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ADAPTIVE CONTROL TECHNIQUES FOR DC-DC BUCK CONVERTER

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ABSTRACT

DC-DC converters are some widely used power electronic circuit that efficiently converts an unregulated DC input voltage to a regulated DC output voltage. This paper demonstrates one of the basic topologies of DC-DC converter i.e. Buck Converter. This paper outlines the State-Space averaged modelling of the DC-DC Buck converter. Various control techniques are developed to control the DC-DC converter. Different control techniques are demonstrated to control the DC-DC converter in this paper.

KEYWORDS: PID and PI control; SMC (Sliding Mode Control); DC-DC Buck Converter.

INTRODUCTION

The DC-DC converter are some of the simplest power electronic circuit that converts sources of direct current from one voltage level to another voltage level by switching action. This can be done by changing the duty cycle of the main switches in the circuits. The switches are transistors and diodes. These converters are mostly used as a regulated switched mode power supplies. Switched mode DC-DC converter converts the unregulated dc input to a controlled dc output [1]-[2].

DC-DC converters have a very large area of applications. They are extensively used in personal computers, office equipment's, appliance control, telecommunication equipment's, DC motor drives, automotive, aircrafts, etc.

The analysis, control and stabilization of switching converters are the main factors that need to be considered. A suitable control technique must deal with the nonlinearity of DC-DC converters, wide voltage and load variation [].Many control methods are used for control of switch mode dc-dc converters such as: Fuzzy Logic Controller, Sliding Mode Controller, PID Controller, PI Controller. In this paper the properties of PID, PI, Sliding Mode Controller has been focused [3].

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THE DC-DC BUCK CONVERTER

Linear Control for a Buck Converter

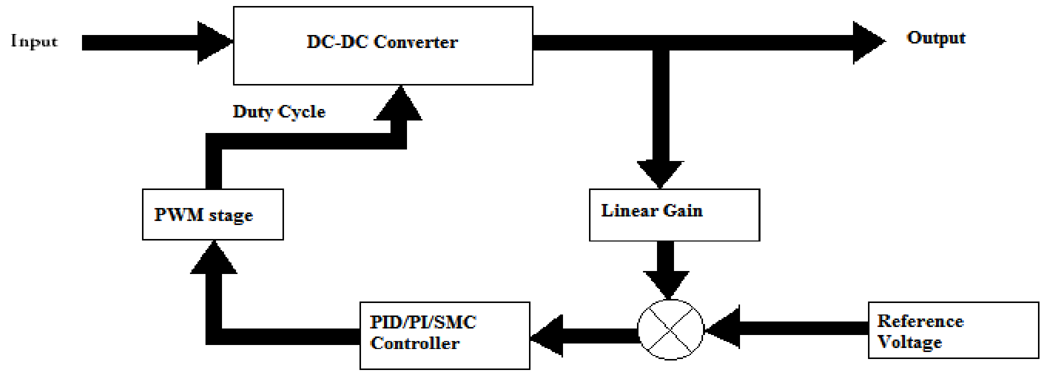

Figure 1: Block Diagram of Controlled Buck Converter

Operational principle

A buck converter is a step down converter that steps down the fixed high voltage to a desired low voltage. The basic buck converter schematic diagram is shown in figure 2 has a capacitor and an inductor along with two switches. The switches operate at the rate of PWM switching frequency.

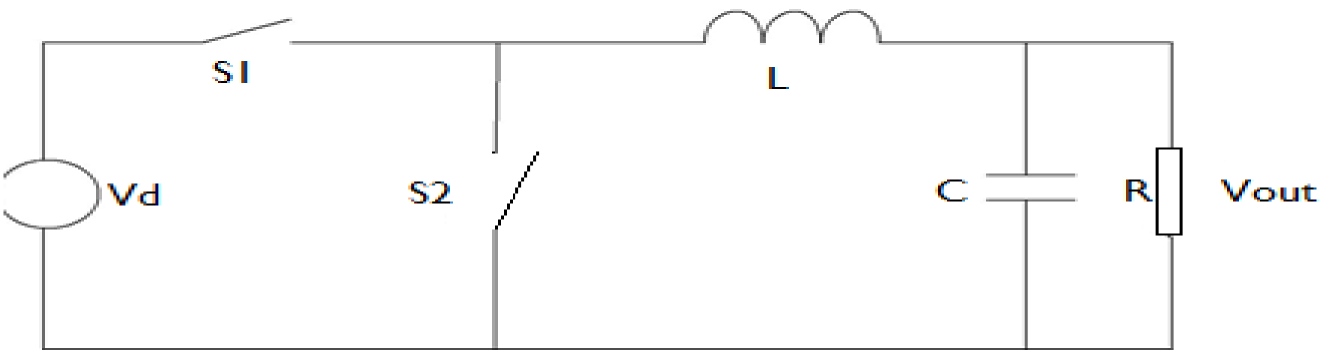

Figure2: Basic Buck Converter

In the converter operation it is assume that the converter operates in CCM. In CCM mode of operation the inductor current flow continuously over the switching period.

In the first sub circuit state when the switch S1 is closed, the diode is reversed biased and the energy is transferred from the source to the inductor and the current through the inductor gradually increases during this time interval as shown in figure 2.1(a). In the next sub-circuit state when the switch S2 is closed, the source is disconnected from the network. The diode will be forward biased and the current will flow through the freewhelling diode. During the second time interval the current through the circuit decreases linearly as the energy in the inductor discharges as shown in the figure 2.1(b).

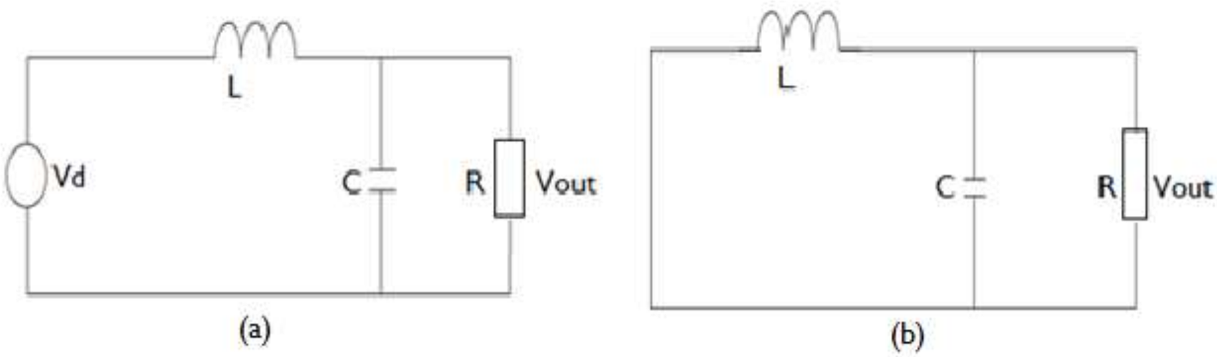

Figure2.1Buck Converter when (a) Switch is ON (b) Switch is OFF

MATHEMATICAL MODELLING OF BUCK CONVERTER

When the switch is closed (ON-state) and diode is reverse biased, the inductor current $i_L(t)$, capacitor voltage $v_c(t)$ and output $V_o(t)$ are

$$\frac{di_L(t)}{dt} = \frac{1}{L}[V_d(t) - V_o(t)]$$
$$\frac{dv_c(t)}{dt} = \frac{1}{C}\left[i_L(t) - \frac{V_o(t)}{R}\right] \& \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (1)$$
$$V_o(t) = v_c(t) + r_c\left[i_L(t) - \frac{V_o(t)}{R}\right]$$

When the switch is open (OFF-state) and diode is forward biased, the inductor current $i_L(t)$, capacitor voltage $v_c(t)$ and output voltage $V_o(t)$ are:

$$\frac{di_L(t)}{dt} = -\frac{1}{L}V_o(t)$$
$$\frac{dv_c(t)}{dt} = \frac{1}{C}\left[i_L(t) - \frac{V_o(t)}{R}\right] \& \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (2)$$
$$V_o(t) = v_c(t) + r_c\left[i_L(t) - \frac{V_o(t)}{R}\right]$$

Model Simplification

On simplifying the above equations, the inductor current and capacitor voltage dynamics can be rewritten as:
When the switch is closed (ON-state)

$$\frac{di_L(t)}{dt} = \frac{1}{L}V_d(t) - \frac{r_c R}{(R+r_c)L}i_L(t) - \frac{R}{(R+r_c)L}v_c(t)$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$
$$\frac{dv_c(t)}{dt} = \frac{R}{(R+r_c)C}i_L(t) - \frac{1}{(R+r_c)C}v_c(t)$$

When the switch is open (OFF-state)

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$$\frac{di_L(t)}{dt} = -\frac{r_c R}{(R+r_c)L} i_L(t) - \frac{R}{(R+r_c)L} v_c(t)$$
$$\frac{dv_c(t)}{dt} = \frac{R}{(R+r_c)C} i_L(t) - \frac{1}{(R+r_c)C} v_c(t) \quad \text{.......................} (4)$$

State-Space model of Buck Converter

The state-space representation of the converter circuit can be expressed in the form:

$$\frac{dx(t)}{dt} = A_1 x + B_1 V_d \qquad \text{During the switch is ON}$$
$$\frac{dx(t)}{dt} = A_2 x + B_2 V_d \qquad \text{During the switch is OFF}$$

Where $[x_1, x_2]^T = [v_c(t) \quad i_L(t)]$ is state vector and A and B are the system matrices.

The state matrices and input vector for both switching state can be expressed as:

$$A_1 = A_2 = \begin{bmatrix} -\frac{Rr_c}{(R+r_c)L} & -\frac{R}{(R+r_c)L} \\ \frac{R}{(R+r_c)C} & -\frac{1}{(R+r_c)C} \end{bmatrix}, B_1 = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}, B_2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

State-Space Averaged model of Buck Converter

Here the state-space averaging method is shown. The duty cycle ‘k’ is a function of ‘x’ as well as ‘u’. Total solution can be obtained by state – space averaging, that is by summing the term for each switched mode.

$$A = A_1 k + A_2 (1-k)$$
$$B = B_1 k + B_2 (1-k) \quad \text{..................................} (5)$$

On averaging the system matrices are:

$$A = \begin{bmatrix} -\frac{Rr_c}{(R+r_c)L} & -\frac{R}{(R+r_c)L} \\ \frac{R}{(R+r_c)C} & -\frac{1}{(R+r_c)C} \end{bmatrix} \& B = \begin{bmatrix} \frac{k}{L} \\ 0 \end{bmatrix} \quad \text{............} (6)$$

The averaged state equation and output equation can be expressed as:

$$\begin{bmatrix} \frac{di_L(t)}{dt} \\ \frac{dv_c(t)}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{Rr_c}{(R+r_c)L} & -\frac{R}{(R+r_c)L} \\ \frac{R}{(R+r_c)C} & -\frac{1}{(R+r_c)C} \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_c(t) \end{bmatrix} + \begin{bmatrix} \frac{k}{L} \\ 0 \end{bmatrix} [V_d(t)]$$

$$y(t) = \begin{bmatrix} \frac{Rr_c}{(R+r_c)} & \frac{R}{(R+r_c)} \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_c(t) \end{bmatrix}$$

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Extracting the Transfer Function of Buck Converter

The buck converter's small signal control-to-output transfer function, derived by the standard state-space averaging technique, is given by:

$$T_P(s) = \frac{\hat{v}_o(s)}{\hat{d}_o(s)} = \left(\frac{(1+sr_cC)}{s^2 + \left(\frac{r_c}{L} + \frac{1}{RC}\right)s + \frac{1}{LC}} \right) \frac{V_d}{LC}$$

In the transfer functions, $\hat{v}_o(s)$ & $\hat{d}(s)$ are the small variations of the output voltage and duty cycle respectively. C is the output capacitance, L is the inductance, and R is the load resistance, r_c is the ESR of C. The control-to-output transfer function is utilized to design the controller.

CONTROL TECHNIQUES USED IN DC-DC BUCK CONVERTER

In DC-DC converter for a given input voltage, the output voltage can be controlled by controlling the ON or OFF duration of the switch. Pulse Width Modulation (PWM) is one of the method in which control circuit regulates the output by varying the ON time of the switch and by fixing the switching frequency [5].

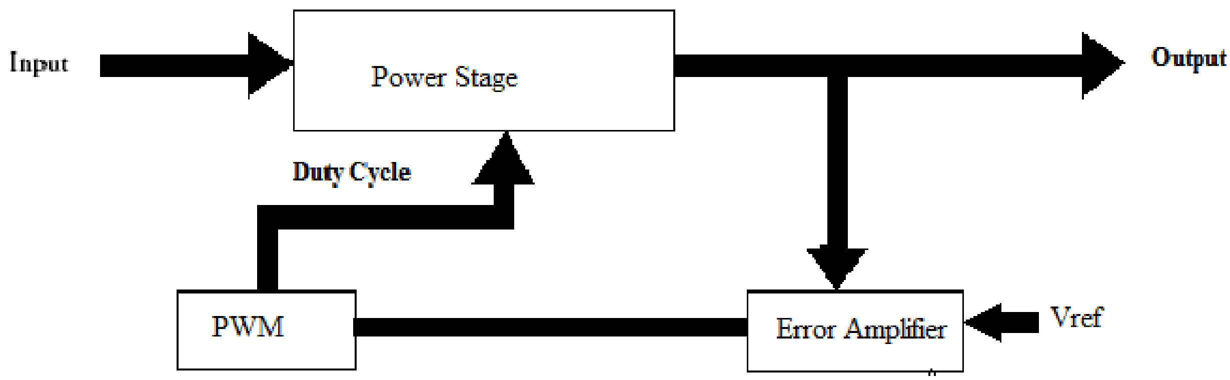

Figure 4: PWM generation

DC-DC converters are nonlinear in nature and the controller used must deal with wide range of input and load variations as well as it must ensures stability in any operating condition. There are various controlling techniques. This paper focus on PID controller, PI controller, Sliding Mode Controller (SMC) [6],[7],[8]

Proportional, Integral and Derivative Controller (PID)

In PID controller, control signal is a linear combination of three signals: (1) the signal obtained by multiplying the the error signal by constant Kp. (2) the signal obtained by differentiating and multiplying the error signal by constant Kd. (3) the signal obtained by integrating and multiplying the error signal by constant Ki.It is given in the form:

$$u(t) = K_p e(t) + K_d \frac{d}{dt} e(t) + K_i \int e(t)dt$$

Taking the laplace transformation of above equation and solving it, an ideal PID controller transfer function can be obtained:

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$$U(s) = K_p E(s) + K_d s E(s) + K_i \frac{1}{s} E(s)$$

$$U(s) = E(s)\left[K_p + K_d s + \frac{K_i}{s} \right]$$

All the three constants are adjustable for an acceptable performance of the converter and this adjustment process is known as tuning. PID controller reduces the error upto an acceptable level and provide acceptable stability and damping.

Proportional, Integral Controller (PI)

In PI controller, control signal is a linear combination of two signals: (1) the signal obtained by multiplying the error signal by constant Kp. (2) the signal obtained by integrating and multiplying the error signal by constant Ki. It is given by:

$$u(t) = K_p e(t) + K_i \int e(t) dt$$

Taking the laplace transformation of above equation and solving it, an ideal PID controller transfer function can be obtained:

$$U(s) = K_p E(s) + K_i \frac{1}{s} E(s)$$

$$U(s) = E(s)\left[K_p + \frac{K_i}{s} \right]$$

The integral term in PI controller reduces the steady-state error to zero which is not possible with derivative term. As the derivative term is more sensitive toward the high-frequency in input so the absence of derivative term make the system more steady in steady state in case of noisy data.

Sliding Mode control (SMC)

Sliding mode control is the only non-linear method. Sliding mode controller is a systematic approach to solve the stability problem and consistence performance. Switch mode controller could be implemented for switch mode power supplies. Switching control action is required to drive the non-linear plants state trajectory into a specified surface in the state space and to maintain the plants state trajectory for subsequent time. The gain of the feedback path depends upon the position of trajectory w.r.t surface. If the trajectory is above the surface feedback path has one gain and the gain will change as the trajectory move below the surface. The surface is known as sliding surface [9],[10]. Ideally response is made to slide along a predefined trajectory with the help of control algorithm. The control detects the deviation of actual trajectory from the reference trajectory and correspondingly changes the trajectory to restore the tracking.

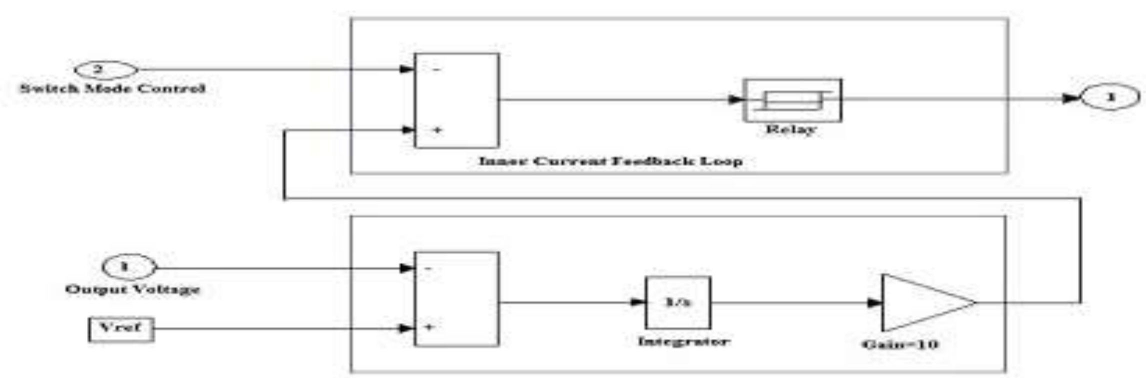

Figure5: Block Diagram of SMC

SIMULINK MODEL AND RESULTS

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List of Parameters

Model Parameter	***Values***
Input Voltage, V_d	24V
Output Voltage, V_o	12V
Inductance, I	$47\mu H$
Capacitance, C	$2\mu F$
ESR, r_c	0.1 Ω
Load Resistance, R	0.1Ω
Switching Frequency, f_s	100kHz
Switch Off	u=0
Switch On	u=1

SIMULATION RESULTS

Buck Converter with PI controller

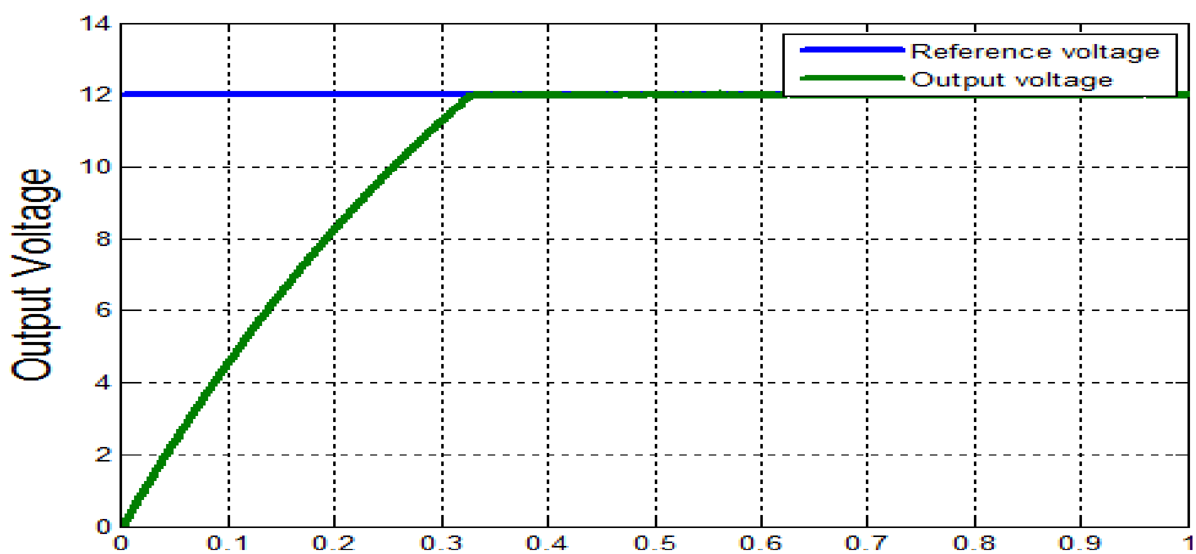

Figure 7: Output Voltage of Buck Converter with PI controller

Buck Converter with PID controller

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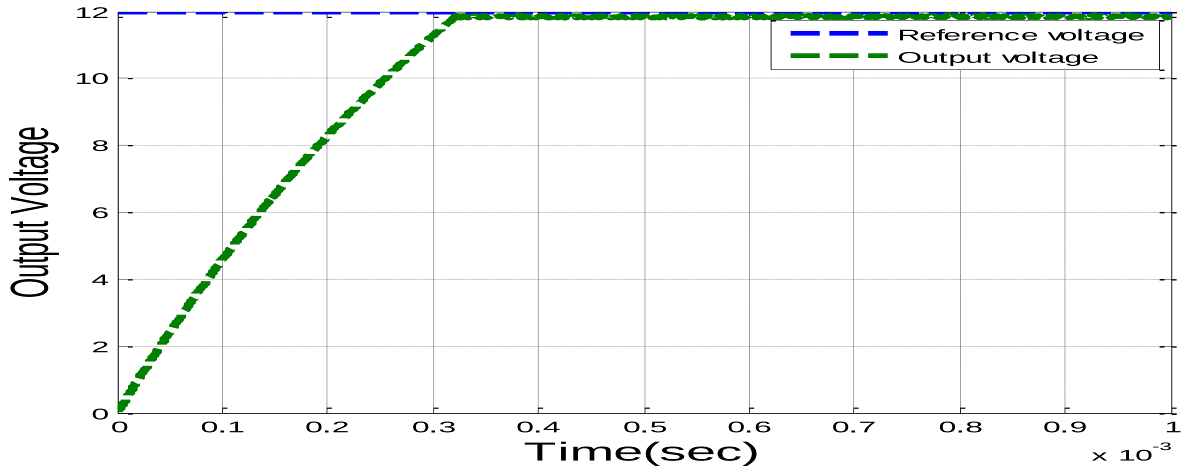

Figure 8: Output Voltage of Buck Converter with PID controller

Buck Converter with Sliding Mode Controller (SMC)

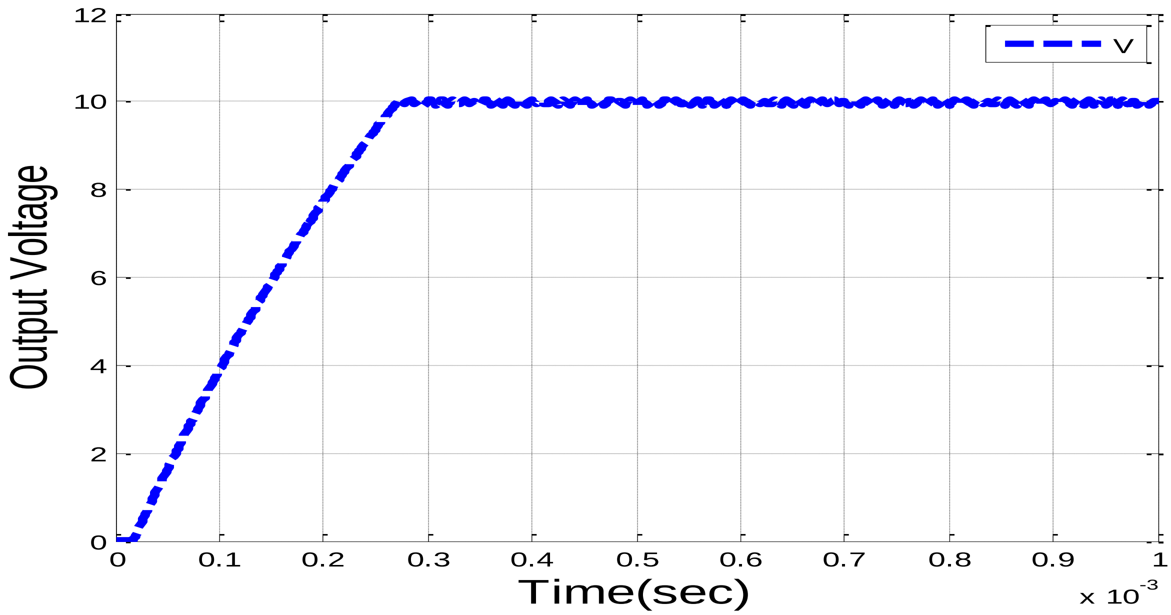

Figure 9: Output Voltage of Buck Converter with Sliding Mode controller

RESULTS

Sl.N.o.	Types of Circuits	Input Voltage	Output Voltage
1	Buck converter with PI controller	24V	12V
2	Buck converter with PID controller	24V	12V
3	Buck converter with SMC	24V	10V

Change in settling time with Variation in the input voltage of the circuit

Sl.No.	Type of Circuit	Reference Voltage (V)	Input Voltage (V)	Settling Time(sec)
1	Buck converter with PI controller	12V	20V	0.42×10^{-3}
			30V	0.25×10^{-3}
			40V	0.18×10^{-3}
2	Buck converter with PID controller	12V	20V	0.42×10^{-3}
			30V	0.25×10^{-3}
			40V	0.18×10^{-3}
3	Buck converter with SMC	12V	20V	0.35×10^{-3}
			30V	0.2×10^{-3}
			40V	0.18×10^{-3}

CONCLUSION

A comparison between PID, PI and SMC controller for dc-dc buck converter is analysed. The dc-dc buck converter is evaluated under the input voltage of 24V in simulation. The output voltage in PI and PID controller is almost similar. In comparison of PI and PID with SMC it is founded that the settling time of SMC is large. In case of large settling time and more voltage accuracy SMC is preferred over PI and PID controller. But in case of less accuracy and complexity PI and PID controller is used.

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