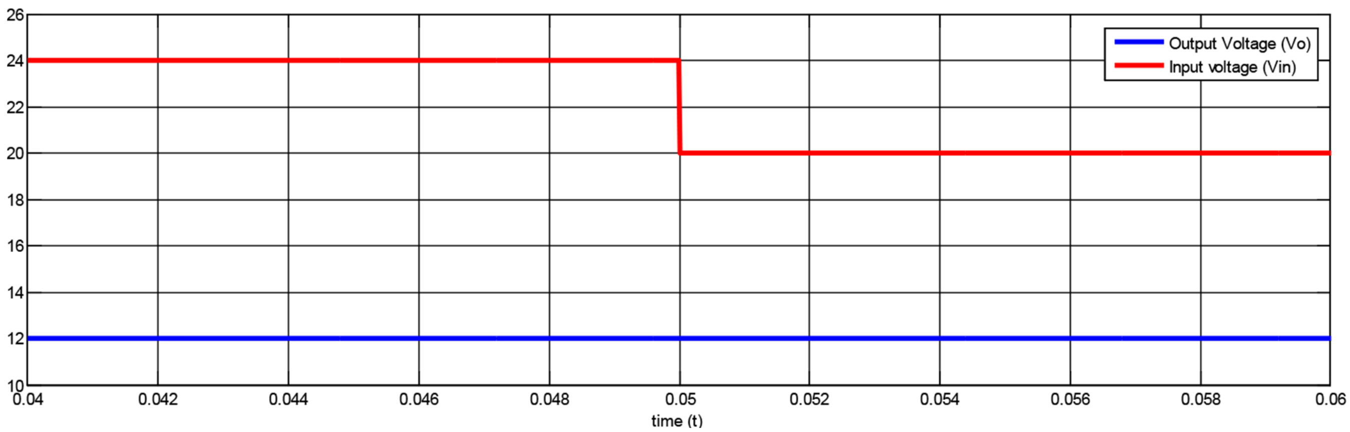

Figure 8. Voltage response of buck converter with proposed SMC when input voltage is changed from 24V to 20V.

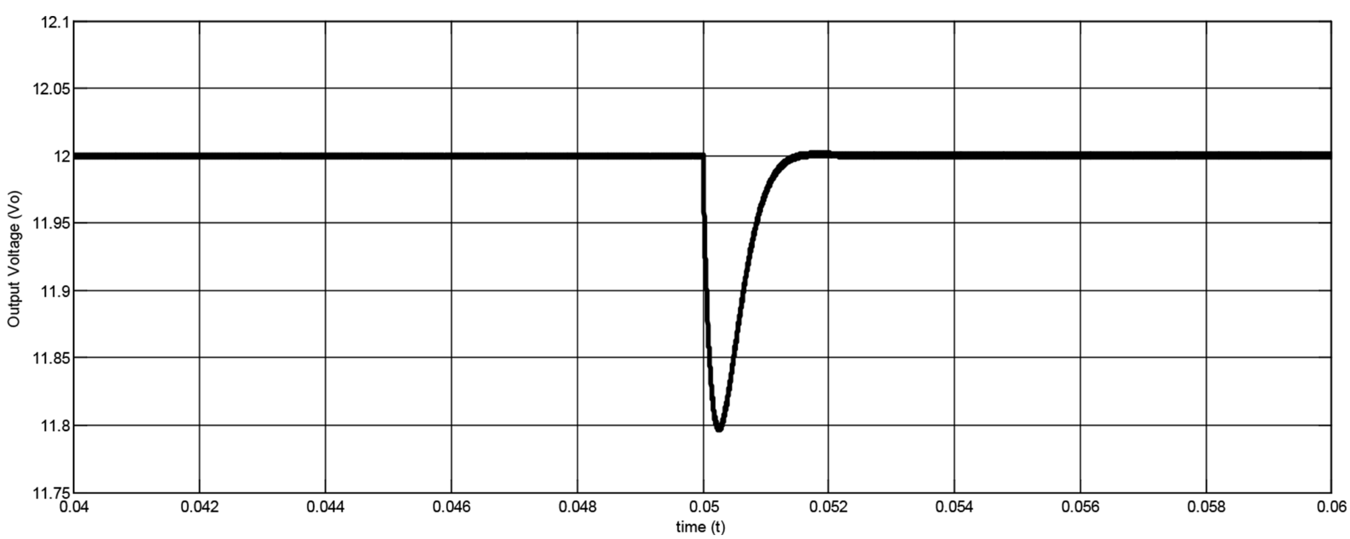

Figure 9. Voltage response to load variation of - 4 Ω.

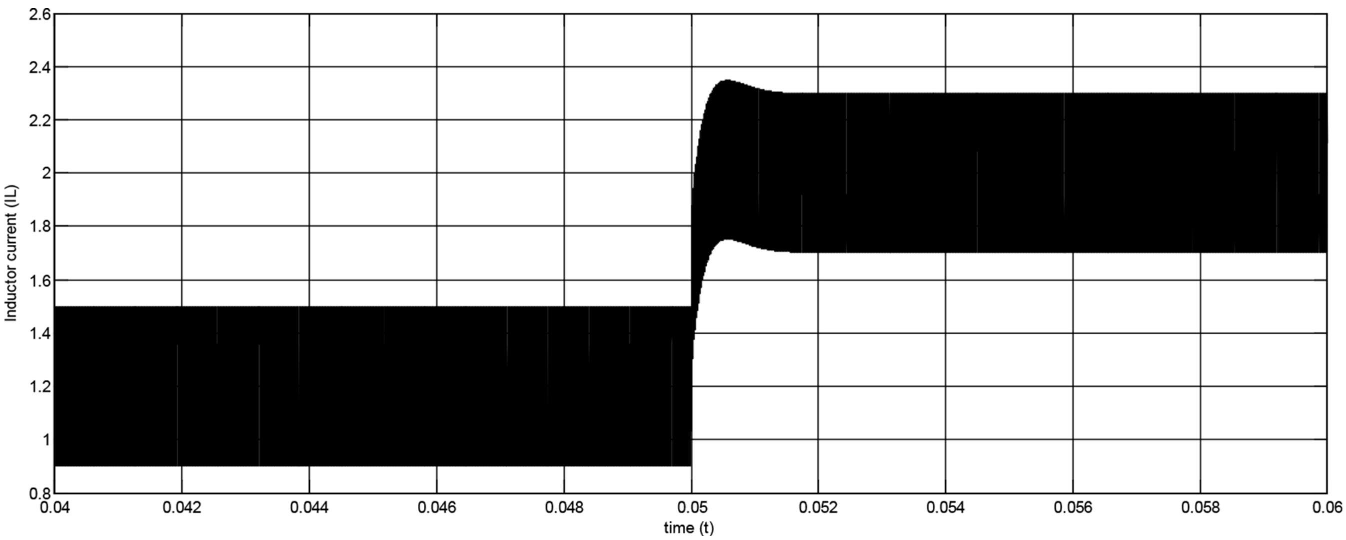

Figure 10. Current response to load variation of - 4 Ω.

6. Acknowledgement

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