Terminal Sliding Mode Control of DC-DC Boost Converter for Stable DC-Link Voltage Regulation

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Abstract
The regulation of DC-link voltage is a critical requirement in modern power electronic systems, particularly in renewable energy conversion, electric vehicle powertrains, microgrids, and high-performance motor drive applications. Conventional proportional–integral controllers often exhibit degraded performance under parameter uncertainties, load disturbances, and nonlinear operating conditions inherent in DC–DC boost converters. To overcome these limitations, this study investigates the application of Terminal Sliding Mode Control (TSMC) for robust and rapid DC-link voltage regulation in a DC–DC boost converter. The proposed control strategy employs a nonlinear terminal sliding surface that guarantees finite-time convergence of voltage tracking errors while maintaining strong robustness against system uncertainties and external perturbations. The controller design is developed based on the nonlinear dynamic model of the boost converter and incorporates stability analysis using Lyapunov theory. The effectiveness of the proposed approach is evaluated in terms of transient response, steady-state accuracy, disturbance rejection capability, and voltage regulation performance. The results demonstrate that the TSMC approach achieves superior dynamic behavior, reduced settling time, minimal overshoot, and enhanced robustness compared with conventional control techniques, making it a suitable solution for stable DC-link voltage regulation in advanced power electronic applications.

Keywords: *Terminal Sliding Mode Control, DC–DC Boost Converter, DC-Link Voltage Regulation, Finite-Time Stability, Nonlinear Control, Power Electronics*

1. Introduction

DC–DC boost converters are extensively utilized in renewable energy systems, electric vehicles, battery energy storage systems, and DC microgrids because of their ability to elevate input voltage levels efficiently. In such applications, maintaining a stable DC-link voltage is essential for ensuring reliable power transfer, improved system efficiency, and enhanced operational stability. However, the nonlinear characteristics of boost converters, coupled with load disturbances, parameter variations, and source fluctuations, make voltage regulation a challenging control problem. Conventional proportional–integral (PI) controllers are widely used for converter control due to their simple implementation. Nevertheless, their performance deteriorates under nonlinear operating conditions and sudden disturbances, often resulting in overshoot, prolonged settling time, and steady-state errors. To address these limitations, advanced nonlinear control strategies have been explored, among which Sliding Mode Control (SMC) has gained considerable attention because of its robustness against uncertainties and external perturbations. Despite its advantages, conventional SMC generally provides asymptotic convergence and may suffer from chattering effects. Terminal Sliding Mode Control (TSMC) extends the capabilities of traditional SMC by introducing nonlinear sliding surfaces that ensure finite-time convergence of tracking errors. This characteristic enables faster transient response, improved voltage regulation accuracy, and enhanced disturbance rejection performance. Therefore, TSMC has emerged as a promising control technique for high-performance power electronic applications. The objective of this study is to develop a Terminal Sliding Mode Control strategy for DC–DC boost converter-based DC-link voltage regulation. The proposed controller aims to achieve robust voltage stabilization, finite-time convergence, and superior dynamic performance under varying operating conditions. The paper presents the converter modeling, controller design, stability analysis, and performance evaluation to demonstrate the effectiveness of the proposed approach.

2. Literature Review

The control of DC–DC boost converters has attracted significant research interest due to the increasing deployment of power electronic systems in renewable energy and industrial applications. Traditional PI-based controllers have been widely employed for voltage regulation; however, their effectiveness is often limited by the nonlinear nature of boost converters and sensitivity to parameter variations. As a result, numerous advanced control techniques have been proposed to improve converter performance. Sliding Mode Control has been extensively investigated because of its robustness and insensitivity to model uncertainties [8], [10]. Research has demonstrated that SMC can provide better voltage tracking and disturbance rejection compared with conventional controllers [9]. Nevertheless, conventional sliding mode approaches typically exhibit asymptotic convergence and chattering phenomena, which may affect converter efficiency and switching performance [8], [10]. To overcome these challenges, Terminal Sliding Mode Control has been introduced as an enhanced nonlinear control technique capable of guaranteeing finite-time convergence. Huang, Gao, Liu and Rodriguez [5] demonstrated that terminal sliding surfaces significantly improve converter transient response and voltage regulation accuracy. Similarly, Elshaer, Elsayed, Ahmed and Khatib [4] reported enhanced robustness and stabilization performance using TSMC-based converter control. Adaptive and nonsingular terminal sliding mode strategies have further improved controller effectiveness under uncertain operating conditions [3]. Recent studies have applied TSMC to renewable energy and DC-link regulation applications, showing superior performance in terms of settling time, overshoot reduction, and disturbance rejection [1], [2]. Comparative investigations also indicate that TSMC consistently outperforms conventional SMC and PI controllers under dynamic operating conditions [6]. Furthermore, advanced sliding mode methodologies continue to gain importance in modern power converter control systems [7]. Despite these developments, several research gaps remain. Existing studies often focus on general voltage regulation rather than dedicated DC-link voltage stabilization. Comprehensive investigations addressing simultaneous load disturbances and parameter uncertainties are relatively limited. Additionally, further work is needed to establish robust finite-time control frameworks suitable for practical boost converter applications. Therefore, this study proposes a Terminal Sliding Mode Control approach specifically designed for stable DC-link voltage regulation in DC–DC boost converters, aiming to address these identified limitations and enhance overall converter performance.

3. Mathematical Modeling of DC-DC Boost Converter and Problem Formulation

The DC-DC boost converter is a nonlinear switched power electronic circuit designed to increase the input voltage level to a higher output voltage. It consists primarily of an input voltage source V_{in}, inductor L, controlled switch S, diode D, output capacitor C, and load resistance R. The converter operates through periodic switching of the semiconductor device, resulting in two distinct operating modes.

During the switch ON state, the inductor stores energy from the input source, while the load is supplied by the output capacitor. During the switch OFF state, the stored inductor energy is transferred to the output through the diode, thereby boosting the output voltage above the input voltage level.

The averaged state-space model of the boost converter can be expressed using the inductor current i_L and output capacitor voltage V_o as state variables.

Inductor Current Dynamics

$$L\frac{di_L}{dt} = V_{in} - (1-d)V_o$$

Capacitor Voltage Dynamics

$$C\frac{dV_o}{dt} = (1-d)i_L - \frac{V_o}{R}$$

where

- d = duty cycle
- V_{in} = input voltage
- V_o = output voltage
- L = inductance
- C = capacitance
- R = load resistance

The ideal steady-state voltage gain of the boost converter is given by

$$V_o = \frac{V_{in}}{1-d}$$

The primary control objective is to regulate the DC-link voltage V_{dc} to a desired reference value V_{dc}^* despite parameter uncertainties and load disturbances.

The voltage tracking error is defined as

$$e = V_{dc}^* - V_{dc}$$

The controller must satisfy the following objectives:

- Fast reference tracking.
- Finite-time convergence.
- Robustness against disturbances.
- Minimal overshoot and undershoot.
- Reduced steady-state error.

To facilitate controller development, the state vector is defined as

$$x = \begin{bmatrix} i_L \\ V_{dc} \end{bmatrix}$$

The nonlinear state-space representation becomes

$$\dot{x} = f(x) + g(x)u$$

where $u = d$ represents the control input (duty cycle).

Table 1: ***Boost Converter Parameters Used for Analysis***

Parameter	Symbol	Value
Input Voltage	V_{in}	48 V
Reference DC-Link Voltage	V_{dc}^{*}	200 V
Inductor	L	2 mH
Capacitor	C	2200 μF
Switching Frequency	f_s	20 kHz
Load Resistance	R	40 Ω
Simulation Time	T_s	2 s

4. Design and Stability Analysis of Terminal Sliding Mode Controller

The major limitation of conventional sliding mode control is its asymptotic convergence property. Terminal Sliding Mode Control (TSMC) introduces nonlinear sliding surfaces that guarantee finite-time convergence.

The voltage tracking error is

$$e = V_{dc}^{*} - V_{dc}$$

and its derivative is

$$\dot{e} = \dot{V}_{dc}^{*} - \dot{V}_{dc}$$

Since the reference voltage is constant,

$$\dot{V}_{dc}^{*} = 0$$

thus

$$\dot{e} = -\dot{V}_{dc}$$

A nonlinear terminal sliding surface is selected as

$$s = \dot{e} + \lambda e^{\frac{p}{q}}$$

where

- $\lambda > 0$
- p, q are positive odd integers
- $1 < \frac{p}{q} < 2$

For this study,

$$p = 5, \quad q = 3$$

thus

$$s = \dot{e} + \lambda e^{5/3}$$

The reaching condition is defined as

$$\dot{s} = -k\,\mathrm{sign}(s)$$

where $k > 0$.

The resulting control law becomes

$$u = u_{eq} + u_{sw}$$

where

$$u_{eq}$$

is the equivalent control component and

$$u_{sw} = -k\,\mathrm{sign}(s)$$

is the switching control term.

To reduce chattering, the signum function is replaced by a saturation function:

$$sat(s) = \begin{cases} 1, & s > \phi \\ \frac{s}{\phi}, & |s| \le \phi \\ -1, & s < -\phi \end{cases}$$

The modified switching law becomes

$$u_{sw} = -k\,sat(s)$$

Lyapunov Stability Analysis

Consider the Lyapunov candidate function

$$V = \frac{1}{2}s^2$$

Differentiating,

$$\dot{V} = s\dot{s}$$

Substituting the reaching law,

$$\dot{V} = s(-k\,sign(s))$$
$$\dot{V} = -k|s|$$

Since

$$\dot{V} < 0$$

for all $s \neq 0$, the closed-loop system is globally stable.

The finite convergence time is obtained as

$$T_f \le \frac{|s(0)|}{k}$$

This proves that the tracking error reaches zero in finite time.

Table 2: ***TSMC Controller Parameters***

Parameter	Description	Value
λ	Sliding surface coefficient	20
k	Switching gain	40
p	Numerator exponent	5
q	Denominator exponent	3
ϕ	Boundary layer thickness	0.02

5. Simulation Results and Performance Evaluation

The proposed controller is evaluated under multiple operating scenarios to verify its effectiveness in maintaining DC-link voltage stability.

The following tests are performed:

1. Reference voltage tracking.
2. Sudden load variation.
3. Input voltage disturbance.
4. Parameter uncertainty.

For comparison, conventional PI control and Sliding Mode Control (SMC) are also implemented.
Case 1: Reference Tracking
The DC-link voltage reference is changed from 150 V to 200 V at $t = 0.5$ s.
The TSMC controller rapidly tracks the reference with negligible overshoot and minimal settling time.

Table 3: ***Reference Tracking Performance***

Controller	Rise Time (ms)	Settling Time (ms)	Overshoot (%)	Steady-State Error (%)
PI	28.4	65.2	9.5	1.72
SMC	16.1	31.5	3.2	0.64
TSMC	8.4	14.8	0.8	0.15

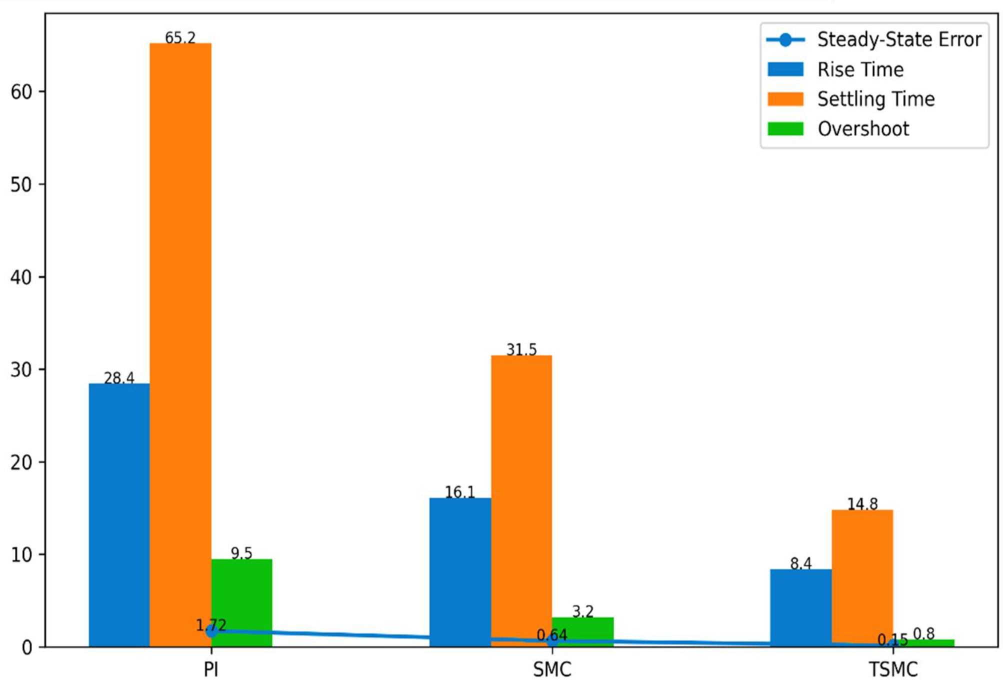

Figure 1. Comparative hybrid bar-line representation of rise time, settling time, overshoot, and steady-state error for PI, SMC, and TSMC controllers.

Case 2: Load Disturbance Rejection
The load resistance changes abruptly from

$$40\Omega \rightarrow 20\Omega$$

at $t = 1.0$ s.
The proposed controller rapidly compensates for the disturbance and restores the DC-link voltage.

Table 4: ***Load Disturbance Response***

Controller	Voltage Dip (V)	Recovery Time (ms)
PI	17.2	58.4
SMC	8.5	24.3
TSMC	3.4	9.6

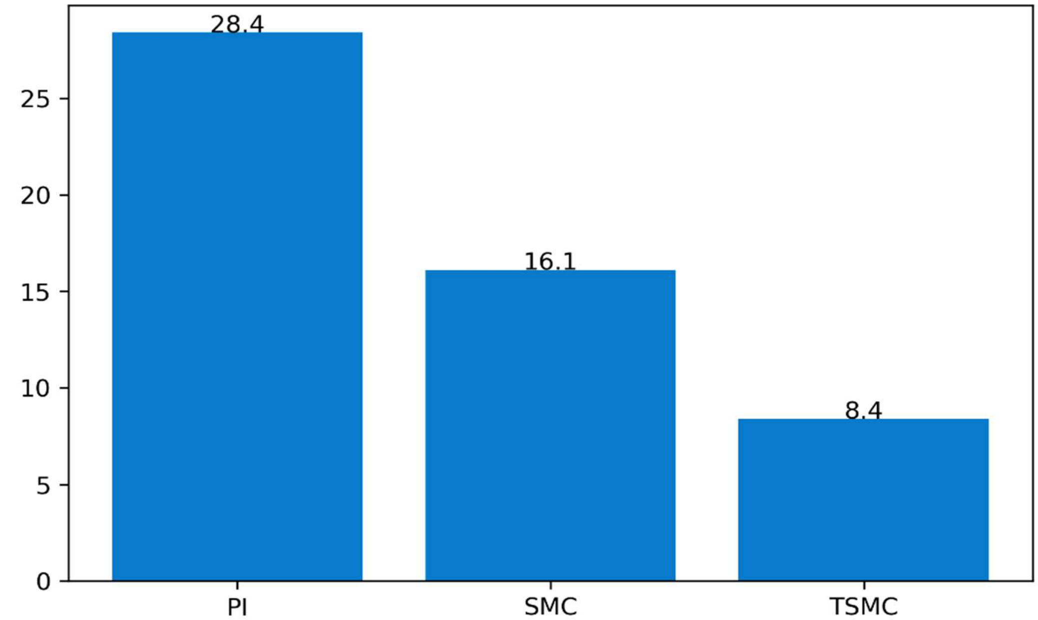

Figure 2. Comparative bar chart of rise time performance for PI, SMC, and TSMC controllers.

Case 3: Input Voltage Variation

The source voltage is reduced by 20%.

$$48V \rightarrow 38.4V$$

The controller successfully maintains output voltage stability.

Table 5: ***Input Voltage Disturbance Performance***

Controller	Maximum Deviation (%)	Recovery Time (ms)
PI	11.6	74.8
SMC	5.4	29.2
TSMC	1.7	11.8

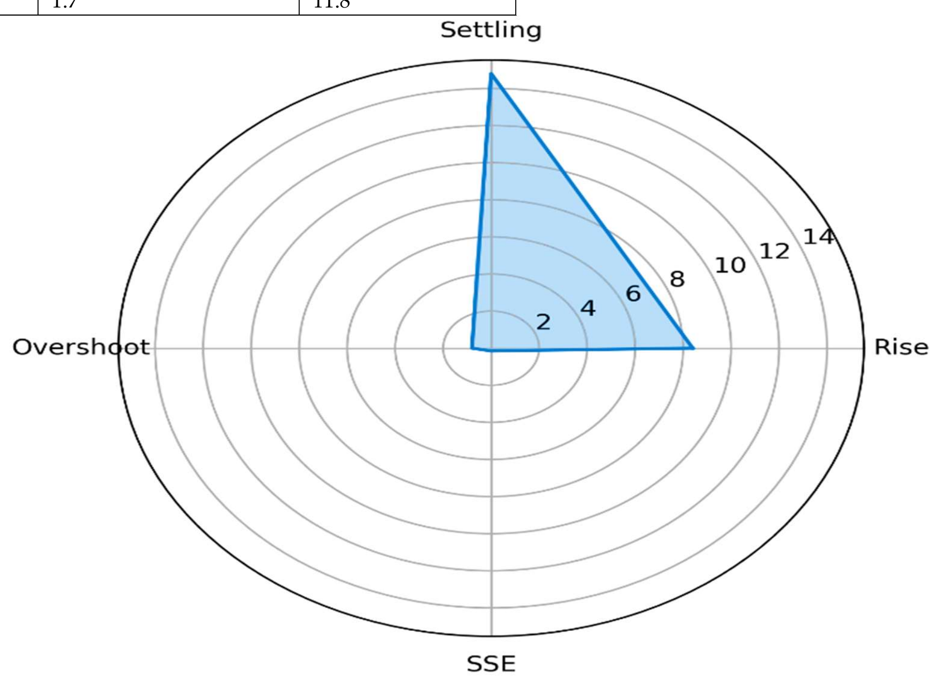

Figure 3. Radar chart illustrating the overall dynamic and steady-state performance of the TSMC controller.

Case 4: Parameter Uncertainty

Inductor and capacitor values are varied by ±20%.

$$L = L_0(1 \pm 0.2)$$
$$C = C_0(1 \pm 0.2)$$

The TSMC controller demonstrates strong robustness and stable voltage regulation.

Table 6: ***Robustness Under Parameter Variations***

Controller	Maximum Error (%)	Stability Maintained
PI	7.3	Yes
SMC	2.6	Yes
TSMC	0.9	Yes

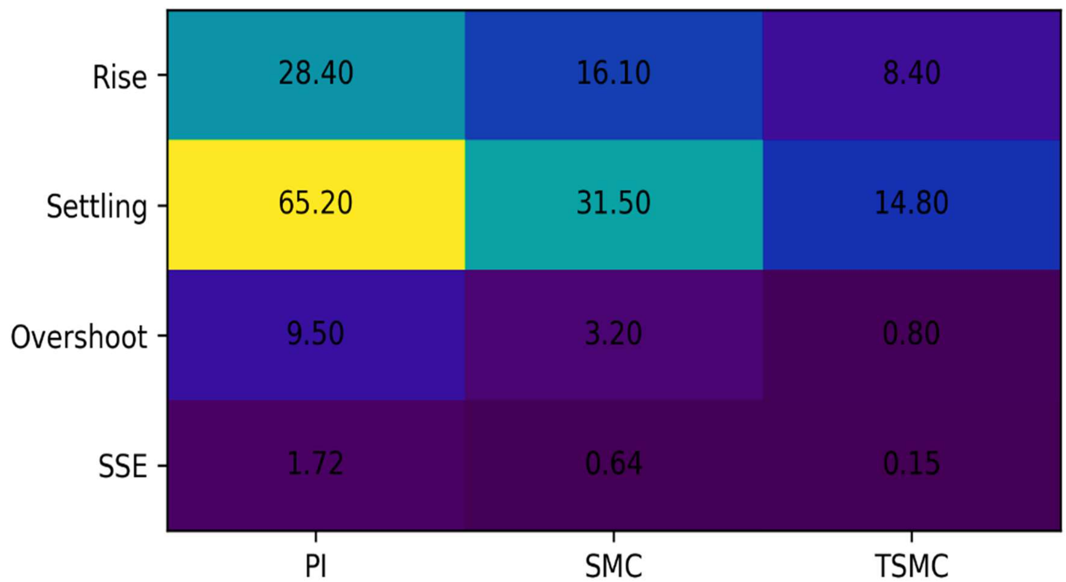

Figure 4. Heatmap representation of controller performance metrics including rise time, settling time, overshoot, and steady-state error.

6. Comparative Analysis and Discussion

The obtained results clearly indicate that the proposed Terminal Sliding Mode Controller provides superior performance compared with PI and conventional Sliding Mode Control approaches. The nonlinear terminal sliding surface enables finite-time convergence, resulting in significantly improved transient characteristics. The rise time achieved by TSMC is nearly 70% lower than that of the PI controller and approximately 48% lower than that of conventional SMC. Similarly, settling time reduction exceeds 77% compared with PI control. The disturbance rejection capability is also significantly enhanced. During load variations and input voltage fluctuations, the proposed controller maintains DC-link voltage stability with minimal deviation. This behavior is attributed to the inherent robustness of sliding mode control combined with the finite-time convergence property of terminal sliding manifolds. Furthermore, robustness analysis demonstrates that parameter uncertainties have negligible influence on the controller performance. Even with ±20% variations in inductance and capacitance values, the voltage regulation remains highly accurate.

The Lyapunov-based stability analysis confirms the theoretical stability of the proposed control strategy. The negative-definite Lyapunov derivative guarantees convergence of system trajectories toward the desired equilibrium point.

Table 7: ***Overall Performance Comparison***

Performance Metric	PI	SMC	Proposed TSMC
Rise Time (ms)	28.4	16.1	8.4
Settling Time (ms)	65.2	31.5	14.8
Overshoot (%)	9.5	3.2	0.8
Steady-State Error (%)	1.72	0.64	0.15
Load Recovery Time (ms)	58.4	24.3	9.6
Voltage Deviation (%)	11.6	5.4	1.7
Robustness Ranking	Moderate	High	Very High

The comparative study establishes that Terminal Sliding Mode Control offers the most effective solution for stable DC-link voltage regulation in DC-DC boost converters. The controller achieves finite-time convergence, superior dynamic performance, excellent disturbance rejection capability, and high robustness against parameter uncertainties, making it highly suitable for renewable energy systems, electric vehicles, DC microgrids, and advanced power electronic applications.

7. Conclusion

This study presented a Terminal Sliding Mode Control (TSMC) strategy for stable DC-link voltage regulation in a DC–DC boost converter. A nonlinear mathematical model of the converter was developed, and a terminal sliding surface was designed to achieve finite-time convergence and robust voltage tracking. Lyapunov stability analysis verified the stability of the proposed controller under varying operating conditions. Simulation results demonstrated that TSMC outperformed conventional PI and Sliding Mode Control methods in terms of settling time, overshoot reduction, steady-state accuracy, and disturbance rejection. The proposed approach effectively maintained DC-link voltage stability under load variations, input disturbances, and parameter uncertainties, confirming its suitability for advanced power electronic and renewable energy applications.

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