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Research Article

Enhancing Stability and Reliability: Robust Control Strategies for Interleaved Buck Converters

Houssam Eddine Ghadbane [1*], Said Barkat [2], Anwar Zorig [3] and Dehmeche Ibrahim [4]

[1] *Electrotechnical and Automatic Engineering Department / Electrical Engineering Laboratory, University of Guelma, Algeria,*
[2] *Electrical Engineering Departement / Electrical Engineering Laboratory, University of M'sila, Algeria*
[3]*Electrotechnical Engineering Department /Telecommunications, Signals and System Laboratory, University of Laghouat, Algeria*
[4] *Electrotechnical Engineering Department / Exploitation and development of Saharan energy resources Laboratory, University of El Oued, Algeria*

[*]*(ghadbane.houssameddine@univ-guelma.dz)*

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Abstract **–** This paper presents an innovative approach to the design and implementation of integral sliding mode control for an interleaved buck (Buk) converter. The interleaved buck converter is a popular topology used in power electronic applications for its efficiency and improved current handling capabilities. Simulation results validate the effectiveness of the integral sliding mode control approach in regulating the output voltage of the interleaved buck converter. The controller demonstrates superior performance compared to PI control techniques, showcasing improved transient response, disturbance rejection, and tracking accuracy. The proposed control strategy contributes to enhancing the overall efficiency and reliability of the interleaved buck converter, making it suitable for a wide range of power electronic applications.

Keywords – Integral Sliding Mode Control, Interleaved Buck Converter, Power Electronics, Robust Control, Disturbance Rejection, Nonlinear Control, Stability Analysis

I. INTRODUCTION

This An interleaved Buck converter is a power electronic circuit used for voltage step-down (buck) conversion. It is characterized by multiple parallel-connected power stages, also known as phases or channels, that share the load current. The key advantage of this topology is the reduced output current ripple and improved efficiency compared to a single-phase converter. Interleaving the phases helps distribute the load and ripple current among multiple inductors, reducing losses and improving overall performance [1]–[3].

Traditional control methods for interleaved buck converters, such as proportional-integral (PI) controllers, may not fully exploit the potential benefits of these systems, especially under varying operating conditions or disturbances [4]. Nonlinear control techniques aim to address these challenges by taking into account the nonlinearities, uncertainties, and dynamics of the system to achieve improved performance and robustness [5].

The Design a non-linear controller that accounts for the system's nonlinearities and ensures desired performance objectives, such as fast transient response, reduced output voltage/current ripple, and improved disturbance rejection. This could involve techniques like sliding mode control [6], [7], backstepping control [8],Fuzzy Logic controller [9], or Adaptive and Predictive Control techniques can be integrated with robust control strategies to enhance the converter's performance by adapting to changing operating conditions and predicting future behavior [10].

In this paper, we apply Integral Sliding Mode Control to an interleaved Buck converter, which involves designing a control law that combines sliding surface design with integral action. The sliding surface defines the desired relationship between the converter's states (such as input voltage, output voltage, and inductor currents) that must be maintained during operation. The integral term assists in regulating any steady-state errors that may arise due to modeling uncertainties or external disturbances.

The Integral Sliding Mode Control ISMC extends the basic sliding mode control concept by adding an integral term to the control law. This integral term helps eliminate steady-state errors and improves the control system's performance, especially in the presence of constant disturbances or modeling inaccuracies. ISMC combines the benefits of both sliding mode control and integral control[11].

In summary, the "Integral Sliding Mode Control of Interleaved Buck Converter" refers to the application of the ISMC strategy to control the operation of an interleaved Buck converter, aiming to achieve robust and accurate voltage regulation and power conversion performance, even in the presence of uncertainties and disturbances. This control approach is suitable for applications where precise control is required, such as in renewable energy systems, electric vehicles, and industrial power supplies[12].

The organization of this paper is as follows: Section 2 introduces the mathematical modeling of the interleaved buck converter. In Section 3, the focus shifts to the integral sliding mode control of the interleaved buck converter. Section 4 presents the simulation results and their corresponding interpretations. Lastly, Section 5 offers the conclusion drawn from the study.

II. INTERLEAVED BUCK CONVERTER MODELING

The instantaneous model of the output voltage and the two arm currents of the interleaved buck converter is provided by:

$$\begin{cases} \dfrac{dV_s}{dt} = \dfrac{i_L}{C_{Buck}} - \dfrac{i_s}{C_{Buck}} \\ \dfrac{di_{L1}}{dt} = \dfrac{u_1 V_e - V_s}{L_1} \\ \dfrac{di_{L2}}{dt} = \dfrac{u_2 V_e - V_s}{L_2} \end{cases} \qquad (1)$$

III. SYNTHESIS OF INTEGRAL SLIDING MODE CONTROL FOR A TWO- LEVEL INTERLEAVED BUCK CONVERTER

The overall diagram of the sliding mode control for the interleaved buck converter is depicted in Fig. 1.

The Integral Sliding Mode Control (ISMC) broadens the fundamental idea of sliding mode control by incorporating an integral component into the control equation. This integral element effectively eradicates unchanging errors in the system's equilibrium and enhances the overall performance of the control system, particularly when confronted with continuous disruptions or imprecise modeling. ISMC amalgamates the advantages of sliding mode control and integral control strategies.

A. *Regulator synthesis using sliding mode control of voltage:*

The expression of the command is given as follows:

$$. \; i_L^* = \frac{C_{buck}}{k_{v1}} \left[\lambda_v sign\left(S_t\right) + k_{v2}\left(V_t^* - V_s\right) \right] + i_s^* \qquad (2)$$

B. *Synthesis of current-Level Integral sliding mode regulators:*

$$u_{(1,2)} = \frac{L}{k_{i1}V_e}\left[\lambda_i sign\left(S_{i(1,2)}\right) + k_{i2}\left(i^*_{L(1,2)} - i_{L(1,2)}\right) + k_{i1}\frac{di^*_{L(1,2)}}{dt}\right] + \frac{V_s}{V_e} \quad (3)$$

with k_{i1}, k_{i2} and k_{v1}, k_{v2} are the current and voltage coefficients of the Integral sliding surface.

λ_v, λ_i are voltage and current positive constants.

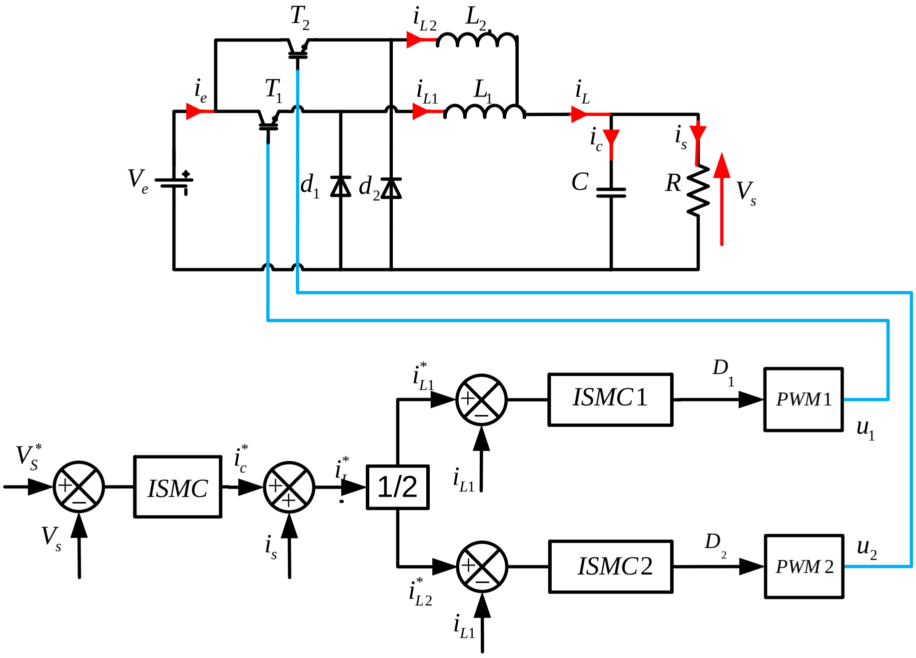


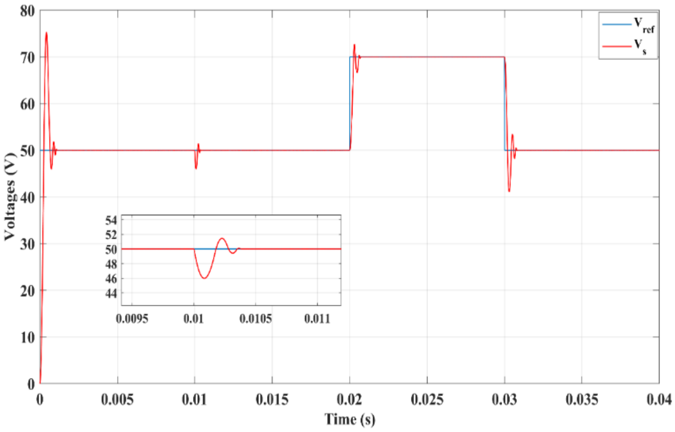
Fig. 1 Overall diagram of the interleaved buck converter control scheme

IV. SIMULATION RESULTS

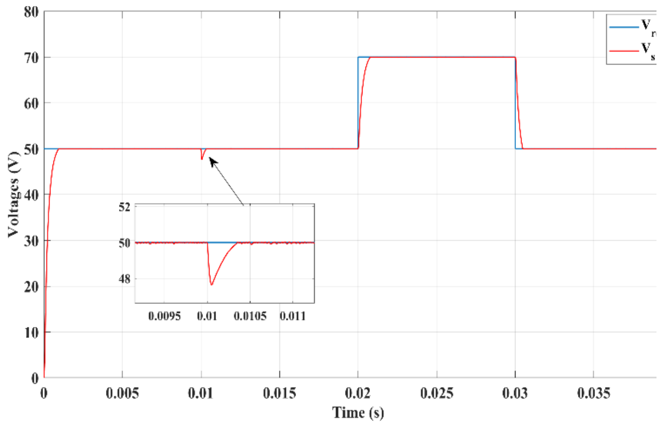
The system depicted in Fig.1 is simulated using the parameters summarized in Table 1. In order to validate the effectiveness of the control structure developed for the converter, we assessed the system's performance under a load variation at time t=0.01s and a reference voltage variation at times 0.002s and 0.003s. The obtained results are shown in Fig .2.

Table 1. Simulation Parameters of the System

Parameters of the interleaved Two-stages buck converter	$f_S = 50kHz$, $C_{buck} = 10\mu F$ $L_1 = L_2 = 8.9\times mH$, $V_e = 100V$
Parameters of the output voltage regulator of the converter	$k_1 = 0.005$, $k_2 = 20$, $\lambda = 50$
Current controller parameters for inductances	$k_1 = 0.1$, $k_2 = 50$, $\lambda = 50$
Load parameters	$R_{ch} = 50\Omega$, $R_{ad} = 50\Omega$



a)



b)

Fig. 2 output voltage: a) PI, b) ISMC

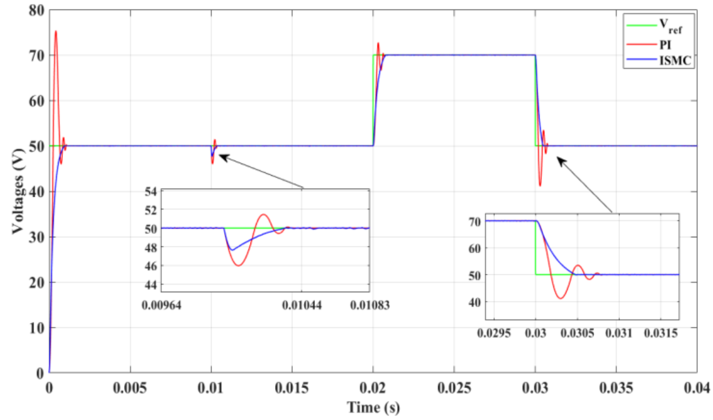
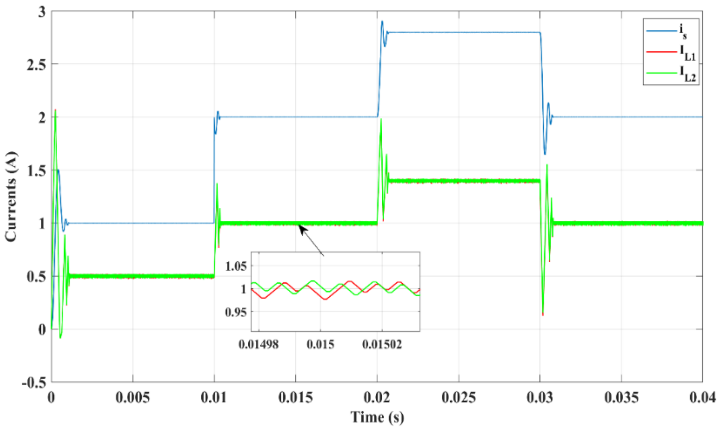
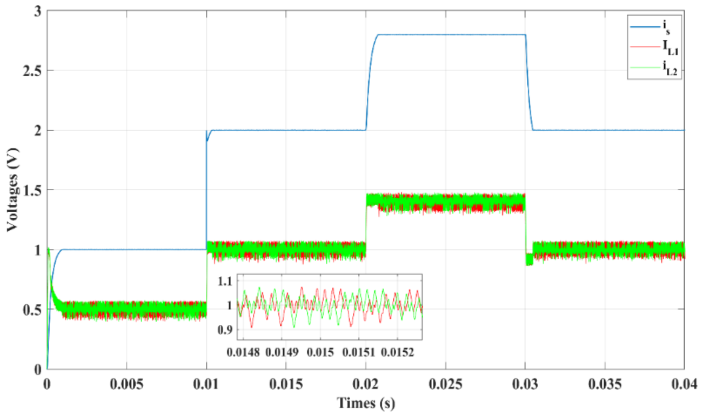


Fig. 3 comparison the output voltage for PI controller and ISMC



a)



b)

Fig. 4 inductor currents and load current: a) for PI controller, b) for ISMC

V. DISCUSSION

According to Fig.2 and Fig.3, it is evident that the output voltage of the buck converter closely follows its reference with nearly zero steady-state error. Additionally, the system exhibits excellent dynamics in terms of response time and overshoots. This outcome demonstrates the effectiveness of the output voltage regulation using Integral sliding mode control.

Fig.4 illustrates that the current regulators of the branches ensure a balanced distribution of the load current. This is reflected in the remarkable tracking of the reference current.

This should explore the significance of the results of the work, not repeat them. The results should be drawn together, compared with prior work and/or theory and interpreted to present a clear step forward in scientific understanding. Combined Results and Discussion sections comprising a list of results and individual interpretations in isolation are particularly discouraged.

VI. CONCLUSION

In conclusion, the integral sliding mode control applied to an interleaved buck converter offers several advantages such Robustness, Improved Transient Response and Reduced Chattering. the ISMC enhances the tracking accuracy of the output voltage or current reference signals, leading to precise regulation and maintaining a desired steady-state performance. The obtained simulation results confirm the effectiveness of the proposed control system when compared to PI based control.

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