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Super-twisting Algorithm Based Sliding Mode Controlled Boost Converter

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Abstract

This work provides analysis of boost converter with super-twisting algorithm under sliding mode operating in continuous conduction mode. The super-twisting algorithm reduces the chattering effect which is inherent in conventional sliding mode control. Generally, chattering increases heat losses, thereby decreasing the performance of the boost converter. The aforementioned control strategy minimizes the initial current peak and provides highly improved output voltage regulation irrespective of the input voltage perturbation and load changes. The performances of boost converter under conventional sliding mode control law and under super-twisting control law are also compared to evaluate the effect of chattering.

Keywords: DC/DC boost converter, chattering, sliding mode control, super-twisting algorithm, loop control structure

INTRODUCTION

Various power electronic systems use DC-DC switched mode power converters. Among the different converter topologies, the boost converter has a number of applications including regulated dc power supplies, electric vehicles, solar power applications, etc. The demand of maintaining the output voltage at a required quantity can be conventionally achieved using an open loop system. But a fixed topology DC-DC converter has a minimum time to respond to the changes in line, load and control. Therefore, optimizing the transient behavior of power converter is a well-known problem that has been addressed by many researchers. For this, an on-off control law is used, which minimizes the energy used in reaching the stable points from zero initial conditions.

A two-loop control structure is used to utilize the motion separation property of power converters and for realizing control operation. The current moves far more quickly than the output voltage in many of the power converters that are in use. In this paper, a cascaded two loops control structure is used. The outer voltage control loop is implemented using standard linear control techniques. The sliding mode controller (SMC) approach is used to create the inner current regulation loop [1]. Effect of chattering is a major drawback for SMC resulting in high switching losses in power electronic circuits. This is rectified by modifying the control law by super-twisting algorithm [2]. The derivatives of the sliding variable are not necessary to be known by the super-twisting sliding mode actuator.

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DESIGN OF SLIDING MODE CONTROLLER FOR BOOST COVERTER

Modeling of Boost Converter

Figures 1 and 2 demonstrate switch ON and OFF of the boost converter where L, C, R_L, V_I, and Vo are the inductor, capacitor, resistive load, input and output voltage, respectively. R represents inductive loss and I_O, I_L, and I_C represent load, inductor, and capacitor currents [3].

There are two kinds of control available on an SMC for switching power converters: voltage control and current mode. Here, current mode is employed, that is, inductor current I_L is to be controlled. The state space description of boost converter under SM current control is described. The control parameters are the inductor current error and the current error dynamics [4].

From the figures, the current dynamics for different switching positions can be derived as follows:
When switch is turned on,

$$\frac{dI_L}{dt} = \frac{V_i - I_L R}{L} \tag{1}$$

$$\frac{dV_C}{dt} = -\frac{V_O}{CR_O} \tag{2}$$

When switch is turned off,

$$\frac{dI_L}{dt} = \frac{V_i - V_O - I_L R}{L}$$

$$\frac{dV_C}{dt} = \frac{I_L}{C} - \frac{V_O}{CR_O}$$

The dynamic behavior of the boost converter in continuous conduction mode can be expressed in compact form by introducing the control variable u_I, so that $u_I = 1$ when switch is turned on (T_{ON}) and $u_I = 0$ when switch is turned off (T_{OFF}). The resulting equations are the following:

$$\frac{dI_L}{dt} = -\frac{V_O}{L}(1-u) - \frac{R}{L} I_L + \frac{V_i}{L} \tag{3}$$

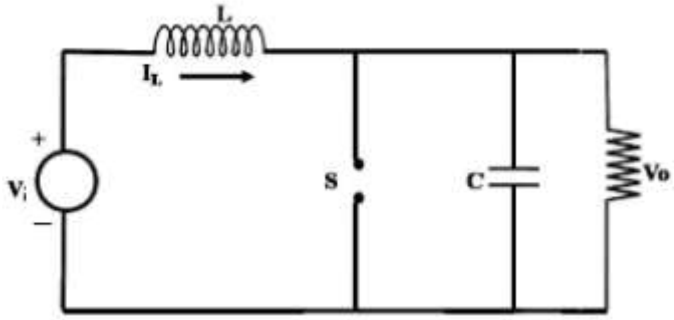


Figure 1. Switch ON condition.

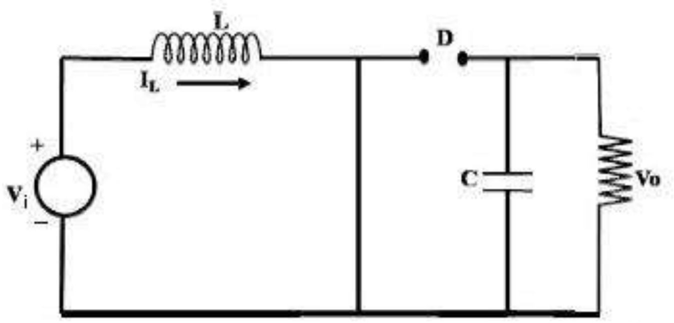


Figure 2. Switch OFF condition.

$$\frac{dV_C}{dt} = \frac{I_L}{C}(1-u) - \frac{V_O}{CR_O} \tag{4}$$

where, V_O is the output voltage and I_L is the input current.

The system e_1 is taken as the error of actual inductor current (I_L) and reference inductor current (I_E).

$$e_1 = I_L - I_E \tag{5}$$

$$e_2 = \dot{e}_1 \tag{6}$$

$$e_2 = \frac{d(I_L - I_E)}{dt} = \frac{dI_L}{dt}$$

$$= -\frac{V_O}{L}(1-u) - \frac{R}{L}I_L + \frac{V_i}{L} \tag{7}$$

Therefore,

$$-\frac{V_O}{L}(1-u) = -e_2 - \frac{R}{L}I_L + \frac{V_i}{L} \tag{8}$$

But from Equation (5), I_L can be written as:

$$I_L = e_1 + I_E \tag{9}$$

Equation (8) becomes,

$$-\frac{V_O}{L}(1-u) = -e_2 - \frac{R}{L}(e_1 + I_E) + \frac{V_i}{L}$$

$$= -e_2 - \frac{R}{L}e_1 - \frac{R}{L}I_E + \frac{V_i}{L} \tag{10}$$

Rearranging,

$$e_2 = -\frac{V_O}{L}(1-u) - \frac{R}{L}e_1 - \frac{R}{L}I_E + \frac{V_i}{L} \tag{11}$$

Taking derivative of Equation (11),

$$\dot{e_2} = -\frac{\dot{V}_O}{L}(1-u) - \frac{R}{L}\dot{e}_1 \tag{12}$$

Substituting for $\dot{V}_O$ and $\dot{e_1}$,

$$\dot{e_2} = -\frac{\frac{I_L}{C}(1-u) - \frac{V_O}{CR_O}}{L}(1-u) - \frac{R}{L}e_2 \tag{13}$$

$$= -\frac{\left((1-u) + \frac{R}{R_O}\right)}{LC}e_1 - \left(\frac{1}{CR_O} + \frac{R}{L}\right)e_2 - \frac{I_E}{LC}\left(\frac{R}{R_O} + (1-u)\right) + \frac{V_I}{LCR_O} \tag{14}$$

Therefore, state equations of the system are:

$$\dot{e}_1 = e_2 \tag{15}$$

$$\dot{e_2} = -\frac{\left((1-u) + \frac{R}{R_O}\right)}{LC}e_1 - \left(\frac{1}{CR_O} + \frac{R}{L}\right)e_2 - \frac{I_E}{LC}\left(\frac{R}{R_O} + (1-u)\right) + \frac{V_I}{LCR_O} \tag{16}$$

Design of Sliding Mode Controller

The design of SMC has two parts. In the first part, a suitable sliding surface is chosen which will yield the desired plant response on which the motions of the switching states are restricted. A control law is created in the second section to provide sliding mode. The sliding mode control have two phases, reaching phase and sliding phase. In the reaching phase, the state trajectories are directories are directed towards the switching surface. The state trajectories never leave the switching surface once they arrive, and as a result, they evolve in accordance with the dynamics dictated by the sliding surface, also known as the sliding mode [5]. The control of the sliding mode control may be divided into two parts as corrective control and equivalent control. To get to the sliding surface, the corrective control makes up for departures from it (reaching phase). The state trajectories remain on the sliding surface (sliding mode) due to the analogous control. Figure 3 shows the schematic circuit for sliding mode controller with super-twisting algorithm.

A two-loop control structure is used. Error of the output voltage loop is given to proportional-integral (PI) controller to get reference current. The error of actual inductor current and reference current is given to the sliding mode control with super-twisting algorithm. Output of the super-twisting algorithm based sliding mode control is a continuous signal. It is then compared with triangular wave of required frequency to get switching pulses. The switching surface used for boost converter is:

$$w(x) = I_L - I_E \tag{17}$$

where I_E is the reference inductor current and I_L is the actual inductor current sensed. Applying invariance conditions as appeared in, $w(x) = I_L - I_E = 0$ and $\frac{dw(x)}{dt} = 0$ in Equations (3) and (4) yields the equivalent control u_{eq}, which is limited by both maximum and minimum values of $u(t)$, that is,

$$0 < u_{eq} < 1 \tag{18}$$

Moreover, a switching law of the type:

$$u(t) = 0 \; if \; w(x) > 0 \tag{19}$$

$$u(t) = 1 \; if \; w(x) < 0 \tag{20}$$

will bring about a sliding control on the switching surface and ensure the sliding-mode existence conditions, because

$$w(x)\frac{dw(x)}{dt} < 0 \tag{21}$$

Applying $w(x) = 0$, Equation (17) becomes,

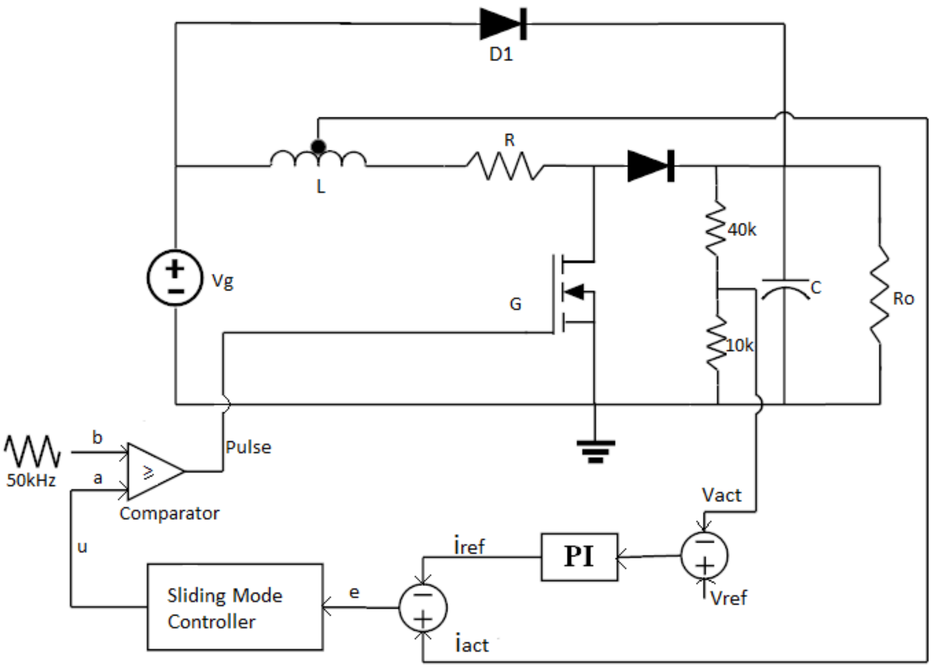


Figure 3. Circuit scheme for sliding mode (super-twisting algorithm) control of boost converter.

$I_L = I_E$

Applying $\frac{dw(x)}{dt} = 0$, Equation (17) becomes,

$\frac{dI_L}{dt} - \frac{dI_E}{dt} = 0$

$\frac{dI_L}{dt} = 0$

Therefore, Equation (3) becomes,

$\frac{dI_L}{dt} = -\frac{V_O}{L}(1-u) - \frac{R}{L}I_L + \frac{V_i}{L} = 0$

that is,

$-\frac{V_O}{L}\left(1-u_{eq}\right) - \frac{R}{L}I_L + \frac{V_i}{L} = 0$

$u_{eq} = 1 - \frac{V_i - RI_E}{V_C}$

Replacing u by u_{eq} in Equation (4) yields,

$\frac{dV_C}{dt} = \frac{I_E}{C}\frac{V_i - RI_E}{V_C} - \frac{V_O}{CR_O}$

Therefore, equivalent control and ideal sliding dynamics for switching surface $w(x)$ is:

$$u_{eq} = 1 - \frac{V_i - RI_E}{V_C} \tag{22}$$

$$\frac{dV_C}{dt} = \frac{I_E}{C}\frac{V_i - RI_E}{V_C} - \frac{V_O}{CR_O} \tag{23}$$

Output voltage dynamics is dependent on the input voltage, reference input current, which is the output of the PI controller.

Output Voltage Regulation:

After inrush current is controlled by the combined action of $w(x)$ and an auxiliary diode branch, output voltage regulation is obtained by modifying I_E in the switching surface as $I_E(t)$ where $I_E(t)$ is given by:

$$I_E(t) = k_1(V_E - V_C) + k_2\int_{+\infty}^{t}(V_E - V_C)dt \tag{24}$$

where, $k_1, k_2 > 0$ has a corrective effect irrespective of both input voltage and load perturbations, where V_E is the desired output voltage. k_1, k_2 are the coefficients of PI controller (k_P, k_I), which are obtained by trial-and-error method. k_P and k_I values used are 0.31 and 220, respectively.

Super-Twisting Controller

One of the main drawbacks of conventional sliding mode control is the chattering effect, that is, the dangerous high-frequency vibration of the controlled system. There exist certain approaches to avoid chattering. To avoid actual discontinuity and maintain the primary characteristics of the entire system, the basic strategy is to alter the motion of the system in a small area around the discontinuity surface [6]. In particular, high gain control with saturation approximates the sign-function and diminishes the chattering, while the on-line estimation of the so-called equivalent control is used to reduce the discontinues control component; the sliding sector method is suitable to control the disturbed linear time invariant systems, the changing speed of the control value is artificially bounded, removing the chattering effect. But the sliding mode's final precision and resilience were somewhat compromised. As opposed to normal sliding modes, which affect the first deviation derivatives, higher order sliding modes generalize the basic sliding mode idea by operating on the higher order time derivatives of the system departure from the constraint. In addition to offering great realization accuracy and completely eliminating the chattering issue, they retain the primary benefit of the original method. The sliding variable's second time derivatives are used in a second order sliding mode. Nonetheless, the primary issue with implementing the second order sliding mode control is the need of the sliding variable. A modified second order sliding mode control that does not require knowledge of the sliding variable's derivatives is known as a super-twisting sliding mean control [7]. By using super-twisting algorithm we have,

$$u_{st} = -\lambda_1 |e_1|^2 sign(e_1) + z_1 \quad (25)$$

$$\dot{z_1} = -\lambda_2 sign(e_1) \quad (26)$$

where λ_1 and λ_2 are given as

$$\lambda_1 = 1.5\sqrt{L}, \lambda_2 = 1.1L \quad (27)$$

or $\lambda_1 = \sqrt{L}, \lambda_2 = 2L$ (28)

where L is known as Lipschitz constant, $L > 0$.

Therefore, the control law is:

$$u = u_{eqvt} + u_{st} \quad (29)$$

$$u = 1 - \frac{V_i - RI_E}{V_C} + -\lambda_1 |e_1|^2 sign(e_1) + z_1 \quad (30)$$

where u is a continuous signal, which is then compared with triangular wave of required frequency to get the switching pulses.

SIMULATION USING MATLAB/SIMULINK

To validate the proposed control, the simulation was carried out in MATLAB/Simulink environment. The simulation parameters used are, $L = 1$ mH, $C = 220$ μF, $R = 0.2$ ohm, $R_O = 20$ ohm, $V_I = 12$ V, $f = 50$ kHz. An auxiliary diode is used to reduce the inrush current (reduces almost 5 A of peak overshoot).

Conventional Sliding Mode Controller

Conventionally, the converters are driven by the SMC. The control signal used is:

$$u = \frac{1 + Ksign(w)}{2}$$

where $K = -1$ and w is the switching surface, which is taken as the difference of actual signal and reference current.

$$when\, w > 0\; u = \frac{1-1}{2} = 0$$

$$when\, w < 0\; u = \frac{1+1}{2} = 2$$

Figure 4 shows the snippet of simulation diagram from MATLAB/Simulink. All parameters are applied and MOSFET is chosen as the switch due to high switching frequency.

Super-Twisting Controller

Super-twisting controller is simulated by implementing the control law, $u = u_{eq} + u_{st}$. Value of Lipschitz constant is taken as 3 [8]. Here, the switching frequency applied to the controller is 50 kHz (Figure 5).

Figure 6 shows the voltage and current waveforms of super-twisting sliding mode control and Figure 7 shows the voltage and current waveforms of conventional sliding mode control. On observing Figures 7 and 6, it is clear that the waveforms obtained are the same.

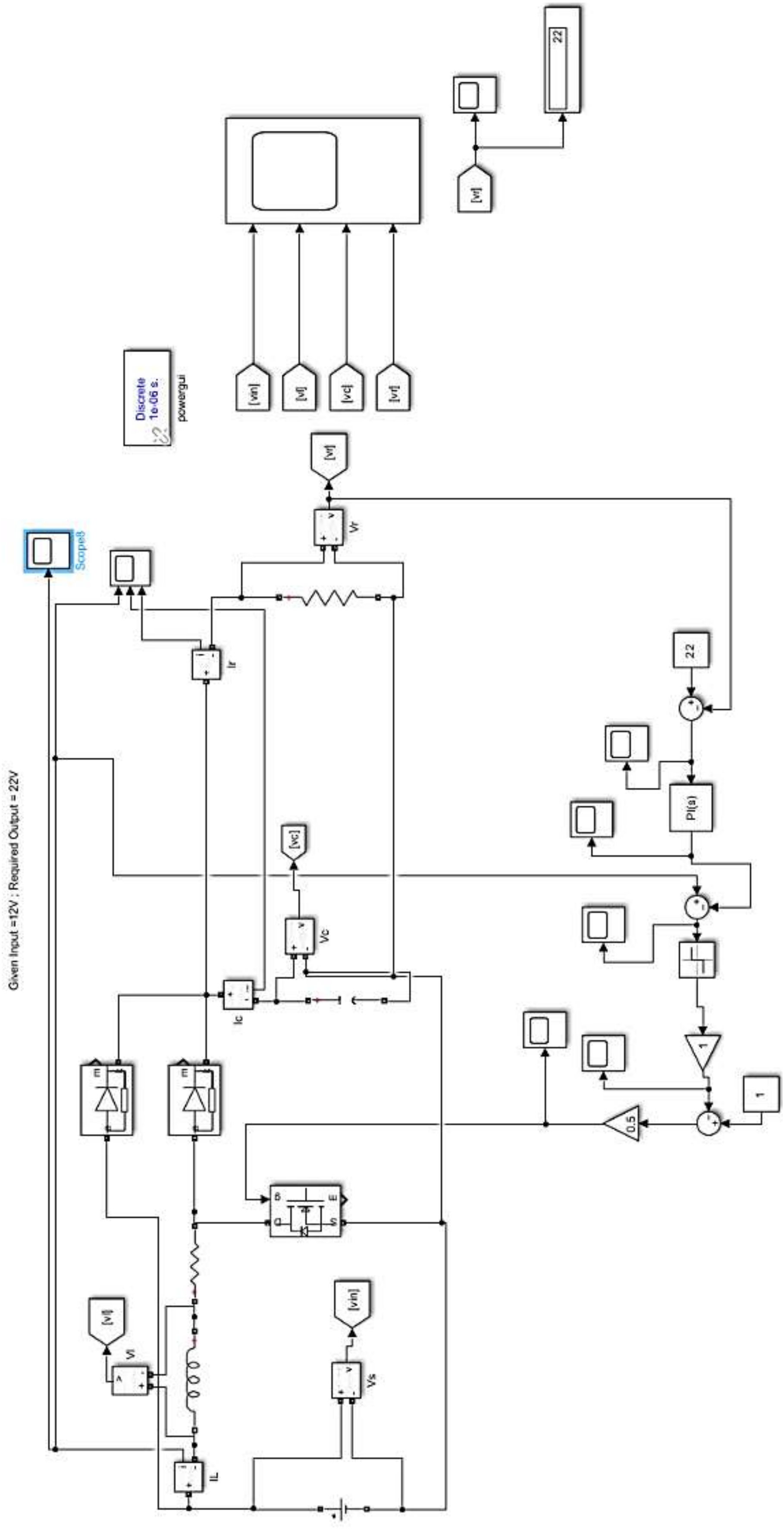


Figure 4. Simulation diagram in MATLAB/Simulink.

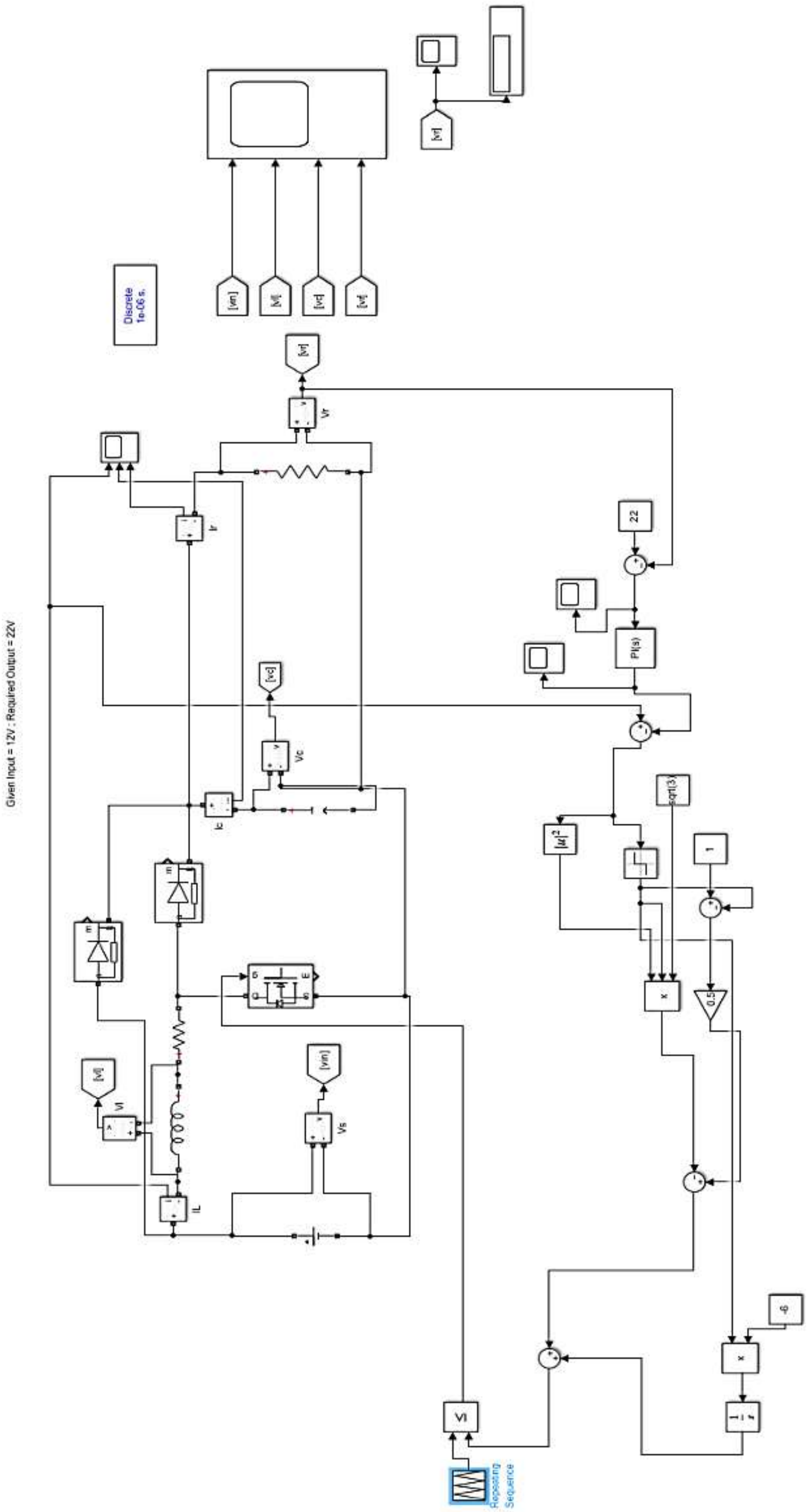


Figure 5. Simulation diagram in MATLAB/Simulink with frequency of 50 kHz.

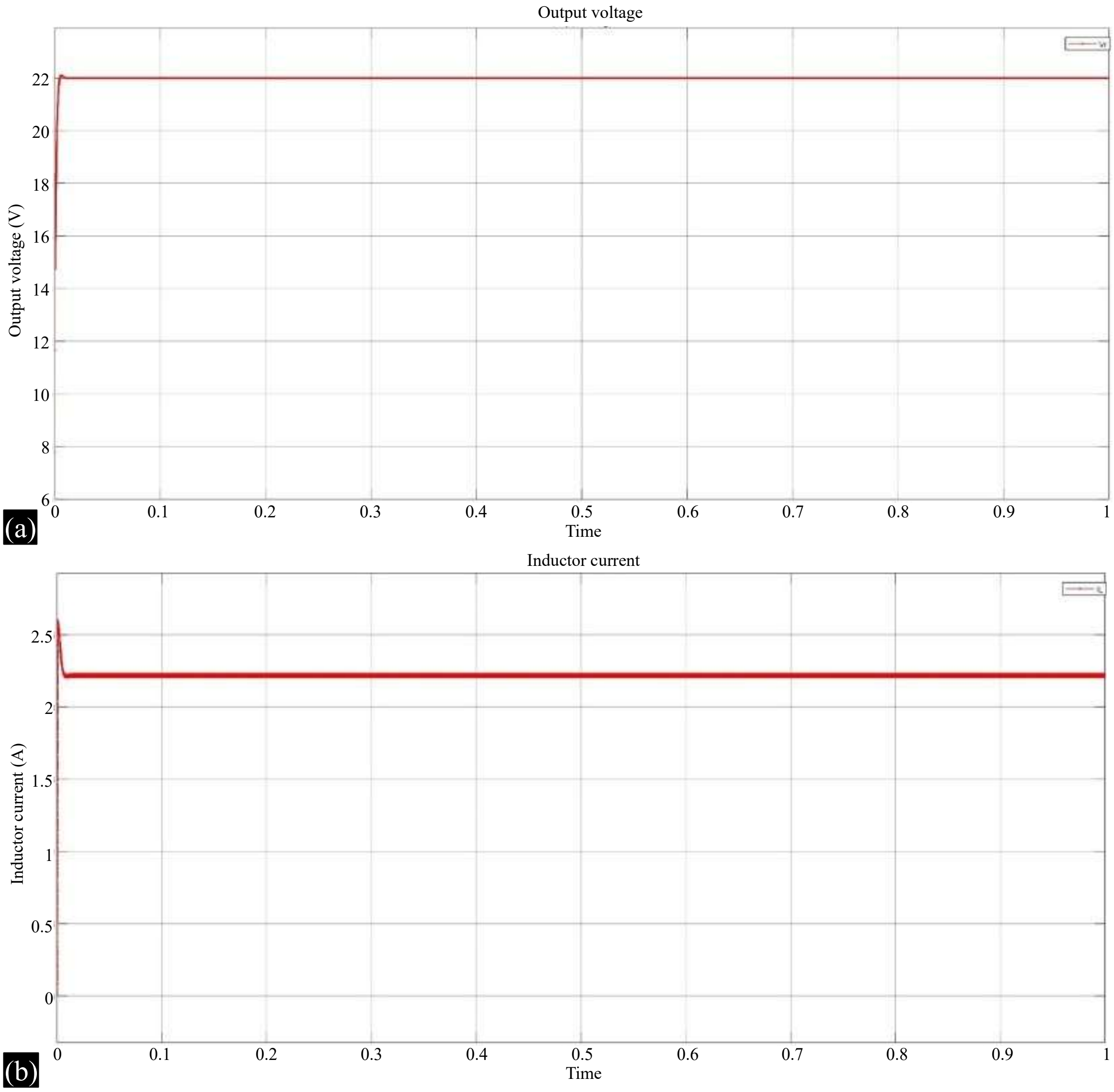
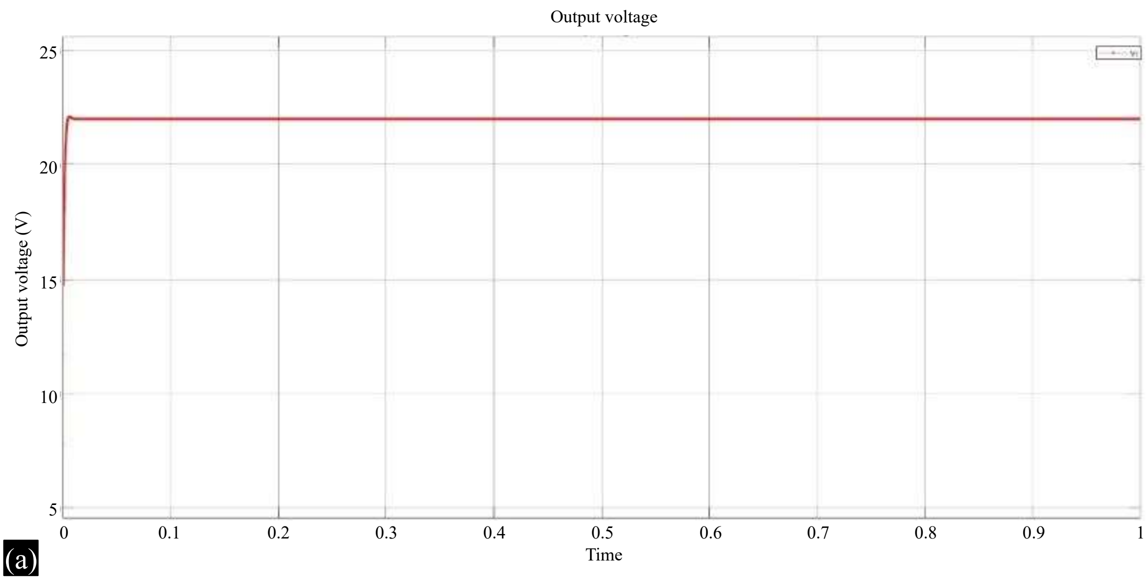


Figure 6. Voltage and current waveforms in super-twisting sliding mode control.



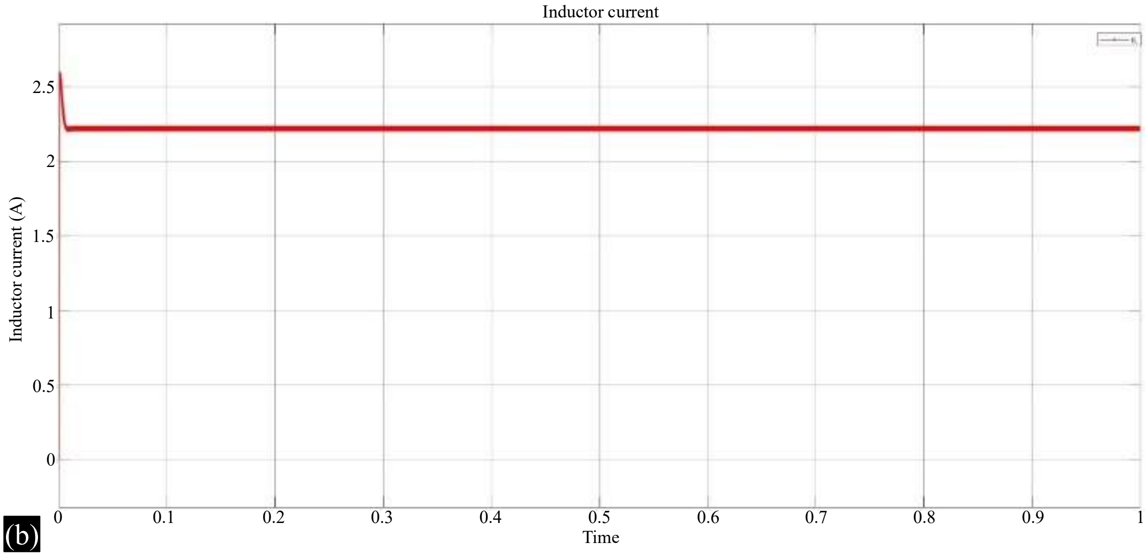


Figure 7. Voltage and current waveforms in conventional sliding mode control.

Effect of Chattering

Effect of chattering in sliding mode controllers can be demonstrated by simulating under varying switching frequencies. Here, frequency is varied from 250 kHz to 300 kHz. The output voltage waveforms of both controllers are chosen for simplicity [9].

Here, Figure 8 depicts the performance of both controllers at varying frequencies. Both waveforms initially had a ripple of approximately 0.01 V. At t = 1 s, frequency is switched from 250 kHz to 300 kHz. Now, both waveforms exhibit disturbances owing to their transient responses. But, after t = 0.015 s, there is observable variations on both waveforms. For conventional sliding mode controller, the transient distortions and increased ripple does not dial out as seen in the super-twisting controller. The primary cause of this is the chattering effect, which is mostly present in theSMC. Chattering results in increased heat loss and overall reduction in performance of the controller. Thus, we can say that super-twisting controller works under a fixed frequency whereas conventional sliding mode controller doesn't.

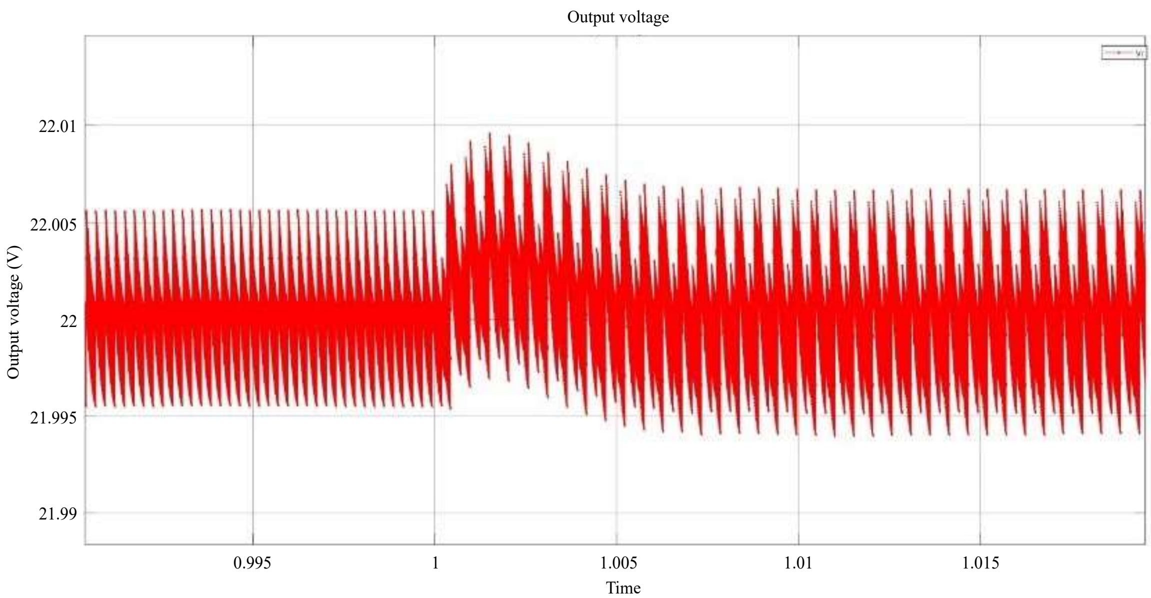


Figure 8. Voltage waveform in conventional sliding mode control.

CONCLUSIONS

Boost converter yields expected performance under sliding mode control operation. The main drawback of having voltage ripples or chattering is reduced by the application of super-twisting algorithm. Also, an auxiliary diode is provided to limit inrush current. It is observed that both control strategies provide the same voltage and current waveforms. But when switching frequencies are varied, super-twisting controller is found to be more stable. Further, as future work, perturbations by changing the resistance value or input voltage can also be analyzed.

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