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Proportional Integral Type Sliding Function For DC-DC Boost Converter In Solar Power System

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Abstract:
Background*: DC-DC Boost Converters are crucial components in solar power systems, requiring effective control for optimal performance. This paper introduces an adaptive sliding mode controller with a modified sliding function to overcome the limitations of classic sliding mode control in DC-DC boost converters.*
Materials and Methods*: The study presents a detailed mathematical model of the DC-DC boost converter and derives a state-space representation. A Proportional-Integral (PI) type sliding function is proposed, introducing an additional tuning parameter γ that can be adaptively adjusted based on load variations. The control law and existence conditions for sliding modes are established, demonstrating the robustness of the proposed method to load changes.*
Results*: Simulation results compare the performance of the proposed PI-type sliding mode control (SMC) with classic SMC for a DC-DC boost converter under varying load conditions. The PI-type SMC demonstrates superior dynamic performance, recovering from a sudden load change in 10 ms compared to 30 ms for classic SMC.*
Conclusion: *The proposed PI-Type Sliding Function for DC-DC Boost Converters in solar power systems offers improved adaptability to load variations and faster dynamic response, potentially enhancing the efficiency and reliability of solar power systems.*
Key Word*: Sliding mode control; Adaptive Sliding function; Power Electronic Converter; Solar power system; boost converter.*

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I. Introduction

DC-DC Boost Converter is utilized in several applications, including solar power systems. Effective converter control is crucial for system performance. This paper introduces an adaptive sliding mode controller with a changed sliding function for a DC-DC boost converter used in solar power systems. The modified sliding function increases the converter's performance by overcoming the restrictions of the classic sliding mode and adding a tuning parameter. Controlling power electronic equipment requires accurate tracking and prompt rejection of load disturbances. Sliding mode control (SMC) is a switching control approach that is effective for power electronic converters due to its inherent robustness in handling matched uncertainty.

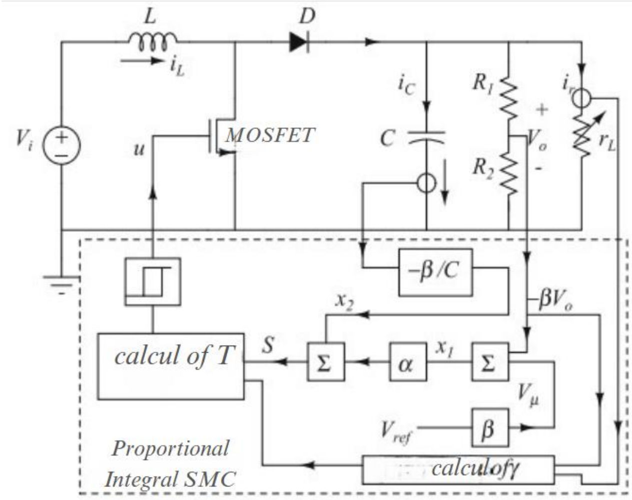
II. Methodology

It is commonly understood that sliding mode control requires a model of the system [1][2]. Researchers reviewed numerous techniques for simulating a power electronic converter [3]. Modeling power electronic systems may be challenging due to the existence of switching components. The mathematical models of power converters provide a bridge to various control approaches explored in a wide range of literature [1][2][4].

Model of the boost converter

Figure 1 shows the DC-DC Boost Converter with adaptive Sliding mode control (SMC). The state-space model of the converter can be derived.

Figure 1. DC-DC Boost converter with proportional integral SMC



Let us define states x_1 and x_2 as,

$$x_1 = V_\mu - \beta V_O, \quad (1)$$
$$x_2 = \dot{x}_1 \quad (2)$$

where $V_\mu = \beta V_d$ is the reference voltage corresponding to the desired load voltage V_d , $\beta = \frac{R_2}{R_1+R_2}$ is the voltage divider ratio. The SW is a MOSFET switch that responds to pulses from the SM controller to turn on or off. L is an inductor, C is a capacitor, D is the free-wheeling diode, V_o is load voltage, V_i is the input voltage, and r_L is the load resistance. Let us define $\overline{u} = 1 - u$, from equation (2) we have :

$$x_2 = -\beta \frac{dV_0}{dt} \quad (3)$$
$$x_2 = -\frac{\beta}{C} i_C \quad (4)$$

where i_C is the capacitor current
Let iL and ir be the inductor current and load current, respectively. Equation 4 can be rewritten as,

$$x_2 = -\beta(i_L - i_r) \quad (5)$$

Let the voltage drop across inductor be v_L then,

$$v_L = \bar{u}(V_i - V_0) \quad (6)$$

$$i_L = \int \frac{\overline{u}(V_i - V_0)}{L} \, dt \quad (7)$$

Eq. 5 can be rewritten as :

$$x_2 = -\frac{\beta}{C}\left[\int \frac{\overline{u}(V_i - V_0)}{L} \, dt - \frac{V_0}{r_L}\right] \quad (8)$$

Differentiating above equation with respect to time, x_2 is obtained as follows:

$$\dot{x}_2 = -\frac{\beta}{C}\left[\frac{\overline{u}(V_i - V_0)}{L} - \frac{dV_0}{dt}\frac{1}{r_L}\right] \quad (9)$$
$$\dot{x}_2 = \frac{dV_0}{dt}\frac{\beta}{r_L C} + \frac{\overline{\beta u}(V_i - V_0)}{LC} \quad (10)$$

From Eq.3, $\dot{x}_2$ can be rewritten as :

$$\dot{x}_2 = -\frac{1}{r_L C} x_2 + \frac{\overline{\beta u}(V_i - V_0)}{LC} \qquad (11)$$

From Eqs. 2 and 11, the state-space model of the Boost Converter may be obtained as

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 0 & -\frac{1}{r_L C} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} 0 \\ \frac{\overline{\beta}(V_i - V_0)}{LC} \end{pmatrix} \qquad (12)$$

Classic Sliding mode control (SMC)

Let us define a sliding function S which establishes a linear relationship among states in Eqs. 1 and 2 such that,[4]

$$S = \alpha x_1 + x_2 \qquad (13)$$

Where α is a scalar and it is tuned to achieve desired performance.
To achieve finite-time convergence, the reaching condition of Eq. 14 must be met.

$$S\dot{S} < 0 \qquad (14)$$

This sets constraints on the presence of sliding modes. The region of existence (ROE) is the area of the phase plane where sliding modes can exist if the phase trajectory is present. The sliding mode control law may be defined using the following rule:

$$\bar{u} = \begin{cases} 0, S > 0 \\ 1, S < 0 \end{cases} \qquad (15)$$

The previous control rule will cause the switching over the sliding manifold S. Due to the frequency constraint of the switching device, the control rule below is employed for actual implementation.

$$\bar{u} = \begin{cases} 0, S > \varepsilon \\ 1, S < \varepsilon \end{cases} \qquad (16)$$

The behavior of the states on sliding surface S = 0 is given by

$$x_1(t) = x_1(t_0) e^{-\alpha(t - t_0)} \qquad (17)$$

where t_0 is any point in time. It can be noted that increasing α makes the system faster. It is required to satisfy the reaching law $\dot{S} < 0$ if S > 0 and vice versa. As discussed above for S > 0, using Eq. 13 $\dot{S} < 0$ can be expressed by

$$x_2\left(\alpha - \frac{1}{r_L C}\right) < 0 \qquad (18)$$

Similarly for S < 0 , $\dot{S} > 0$ can be expressed by

$$x_2\left(\alpha - \frac{1}{r_L C}\right) + \frac{\beta(V_i - V_0)}{LC} > 0 \qquad (19)$$

Inequalities (18) and (19) emphasize the need to properly select the value α. To align the phase trajectory with the region of existence (ROE) on the phase plane, choose $\alpha > \frac{1}{r_L C}$ when the load varies significantly—the disparities concern α, which impacts the ROE on the phase plane. As previously stated, the choice of α is limited due to its impact on state reactions. Furthermore, the ROE fluctuates as the load changes.

If the phase trajectory extends beyond the ROE in the phase plane, sliding modes may not be assured. By altering the sliding function, we may add another tuning parameter to account for load changes. It renders the ROE independent of load changes. The α parameter can be adjusted to meet slower or quicker dynamics needs. The adjustment in the sliding function improves both steady-state and dynamic performance.

Proportional – Integral (PI) type sliding mode function

Let a proportional-integral (PI)-type function of sliding function be defined as [5]

$$T = S + \gamma sgn(S) \int_0^t |S| \, dt \qquad (20)$$

Where T is the sliding function, 'sgn' represents the signum function, and $\gamma > 0$ indicates a scalar value. Note that T and S change polarity at the same time, therefore the existence regions may be specified on the phase plane, similar to a standard sliding function.
Let us define the control law such that,

$$\bar{u} = \begin{cases} 0, T > \varepsilon \\ 1, T < -\varepsilon \end{cases} \qquad (21)$$

Sliding modes can occur on the phase plane if specified teaching conditions are met.

$$\lim_{t \to 0^+} \dot{T} < 0 \qquad (22)$$

$$\lim_{t \to 0^+} \dot{T} > 0 \qquad (23)$$

Existence of sliding modes

The existence of sliding modes is possible if the inequalities Eqs. 21, 22 are satisfied.
For T > 0, $\dot{T} < 0$. So,

$$S + \gamma \dot{S} < 0 \qquad (24)$$

$$\alpha \dot{x}_1 \dot{+} \dot{x}_2 + \gamma \alpha x_1 + \gamma x_2 < 0 \qquad (25)$$

Using Eq.12 and considering u = 0 for T > 0 we may get,

$$\gamma \alpha x_1 + \left(\alpha - \frac{1}{r_L C} + \gamma\right) x_2 < 0 \qquad (26)$$

For T < 0, considering Eq. 12 and u = 1,

$$\gamma \alpha x_1 + \left(\alpha - \frac{1}{r_L C} + \gamma\right) x_2 + \frac{\beta(V_i - V_0)}{LC} > 0 \qquad (27)$$

The equivalent control law u_{eq} can be derived as follows:

$$\gamma \alpha x_1 + \left(\alpha - \frac{1}{r_L C} + \gamma\right) x_2 + \frac{\beta(V_i - V_0)}{LC} u_{eq} = 0 \qquad (28)$$

$$u_{eq} = -\frac{LC}{\beta(V_i - V_0)} \left[\gamma \alpha x_1 + \left(\alpha - \frac{1}{r_L C} + \gamma\right) x_2\right] \qquad (29)$$

It can be noted that sliding modes exist along with switching action and u_{eq} is zero in case of ideal sliding mode. However, it is not practically possible, and switching action is inevitable.

The inequalities in Eqs. 26, and 27, demonstrate that the area in the phase plane is enclosed by two parallel lines and manifold T, S = 0. With $\gamma = \frac{1}{r_L C}$, load variance has no effect on ROE, indicating a strong control system. The tuning parameter can be adjusted to meet quicker or slower response needs., which was achievable because of the redesigned SMC. The load may be approximated as $r_L = \frac{V_0}{i_r}$, and the value γ can be adjusted based on the load. This demonstrates that the proposed SMC is adaptive to the load variations unlike the classic SMC presented below. Figure 1 shows the system and the proposed SMC where the load voltage and current are continuously monitored for in-line computation of T and γ .

III. Simulation Results

To show the efficacy of the proposed PI-type sliding mode control, a simulation is carried out with the system parameters shown in Table 1

Table no 1: Parameters of the boost converter with PI SMC

Parameter	Value
Inductance L	300 µH
Capacitance	250 µF
Tuning α	5000
Voltage divided ratio β	0,0909
Supply voltage V_i	12V
Desired voltage Vd	12- 20V
Load resistance r_L	24 - 10 Ω
Tuning γ	166,6
Initial capacitor voltage	22V

The simulation results with classic SMC and PI-type SMC are presented in Figs. 2, 3, 4, and 5 for tracking control where the reference voltage is changed from 12 V to 20 V at time t = 1 s.

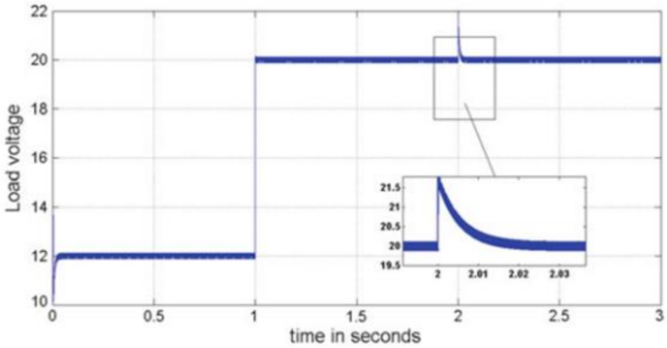


Figure 2: Load voltage response with classic SMC

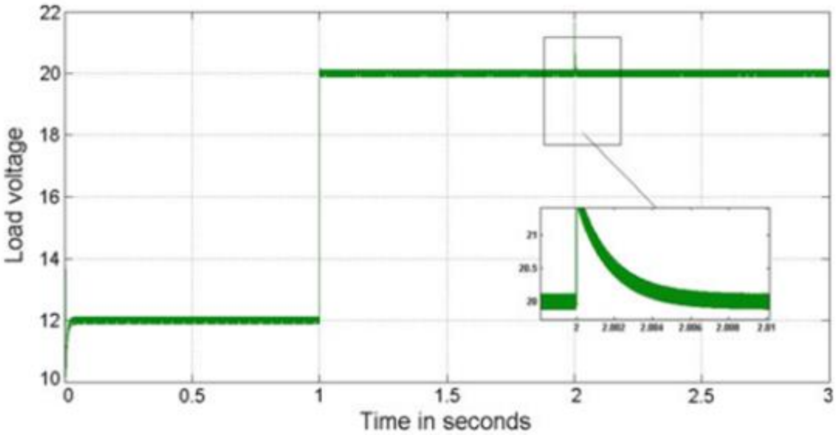


Figure 3: Load voltage response with PI-type SMC

Figures 2 and 3 show that the performance of the converter is satisfactory and tracks the reference voltage under both strategies. To check the dynamic performance and robustness, the load disturbance is given by suddenly changing the load from 24Ω to 10Ω at t = 2 s. The performance of both the conventional and proposed techniques is shown in the magnified windows in Figs. 2 and 3. It is observed that the PI-type SMC technique is faster than conventional SMC as it takes 10 ms to recover the reference voltage compared to 30 ms after the load disturbance is introduced.

Figures. 4 and 5 show the variations in the load current corresponding to load changes.

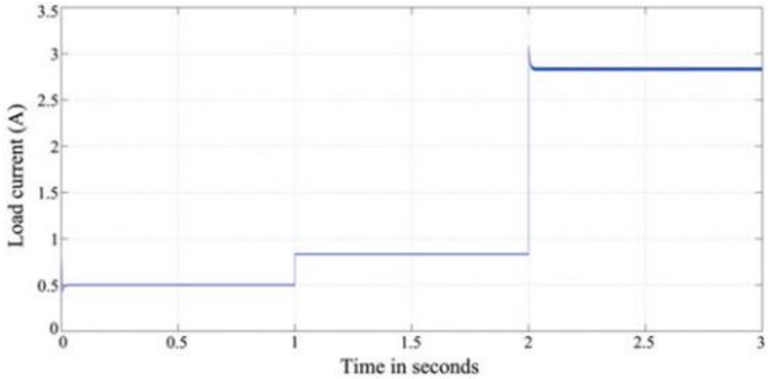


Figure 4: Load current with classic SMC

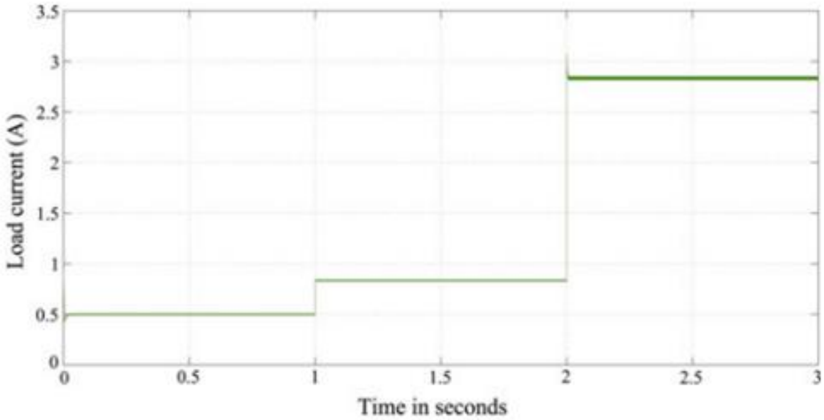


Figure 5: Load current with PI-type SMC

IV. Discussion

The PI_type Sliding Function for DC-DC Boost Converters in solar power systems demonstrates significant improvements over classic SMC. in terms of dynamic performance and adaptability to load changes. The key advantage of the PI-type SMC lies in its ability to introduce an additional tuning parameter γ, which can be adaptively adjusted based on load variations. This adaptive nature allows the control system to maintain a consistent Region of Existence in the phase plane, independent of load changes. The ability of the PI-type SMC to adaptively tune the γ parameter in response to load changes is particularly valuable in solar power systems, where load variations are common. This adaptive nature ensures that the overall system response becomes faster and more robust across various operating conditions. It's important to note that while these simulation results and supporting studies provide strong evidence for the efficacy of the PI-type SMC, further experimental validation would be beneficial to confirm its performance in real-world applications.

V. Conclusion

The PI-Type Sliding Function for DC-DC Boost Converters in solar power systems presents a promising control strategy that addresses the limitations of classic SMC. Its adaptive nature and improved dynamic performance make it a valuable approach for enhancing the efficiency and reliability of solar power systems.

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