

# A Sliding Mode Controller Design for Buck Converters in Robotic Power Systems

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## ABSTRACT

Robotic power systems rely on buck converters to step down voltages and supply regulated DC voltages to sensors, controllers, and actuators, hence they are essential for the stable and efficient operation of robotic systems. However, maintaining an accurate output voltage under changing loads and battery conditions requires robust, non-conventional control strategies in robotics. This paper proposes the use of a Sliding Mode Controller (SMC) to control the buck converter output voltage in robotic applications. The proposed SMC is designed to maintain a reference voltage of 25 V accurately across changing load conditions. MATLAB/Simulink has been used as the simulation environment to confirm the controller's effectiveness, and the results show that the SMC is superior in reducing overshoot, limiting voltage fluctuations from 30–35 V (in the constant duty cycle case) to a narrow range of 25–25.5 V, and maintaining accuracy under dynamic power requirements. The findings confirm the potential of the proposed control mechanism to improve energy efficiency and reliability in robotic applications, particularly for robotic manipulators, mobile robots, and autonomous systems in general.

**Keywords**-DC-DC buck converter; robotics; Sliding Mode Controller (SMC); MATLAB

## I. INTRODUCTION

Robotic systems, such as manipulators, mobile robots, drones, and autonomous vehicles, require a stable and efficient power supply to ensure the reliable operation of their diverse components, such as actuators, sensors, and control units [1-2]. Among the various DC-DC converter topologies, buck converters play an important role in robotic power systems by ensuring precise voltage regulation and efficient power delivery. However, one of the challenges in robotic systems is that the voltage must remain stable despite the large load variations and supply fluctuations (e.g., when motors change speed suddenly or when batteries discharge).

Conventional linear controllers (such as PID) are often used to regulate the buck converter output [3]. Although a well-designed and tuned PID controller can eliminate steady-state error, it may perform poorly when the system parameters change significantly or under rapid external disturbances [4-6]. In robotics, both loads and input conditions can vary abruptly, and classical PID control may be insufficient due to its lack of robustness and adaptability [7]. This necessitates a robust control method that can ensure stability and performance even under uncertainties and disturbances. Fuzzy logic controllers

offer improved adaptability, yet they require extensive tuning and may still lack robustness in highly dynamic scenarios. A Sliding Mode Controller (SMC) has gained attention as a nonlinear control approach known for its robustness to parameter variations and disturbances, and, accordingly, it offers a promising solution to regulate buck converter output in robotic systems [8]. The SMC can force the converter to follow the desired dynamics with minimal sensitivity to fluctuations and, hence, maintain output voltage regulation under severe variations and uncertain conditions, which are typical in robotic systems [9].

Previous studies have demonstrated the effectiveness of SMC in DC-DC converters and certain robotic applications [10-28], but most focus on fixed or slowly varying loads. Accordingly, there is a gap in addressing the rapid load changes typical of robotic systems.

This work proposes an SMC-based control design for buck converters in robotic power systems to ensure accurate and fast voltage regulation for load voltage changes between 30 V and 35 V with a fixed reference of 25 V. The main contributions of this work are:

1. Building a custom SMC design for high-precision voltage tracking under rapidly changing load conditions.
2. Carrying out a comparative evaluation with PID and fuzzy controllers under identical simulation scenarios, and evaluating overshoot, settling time, and voltage ripple.

The controller design is validated using MATLAB/Simulink, and its performance is evaluated using metrics such as overshoot, settling time, voltage ripple, and tracking error.

## II. SLIDING MODE CONTROLLER OPERATION

The proposed SMC design is developed based on the dynamic power demand of robotic systems. This section provides the steps for designing an SMC for DC-DC converters integrated into robotic power systems. These steps ensure adaptability to the changing and unpredictable loads found in robotic applications.

First, a suitable type of converter for the given robotic application must be selected. In general, buck converters are widely used to power low-voltage robotic actuators and sensors. A converter model must be developed by taking into account the switching states (ON/OFF) of its components. The model should capture the dynamic behavior of the converter to ensure precision in controller design. The key dynamic equations governing the current and output voltage of the converter must be established in this step. These equations are necessary for designing an SMC capable of maintaining stability under variable robotic loads.

The next step is to design the SMC itself by defining the sliding surface ( $S$ ) and its time derivative ( $dS/dt$ ) with the control objective of achieving zero error and zero error rate to enable smooth transitions and precise tracking of reference voltages, which is essential for maintaining the stability of the given robotic system [29].

The next step is to determine the switching states of the converter using the equivalent control component ( $u_{eq}$ ) and the nonlinear component ( $u_n$ ). This step ensures real-time adaptability to dynamic load variations typical in robotics.

The above steps are implemented in MATLAB/Simulink to verify the proposed controller's performance in a simulated robotic power system. The next sections provide details of the modeling, design, and simulation results.

## III. DC-DC BUCK CONVERTER MODELING

Robotic systems require a precise and efficient voltage regulator to power their components, such as actuators, sensors, and control units. This section models the DC-DC buck converter, which is a fundamental component in robotic power systems, along with the dynamic behavior necessary for the subsequent SMC design.

A typical circuit of a buck converter is shown in Figure 1 [30]. It consists of an inductor, a capacitor, a switching element, and a diode.

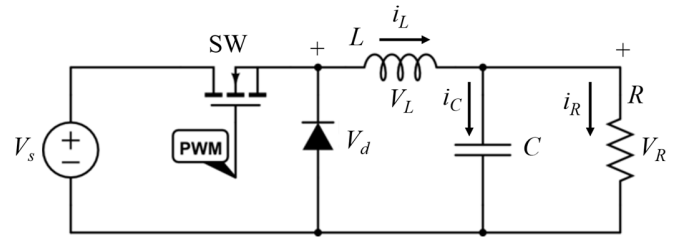


Fig. 1. DC-DC buck converter.

The net rate of change of the inductor current ( $i_L$ ) after a full duty cycle ( $D$ ) is zero, in which the switch is ON during  $DT$  (which is referred to as  $T_{ON}$ ) and OFF during  $(1 - D)T$  (or  $T_{OFF}$ ), where  $T$  is the full period ( $T = T_{ON} + T_{OFF}$ ). This condition is expressed as [31-33]:

$$\left(\frac{di_L}{dt}\right) \text{ at ON state} + \left(\frac{di_L}{dt}\right) \text{ at OFF state} = 0 \quad (1)$$

The inductor current change during the ON and OFF intervals is given by:

$$(\Delta i_{L(ON \text{ state})}) = \left(\frac{V_S - V_o}{L}\right) DT \quad (2)$$

$$(\Delta i_{L(OFF \text{ state})}) = -\left(\frac{V_o}{L}\right) (1 - D)T \quad (3)$$

where  $V_S$  is the input DC voltage and  $V_o$  is the converted (output) DC voltage.

Substituting (2) and (3) into (1) after rearranging yields:

$$\left(\frac{V_S - V_o}{L}\right) D - \left(\frac{V_o}{L}\right) (1 - D) = 0 \quad (4)$$

Rearranging and simplifying (4) yields:

$$V_o = V_S D \quad (5)$$

Therefore, using this converter, an unregulated input voltage can be regulated to a desired level lower than the input voltage level (because  $0 < D < 1$ ).

A controller is required to dynamically adjust the duty cycle  $D$  to maintain precise voltage regulation. This is particularly important in robotics since the power fluctuates due to varying load conditions caused by actuator position changes or varying operating speeds.

## IV. SLIDING MODE CONTROLLER DESIGN

An SMC is designed using the dynamic equations of the output voltage  $dV_o/dt$  and inductor current  $di_L/dt$  as an initial step of the design. From (1) to (3) and by considering the switching state  $u$  (0 or 1) as a duty cycle or switch control during  $DT$  time, the inductor current variation with time becomes [8]:

$$\frac{di_L}{dt} = \frac{u V_S}{L} - \frac{V_o}{L} \quad (6)$$

Referring to Figure 1, the capacitor current is the inductor current minus the resistor current:

$$i_C = i_L - i_R \quad (7)$$

and using  $i_C = C \frac{dV_o}{dt}$  and  $i_R = \frac{V_o}{R}$  in (7) and rearranging yields:

$$\frac{dV_o}{dt} = \frac{i_L}{C} - \frac{V_o}{RC} \tag{8}$$

Equations (6) and (8), expressing the converter dynamics, will be used in the next step of controller design. The SMC drives the error and its derivative to zero on the sliding surface, i.e.,  $S = 0$  and  $dS/dt = 0$ , thereby controlling the state of the converter switch through drive pulses:

$$S = \frac{dS}{dt} = 0 \tag{9}$$

Sliding mode control guarantees  $S = 0$ , which is equivalent to zero error voltage ( $V_{err}$ ), and zero error variation ( $\Delta V_{err}$ ), as shown in (10)–(12):

$$S = V_{err} + \Delta V_{err} \tag{10}$$

$$V_{err} = V_r - V_o \tag{11}$$

where  $V_r$  is the reference voltage. The error variation is given by:

$$\Delta V_{err} = \frac{dV_{err}}{dt} = - \frac{dV_o}{dt} \tag{12}$$

Substituting (11) and (12) into (10) yields:

$$S = (V_r - V_o) - \frac{dV_o}{dt} \tag{13}$$

Using (8) in (13) and simplifying yields:

$$S = - \frac{1}{C} i_L + \left(\frac{1}{RC} - 1\right) V_o + V_r \tag{14}$$

Then,  $dS/dt$  can be obtained from (14) by differentiation:

$$\frac{dS}{dt} = \dot{S} = - \frac{1}{C} \frac{di_L}{dt} + \left(\frac{1}{RC} - 1\right) \frac{dV_o}{dt} \tag{15}$$

and after substituting (6) and (8) into (15), we get:

$$\dot{S} = - \frac{1}{C} \left(\frac{uV_s}{L} - \frac{V_o}{L}\right) + \left(\frac{1}{RC} - 1\right) \left(\frac{i_L}{C} - \frac{V_o}{RC}\right) \tag{16}$$

The last step in SMC design is to determine the switching state  $u$ , which has two components: the non-linear component  $u_n$ , which represents the sign of  $S$ , and the equivalent component  $u_{eq}$ , which can be determined by equating (16) to zero. The equivalent component is given by:

$$u_{eq} = \frac{V_o(R^2C - L + RLC) + RL i_L(1 - RC)}{R^2CV_s} \tag{17}$$

Here, it is important to note that the value of  $u_{eq}$  can be updated based on the variable load or any other component in the system by considering the instantaneous values of the voltage and current through that component. For example, in case of a variable load resistor, by continuously measuring the voltage and current of the load and their rate of change, an updated value of load resistor can be estimated.

The following pseudocode outlines the SMC design workflow for a buck converter in robotic power systems, providing a step-by-step representation of the process, including the definition of system parameters, computation of the sliding surface and its derivative, design of the control law, and application of the control input to the converter.

Figure 2 shows the sliding mode control system design workflow.

### Sliding Mode Control System Design Workflow

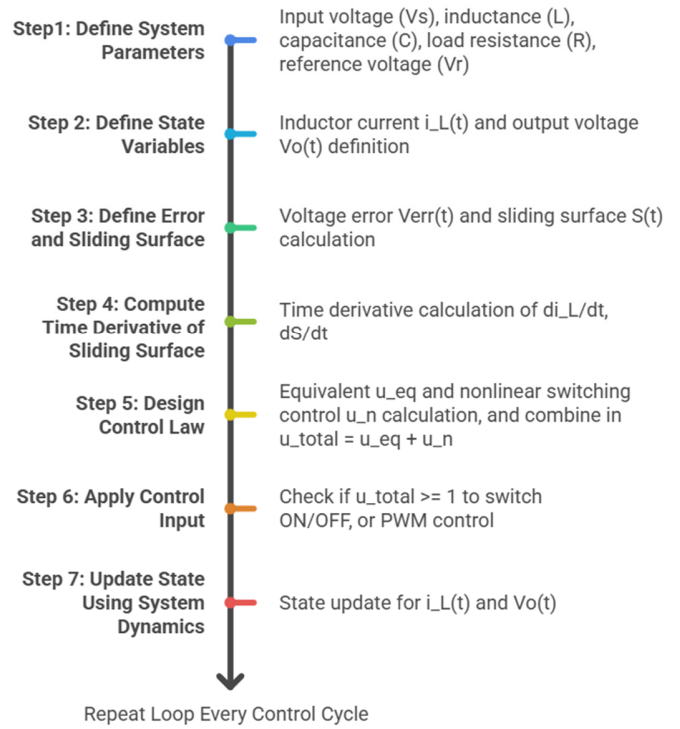


Fig. 2. Sliding mode control system design workflow.

```

BEGIN
// Step 1: Define System Parameters
INPUT:Vs (input voltage), L (inductance),
      C (capacitance), R (load
      resistance), Vr (reference voltage)
// Step 2: Define State Variables
STATE:iL(t) - inductor current
      Vo(t) - output voltage
// Step 3: Define Error and Sliding
Surface
COMPUTE:
  Verr(t) = Vr - Vo(t) // Voltage error
  dVo/dt = (iL(t) - Vo(t)/R) / C // From
  capacitor dynamics
  S(t) = Verr(t) - dVo/dt // Sliding
  surface
// Step 4: Compute Time Derivative of
Sliding Surface
COMPUTE:
  diL/dt = (u Vs - Vo(t)) / L // From
  inductor dynamics
  dS/dt = - (1/C) diL/dt + (1/RC - 1)
  dVo/dt
// Step 5: Design Control Law
COMPUTE:
  ueq = value of u that sets dS/dt = 0 //
  Equivalent control
  un = -K sign(S) // Nonlinear switching
  control (K > 0)
    
```

```

COMBINE:
    utotal = ueq + un
// Step 6: Apply Control Input
IF utotal ≥ 1 THEN
    u = 1 // Switch ON
ELSE IF utotal ≤ 0 THEN
    u = 0 // Switch OFF
ELSE
    u = utotal // Use intermediate PWM
    value if implemented
// Step 7: Update State using System
Dynamics
UPDATE:
    iL(t) = iL(t) + Δt diL/dt
    Vo(t) = Vo(t) + Δt dVo/dt
REPEAT loop every control cycle
END
    
```

The stability of the SMC algorithm must be maintained according to a stability condition. For this purpose, a Lyapunov function is defined as [16]:

$$V(S) = \frac{1}{2} S^2 \tag{18}$$

and its derivative is defined as:

$$\dot{V} = S \cdot \dot{S} \tag{19}$$

For the system to reach and maintain the sliding surface, the following condition must be satisfied:

$$\dot{V} \leq -\eta |S| \tag{20}$$

where  $\eta > 0$ . By designing the control input such that:

$$u = u_{eq} - K \cdot \text{sign}(S) \tag{21}$$

and with  $K > \eta$ , the system ensures global convergence to the sliding manifold and robustness against disturbances and uncertainties.

### V. SIMULATION RESULTS AND DISCUSSION

To validate the effectiveness of the proposed SMC in robotic applications, simulations were conducted using MATLAB/Simulink. The simulation setup replicates a robotic power system where the buck converter provides power to the actuators, and the results compare a conventional constant duty cycle approach with the proposed SMC approach. In this study, the design of the DC-DC buck converter is carried out based on the equations provided in reference [34]. The system is simulated using the converter parameters shown in Table I, and Figure 3 shows a block diagram of the system used to evaluate the performance of the proposed SMC.

TABLE I. BUCK CONVERTER PARAMETERS

Converter parameter	Value
DC link voltage $V_s$	50 V
Reference voltage $V_r$	25 V
Load current $i_r$	0.25 A to 2.5 A (step 0.25 A)
Duty ratio $D$ (without SMC)	0.5
Capacitor $C$	1.5 mF
Inductor $L$	4 mH
Switching frequency $f_s$	20 kHz

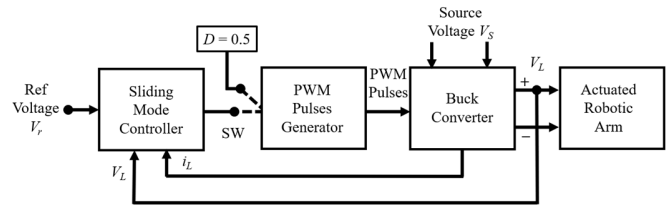


Fig. 3. Block diagram of the proposed system.

First, system simulation is carried out using a constant duty ratio  $D = 0.5$  to evaluate the performance without the proposed SMC. Figure 4 shows the Simulink model of the proposed system.

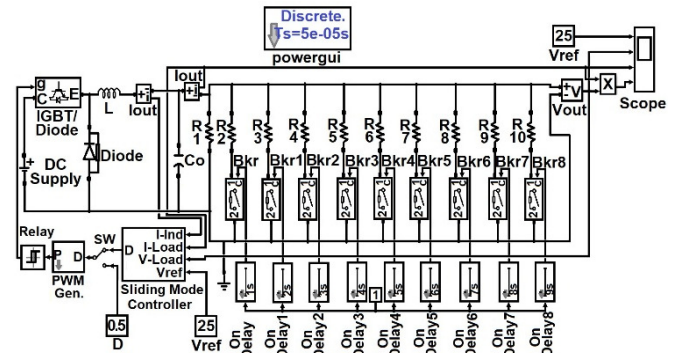


Fig. 4. Simulink model of the proposed system.

The simulation model consists of a DC–DC buck converter topology including a power MOSFET switch, a diode, inductor, and output capacitor. The converter is supplied by a constant DC voltage source, and the output is regulated to a reference voltage of 25 V under varying load conditions. The designed SMC block receives real-time measurements of the inductor current and output voltage, computes the sliding surface and its derivative, and dynamically adjusts the control signal to drive the system toward the desired output. The SMC output is used to generate switching pulses via a PWM signal generator. To simulate dynamic load conditions, a sequence of resistive loads is connected and disconnected using switching blocks at different simulation times, causing the load current to vary. The model provides the ability to observe the controller's performance using monitoring blocks (e.g., scopes and voltage/current measurement blocks) to investigate reference voltage tracking, overshoot, and voltage regulation output under dynamic loading conditions.

Simulation results for the reference voltage, load voltage, load current, and load power for different load resistors are shown in Figure 5. The figure demonstrates significant inaccuracy and fluctuations in the load voltage for a desired reference voltage of 25 V, leading to a load voltage variation between 30 V and 35 V due to having a constant duty cycle ( $D = 0.5$ ). The corresponding load current fluctuation is in the range of 3.25 A to 3.5 A and the power levels are between 97.5 W and 122.5 W. Such fluctuations have a negative impact on system performance, especially in robotics applications where high and dynamic currents are common.

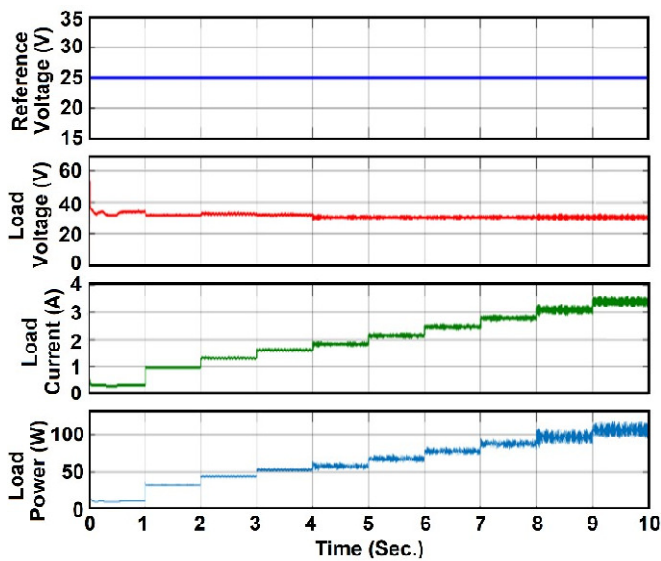


Fig. 5. Simulation results without controller (constant duty cycle  $D = 0.5$ ).

Without a controller (i.e., constant duty cycle case), the simulation results have revealed significant fluctuations and inaccuracies in the load voltage. These imperfections impact robotic systems negatively, particularly under high loading conditions, where voltage deviations lead to poor actuator and sensor performance. Also, it can be observed from Figure 5 that there is an overshoot in load voltage during load changes with high fluctuation levels, especially under dynamic load conditions. Clearly, the system is unable to maintain the required reference voltage.

Figure 6 shows the simulation results for the same DC-DC converter regulated by the proposed SMC. The results demonstrate a highly stable load voltage within a narrow fluctuation range of 25–25.5 V, with precise tracking of the required reference voltage (25 V). The load current response is also accurate across varying loads without observable fluctuations. The load voltage vs. time graph confirms smooth reference voltage tracking, and the load current vs. time graph shows consistent current delivery under dynamic loading conditions.

With the proposed SMC design, the system has achieved smooth and accurate load voltage regulation. The controller has managed to adjust the duty cycle dynamically to maintain stability and precision, even under varying load conditions, which is typical in robotic systems. The load voltage tracks the reference voltage precisely with almost no errors, and the operation of actuators and sensors is more reliable because there is no overshoot or fluctuations. When it comes to robotic applications, smooth operation of actuators and sensors

depends highly on having stable and accurate voltage regulation. The proposed SMC design can significantly enhance power stability and reduce the risk of performance degradation resulting from voltage fluctuations.

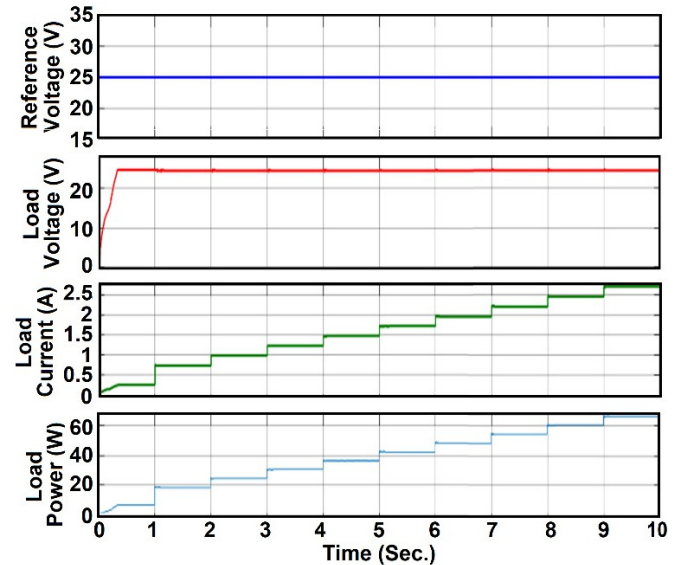


Fig. 6. Simulation results with the proposed SMC (variable duty cycle  $D$ ).

A PID controller and a fuzzy controller were applied to the same buck converter model for comparison with the proposed SMC design, and metrics such as overshoot, settling time, voltage ripple, and tracking error were evaluated. Table II summarizes the comparison results of the three controller types. It can be observed that the SMC design is superior compared to the other two controllers in all metrics. It should be mentioned that the numerical values provided in this table are obtained under identical simulation conditions for all three controllers using the same buck converter model.

TABLE II. CONTROLLER PERFORMANCE COMPARISON

Controller	Overshoot (V)	Settling time (ms)	Voltage ripple (V)	Steady-state error
PID	2.1	6.5	0.9	0.35
Fuzzy	1.6	5.8	0.6	0.2
SMC	0.8	2.2	0.5	<0.1

Recent comparative studies provide direct performance assessments of PID, fuzzy logic, and adaptive controllers, including adaptive fuzzy PID and SMC, for buck converter control in robotics and related fields. Table III provides the comparative performance in robotics-related buck converter control for a number of controllers including the SMC.

TABLE III. COMPARATIVE PERFORMANCE OF BUCK CONVERTER CONTROLLERS IN ROBOTICS APPLICATIONS

Controller	Voltage ripple	Adaptability/robustness	Complexity	Ref.	SMC comparison
PID	Moderate-high	Low-moderate	Low	[35], [36]	Less effective
Fuzzy	Low	High	Moderate	[37], [38]	Less effective
Adaptive fuzzy PID	Lower	High	Moderate-high	[37], [39]	Slightly less effective
Fuzzy SMC	Very low	Very high	High	[39], [40]	-
Adaptive SMC	Very low	Highest	High	[40]	-

As shown in the table, for robotic applications using buck converters, fuzzy logic and adaptive controllers deliver proven improvements over PID, whereas SMC (or fuzzy SMC) is preferred where high robustness is needed, despite implementation complexity [37, 39-40]. It should be mentioned that direct numerical performance comparison with results from [39] and [40] with the proposed SMC controller was not included because the simulation and experimental conditions in these works differ significantly from those in this study.

## VI. PRACTICAL IMPLEMENTATION CONSIDERATIONS

When implementing an SMC for a buck converter in robotic systems, a number of considerations are involved, such as sensor precision (for current and voltage feedback), switching frequency constraints, and real-time control hardware (e.g., DSP or microcontroller). Noise in sensor signals can affect the discontinuous nature of the SMC, requiring filtering or boundary layer modifications. Chattering can potentially cause problems, such as hardware stress or switching losses. To address these problems, techniques such as hysteresis band control or higher-order SMC can be employed. Implementing the controller on real-time platforms like STM32 or TI C2000 microcontrollers with suitable PWM modules can also be a viable solution.

## VII. CONCLUSIONS

This study has provided a powerful Sliding Mode Controller (SMC) design to regulate DC-DC buck converters for robotic systems. This controller was built using the converter dynamic equations of inductor current and output voltage to ensure precise and stable voltage regulation, which is essential to power critical robotic components such as actuators and sensors.

Unlike traditional controllers, the proposed SMC dynamically adjusts the duty cycle to deliver better tracking of reference voltages, minimizes overshoots, and maintain stability even when loads change unpredictably, which is common in robotics. Simulation results have shown that this SMC improves both reliability and efficiency compared to standard controllers, which often struggle with nonlinearity and changing parameters. Given the fluctuating demands robots face, a robust control approach is essential, and sliding mode control stands out because it naturally resists disturbances and uncertainties through its sliding surface mechanism, which forces the system to respond to deviations dynamically.

The design methodology included mathematical modeling the converter, formulating a sliding surface, and crafting a switching law that guarantees stability. These key steps were all validated through comprehensive simulation. When compared to traditional controllers (e.g., PID), which underperform with significant system variations, or controllers that require meticulous tuning (e.g., fuzzy logic), the proposed SMC consistently demonstrated faster response and more reliable voltage regulation. Compared to conventional PID and fuzzy logic controllers, the proposed SMC achieved significantly lower overshoot and improved voltage regulation, as confirmed through simulation. These results confirm the

robustness and fast response of the SMC under variable load conditions, which is typical for robotic applications.

While the proposed SMC has demonstrated robust performance in simulation, practical validation using a buck converter prototype would provide further evidence of its applicability. A hardware setup using a microcontroller-based PWM controller with real-time current and voltage feedback is planned as future work. Such validation would confirm the controller's robustness in the presence of real-world uncertainties, switching delays, and sensor noise. Additionally, combining SMC with adaptive elements, such as disturbance observers, and using higher-order sliding modes (such as twisting and super-twisting algorithms) to further boost performance for precision-demanding robots could be a promising approach.

In conclusion, sliding mode control offers a robust solution for power management in robotics by addressing challenges that conventional controllers struggle with. As robotic systems continue to develop, hybrid approaches combining SMC with machine learning or predictive control are expected to enhance the control of adaptable robotic systems.

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