

Robust Passivity-Based Control of a Non-Inverting Buck–Boost Converter Using an Adaptive Disturbance Observer

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Abstract— This paper presents a robust composite control strategy for a non-inverting Buck–Boost DC–DC converter that integrates Passivity-Based Control (PBC) with an adaptive Disturbance Observer (DO). Buck–Boost converters are widely used in renewable energy systems, electric vehicles, and battery-powered equipment, where the input voltage and the load are subject to frequent and often unpredictable variation. Because the converter dynamics are nonlinear, classical linear controllers such as PID lose accuracy once operating conditions drift far from their design point. The proposed strategy addresses this limitation by combining the energy-shaping and damping-injection properties of PBC, which guarantee stability under the port-controlled Hamiltonian structure of the converter, with a Lyapunov-based adaptive observer that estimates the unknown load conductance on-line from measurable signals only. A state-space averaged model of the converter feeding a DC-motor load is first derived and cast into port-Hamiltonian form; an exponentially convergent disturbance observer is then designed using a logarithmic nonlinear injection function, and a robust passivity-based control law is obtained by combining feed-forward steady-state inversion with damping-injection feedback. A formal Lyapunov stability proof establishes global exponential stability in the absence of estimation error and Input-to-State Stability (ISS) with respect to the observer error. The proposed Robust Passivity-Based Control (RPBC) scheme is validated through MATLAB/Simulink simulations and through hardware-in-the-loop experiments on a TMS320F28335 + FPGA-based test bench under step changes in the input voltage, in the load resistance, and in the observer gain. Simulation and experimental results show fast disturbance rejection, settling times below 0.3 s, output-voltage overshoot below 1.5 V and steady-state error within ± 0.3 V, together with close agreement between simulated and measured responses, confirming that the proposed PBC–DO strategy provides a practical and computationally inexpensive alternative to sliding-mode, H_∞ , and model-predictive controllers for uncertain power-electronic conversion systems.

Keywords— Robust control; Buck–Boost converter; Passivity-based control; Disturbance observer; Port-controlled Hamiltonian systems; Load disturbance rejection.

1. Introduction

DC–DC power converters are core building blocks of modern power-electronic systems: they regulate and reshape electrical energy so that a source and a load with different voltage requirements can be interfaced efficiently. Non-isolated converters — Buck, Boost, and Buck–Boost topologies — are the most common choice whenever galvanic isolation is not

required [9], [14]. Among these, the Buck–Boost converter is unique in that it can step the output voltage either above or below the input voltage from the same topology, which makes it the preferred choice whenever the input source (e.g., a photovoltaic array, a battery, or a fuel cell) varies over a range that straddles the desired output voltage [1], [2]. Table 1 summarizes the main features that distinguish the Buck, Boost, and Buck–Boost topologies.

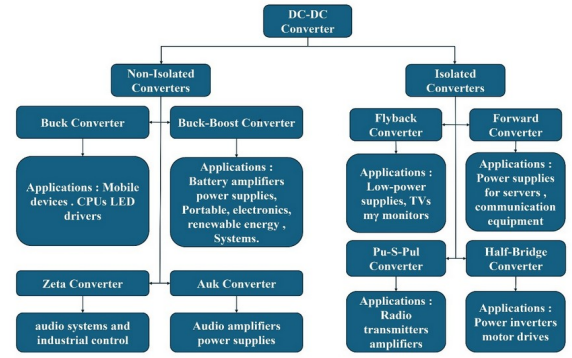


Fig. 1. Classification of DC–DC converters with representative applications.

TABLE 1
Comparison of Buck, Boost, and Buck–Boost Converters

Feature	Buck	Boost	Buck–Boost
Function	Steps down	Steps up	Steps up or down
Output polarity	Same as input	Same as input	Inverting / non-inverting variants
Switch position	Input–inductor	Inductor–output	Inductor–ground
Output range	$0 < V_{out} < V_{in}$	$V_{out} > V_{in}$	$V_{out} \geq V_{in}$
Efficiency	up to 95%	85–95%	80–90%
Typical use	CPUs, LEDs	EVs, tools	Batteries, renewables, medical

These characteristics make the Buck–Boost converter attractive in renewable-energy front ends, electric-vehicle powertrains, and battery-management systems, where the source voltage decreases or increases significantly over time and where sudden load transients — acceleration events, changing solar irradiance, switching loads in industrial and data-centre power supplies — are the norm rather than the exception [8], [16]. In all of these applications, the converter must maintain a tightly regulated output voltage despite (i) a nonlinear switched

dynamics, (ii) an unknown and possibly time-varying load conductance, and (iii) disturbances that enter the system in a fast and often unmeasurable way. This combination of nonlinearity and disturbance sensitivity is exactly where classical linear controllers, most notably PID and fixed-gain voltage-mode control, tend to lose performance [11], [12].

1.1 Related Work and Motivation

A large body of literature has investigated advanced control strategies for DC–DC converters operating under load and source uncertainty. Sliding-mode control (SMC) provides strong robustness to matched disturbances but suffers from chattering, which increases switching losses and electromagnetic interference [17], [18]. Model Predictive Control (MPC) can, in principle, deliver optimal transient performance but requires a fast, accurate model and a computational budget that is difficult to meet with low-cost digital signal processors, particularly at high switching frequencies [13]. Backstepping and fuzzy-logic controllers improve robustness at the price of increased design and tuning complexity [11], [19].

Passivity-Based Control (PBC) offers an attractive alternative because it exploits the physical energy-storage structure of the converter directly, through energy shaping and damping injection, rather than opposing the plant dynamics [2], [3], [7]. Because a passive system cannot generate energy internally, PBC designs are intrinsically robust to a broad class of disturbances and preserve a clear physical interpretation of the closed-loop behaviour [15], [16], [20]. Its principal limitation is that classical PBC assumes the load parameters — in particular the load conductance GL — are known; when GL drifts or is simply unknown, the steady-state feed-forward term used by PBC becomes inaccurate and a steady-state tracking error appears [2], [4].

Disturbance observers (DO) address exactly this gap: rather than measuring a disturbance directly, a DO reconstructs it from the discrepancy between the measured plant behaviour and a nominal model, in a manner conceptually similar to active noise cancellation [11], [12], [19]. DOs have been used successfully for load-disturbance rejection [5], [6] and, more recently, in combination with PBC and sliding-mode controllers for DC–DC converters [7], [10]. However, most existing studies (a) validate the composite controller only in simulation, (b) treat the load as a static resistance rather than the more general DC-motor load encountered in electromechanical drive applications, or (c) do not provide a rigorous coupled stability proof for the observer–controller interconnection [6], [9].

1.2 Contributions

Building on this body of work, the present paper develops and experimentally validates a Robust Passivity-Based Control (RPBC) strategy that couples an adaptive load-conductance observer with an energy-shaping passivity-based controller for

a non-inverting Buck–Boost converter feeding a DC-motor load. The specific contributions are as follows.

- 1) A compact port-controlled Hamiltonian (PCH) model of the Buck–Boost converter driving a DC-motor load is derived directly from the averaged state-space equations, explicitly separating the interconnection, dissipation, and back-EMF disturbance terms.
- 2) A Lyapunov-based adaptive observer is designed to estimate the unknown load conductance GL from the measurable inductor current, capacitor voltage, and duty cycle only; a logarithmic nonlinear injection function is shown analytically to render the estimation-error dynamics linear and exponentially stable, independent of the operating point.
- 3) A robust passivity-based control law is obtained by combining feed-forward steady-state inversion — made adaptive through the on-line load estimate — with damping-injection feedback, and a full Lyapunov stability analysis establishes global exponential stability with zero estimation error and Input-to-State Stability (ISS) with respect to bounded estimation error, i.e., the observer and controller can be tuned independently while overall closed-loop stability is preserved (a separation-type property).
- 4) The proposed RPBC scheme is validated in MATLAB/Simulink under input-voltage, load, and observer-gain variations, and subsequently verified experimentally on a TMS320F28335 + FPGA hardware-in-the-loop test bench, with close agreement between simulated and measured transient performance.

1.3 Paper Organization

The remainder of the paper is organized as follows. Section 2 derives the averaged state-space model of the Buck–Boost converter and its port-Hamiltonian representation. Section 3 presents the design and convergence proof of the adaptive disturbance observer. Section 4 develops the robust passivity-based control law. Section 5 gives the closed-loop Lyapunov stability analysis. Section 6 reports the simulation studies, and Section 7 the experimental validation on the hardware test bench. Section 8 discusses the results in relation to existing control strategies, and Section 9 concludes the paper and outlines directions for future work.

2. Converter Modeling and Port-Hamiltonian Representation

This section develops the averaged dynamic model of a non-inverting Buck–Boost converter operated as a front-end supply for a DC motor, and then recasts the model into port-controlled Hamiltonian (PCH) form, which will be used throughout the paper for both observer and controller design.

2.1 Circuit Equations

The converter consists of an inductor L , a single output capacitor C , and a resistive load RL connected in parallel with a

DC machine that presents a back electromotive force (EMF) E to the converter. Energy transfer is governed by a MOSFET switching element modulated by pulse-width modulation (PWM); $u_{av} \in (0,1)$ denotes the average duty cycle over one switching period. Applying Kirchhoff's Voltage Law (KVL) around the inductor loop and averaging over one switching cycle gives the inductor current dynamics,

$$L \, di_L/dt = (1 - u_{av}) v_C + E u_{av} \quad (1)$$

in which the term $(1 - u_{av}) \cdot v_C$ represents the capacitor voltage seen across the inductor while the switch is off, and $E \cdot u_{av}$ represents the motor back-EMF contribution while the switch is on. Applying Kirchhoff's Current Law (KCL) at the capacitor node yields the capacitor voltage dynamics,

$$C \, dv_C/dt = -(1 - u_{av}) i_L - v_C / R_L \quad (2)$$

Table 2 lists the physical parameters and state variables used throughout the model.

TABLE 2
Key Circuit Parameters and State Variables

Symbol	Description	Unit
L	Inductance	H
C	Capacitance	F
R_L	Load resistance	Ω
$GL = 1/R_L$	Load conductance (unknown, possibly time-varying)	S
i_L	Inductor current (state)	A
v_C	Capacitor / output voltage (state)	V
u_{av}	Average duty cycle (control input)	—
E	DC-motor back-EMF (exogenous disturbance)	V

2.2 Load Conductance and Compact State-Space Form

To linearize the load term and make the unknown load parameter appear linearly alongside the measurable output voltage, the load is represented through its conductance $GL = 1/R_L$ rather than its resistance, giving

$$C \, dv_C/dt = -(1 - u_{av}) i_L - G_L v_C \quad (3)$$

Collecting the inductor current and capacitor voltage into the state vector $x = [i_L, v_C]^T$, the converter dynamics (1) and (3) take the compact averaged state-space form

$$di_L/dt = [(1 - u_{av}) v_C + E u_{av}] / L \quad (4)$$

$$dv_C/dt = [-(1 - u_{av}) i_L - G_L v_C] / C \quad (5)$$

Equations (4)–(5) constitute two coupled nonlinear ordinary differential equations in which the control input u_{av} and the uncertain load conductance GL both appear explicitly. This structure is the starting point for the disturbance observer and passivity-based controller developed in Sections 3 and 4.

2.3 Port-Controlled Hamiltonian Representation

The port-controlled Hamiltonian (PCH) framework represents the converter in terms of stored energy, power-preserving interconnection, and dissipation, which provides both a natural Lyapunov candidate and a systematic basis for passivity-based control design [2], [3]. The total stored energy (magnetic plus electric) is

$$H(x) = (1/2) L \, i_L^2 + (1/2) C \, v_C^2 \quad (6)$$

with inertia matrix $A = \text{diag}(L, C)$. The skew-symmetric interconnection matrix $J(u_{av})$, which captures the power-preserving exchange between the inductor and the capacitor, and the positive-semidefinite dissipation matrix R , which represents the resistive loss at the load, are given by

$$J(u_{av}) = \begin{bmatrix} 0, 1 - u_{av}; -(1 - u_{av}), 0 \end{bmatrix}, \quad R = \begin{bmatrix} 0, 0; 0, G_L \end{bmatrix} \quad (7)$$

Since $J^T(u_{av}) = -J(u_{av})$, the interconnection matrix preserves energy exactly, while R models the only source of dissipation in the averaged model — the resistive load. Defining the gradient of the Hamiltonian, $\partial H/\partial x = [L \, i_L, C \, v_C]^T$, and the input and disturbance vectors $g = [E, 0]^T$ and $\eta = [0, 0]^T$, the full PCH form of the converter dynamics is

$$A \dot{x} = J(u_{av}) \partial H/\partial x - R \partial H/\partial x + g \, u_{av} + \eta \quad (8)$$

Equation (8) shows explicitly that $J(u_{av})$ redistributes energy losslessly between the inductor and capacitor, R dissipates energy into the load, $g \cdot u_{av}$ injects controlled power, and η carries the external disturbance. This energy-based structure is the foundation of the observer design in Section 3 and the passivity-based control law in Section 4.

3. Adaptive Disturbance Observer Design

In practical operation, the load conductance GL is unknown and may vary with time — for instance, because of mechanical loading changes at the DC motor — and cannot be measured directly. This section designs an observer that estimates GL on-line using only the inductor current i_L , the output voltage v_C , and the duty cycle u_{av} , none of which requires additional sensing hardware.

3.1 Estimation Error Dynamics

Let $\hat{G}_L$ denote the on-line estimate of the load conductance and define the estimation error

$$\tilde{G}_L = \hat{G}_L - G_L \quad (9)$$

The observer design objective is to shape the update law for $\hat{G}_L$ so that $\tilde{G}_L(t) \rightarrow 0$ as $t \rightarrow \infty$, regardless of the (unknown) initial value of GL . The proposed observer structure combines a dynamic internal state PI with a static nonlinear injection function $x(v_C)$,

$$\dot{\hat{G}}_L = P_I + R \, x(v_C) \quad (10)$$

where $R > 0$ is a tunable observer gain that sets the rate of convergence. Differentiating (10) and substituting the capacitor voltage dynamics (3) gives the time derivative of the estimate in

terms of measurable signals and the unknown GL. Choosing the update law for the internal state as

$$\dot{P}_I = -R \dot{x}(v_C) [(u_{av} - 1) i_L - \hat{G}_L v_C] / C \quad (11)$$

eliminates the dependence on the unknown GL and yields a closed-form differential equation for the estimation error alone,

$$\dot{\tilde{G}}_L = R \dot{x}(v_C) \tilde{G}_L v_C / C \quad (12)$$

3.2 Nonlinear Injection Function and Exponential Convergence

For the estimation error to converge exponentially and independently of the operating voltage v_C , the injection function $x(v_C)$ must cancel the v_C -dependence in (12). Choosing the logarithmic function

$$x(v_C) = -C \ln v_C, \quad \dot{x}(v_C) = -C / v_C \quad (13)$$

substituted into (12) gives

$$\dot{\tilde{G}}_L = -R \tilde{G}_L \quad (14)$$

which is a first-order linear differential equation with the closed-form exponentially decaying solution

$$\tilde{G}_L(t) = \tilde{G}_L(0) e^{-Rt} \quad (15)$$

This choice of injection function is motivated by three properties: (i) $\ln(v_C)$ is strictly decreasing and differentiable for the physically meaningful range $v_C > 0$, which always holds under normal converter operation; (ii) its derivative introduces a $1/v_C$ term that exactly cancels the v_C -dependence of the raw error dynamics (12); and (iii) the resulting closed-loop error equation (14) is a canonical linear stable form whose convergence rate is set entirely by the design parameter R , independent of the load or the operating point.

3.3 Implementable Observer

Substituting (13) into (10) and (11) gives the final, directly implementable observer equations,

$$\dot{\hat{G}}_L = P_I - R C \ln v_C \quad (16)$$

$$\dot{P}_I = (R / v_C) [(u_{av} - 1) i_L - (P_I - R C \ln v_C) v_C] \quad (17)$$

The internal state P_I is updated at every sampling instant from the measured signals i_L , v_C , and u_{av} ; the current load-conductance estimate $\hat{G}_L$ is then obtained directly from (16). The observer requires only elementary arithmetic and a single logarithm evaluation per update, so its computational cost is negligible on standard DSP and FPGA control platforms. Because the convergence result (15) holds independently of the true value of GL, the observer requires no prior knowledge of the load and is inherently robust to parameter variation.

4. Robust Passivity-Based Control Design

This section designs a passivity-based controller for the non-inverting Buck-Boost converter that regulates the output voltage v_C and the inductor current i_L to desired reference values, and then augments it with the load estimate $\hat{G}_L$

produced by the observer of Section 3 to obtain the proposed Robust Passivity-Based Control (RPBC) law.

4.1 Reference Trajectory Generation

At steady state ($\dot{i}_L = 0$, $\dot{v}_C = 0$), the PCH balance (8) reduces to a static energy-flow condition from which the desired duty cycle and inductor current can be solved in terms of the desired output voltage v_{Cd} . From the steady-state inductor equation,

$$u_{av,d} = v_{Cd} / (v_{Cd} - E) \quad (18)$$

and, from the steady-state capacitor equation, the desired inductor current is

$$i_{L,d} = v_{Cd}(v_{Cd} - E) / (R_L E) \quad (19)$$

Equations (18)–(19) define the physically consistent steady-state operating point of the converter for any admissible voltage set-point v_{Cd} and motor back-EMF E .

4.2 Adaptive Reference Using the Load Estimate

Because RL (equivalently GL) is generally unknown, the reference current (19) is made adaptive by substituting the on-line estimate $\hat{G}_L$ for GL,

$$i_{L,d}(\hat{G}_L) = \hat{G}_L v_{Cd}(v_{Cd} - E) / E \quad (20)$$

This adaptive reference tracks the true steady-state operating point in real time as the load changes, without requiring any offline re-tuning; it uses only the converter's own steady-state physics together with the observer output, so the reference trajectory remains consistent with the plant model at every operating condition.

4.3 Control Law and Closed-Loop Error Dynamics

Let $x_d = [i_{L,d}, v_{Cd}]^T$ denote the reference state and define the tracking error $e = x - x_d = [e_{iL}, e_{vC}]^T$. To inject damping into the closed-loop error dynamics, a symmetric positive-definite damping matrix $R_d = \text{diag}(R_{d1}, R_{d2})$, $R_{d1}, R_{d2} > 0$, is introduced, and the reference dynamics are written in augmented PCH form as

$$A \dot{x}_d = [J(u_{av}) - R] \partial H(x_d) / \partial x_d + R_d \partial H(e) / \partial e + g u_{av} + \eta d \quad (21)$$

Combining the feed-forward term (18) with a feedback term proportional to the current-tracking error and scaled by the damping gain R_{d1} gives the robust passivity-based average duty-cycle control law,

$$u_{av} = v_{Cd} / (v_{Cd} - E) + [R_{d1} / (v_{Cd} - E)] e_{iL} \quad (22)$$

whose two terms have a direct physical interpretation: the first term counteracts the motor back-EMF and imposes the nominal steady-state operating point, and the second term is a proportional feedback correction on the inductor-current tracking error, scaled by the damping gain R_{d1} . The corresponding reference-voltage derivative used by the observer/controller pair is

$$\dot{v}_{Cd} = (u_{av} - 1) i_{L,d} / C - \hat{G}_L v_{Cd} / C - (R_{d2} / C) e_{vC} \quad (23)$$

Substituting (22) into the state error dynamics and accounting for the observer error $\tilde{x}$ (the same quantity as $\tilde{G}L$, expressed as it enters the state equations) yields the closed-loop error dynamics

$$A \dot{e} = J(u_{av}) e - \bar{R} e - M \tilde{x} \quad (24)$$

where $\bar{R} = R + R_d = \text{diag}(R_d1, 1/RL + R_d2)$ is the total (natural plus injected) dissipation and $M = [0, vC/C]^T$ projects the observer error onto the state-error dynamics. Equation (24) is passivity-preserving and forms the basis of the stability analysis in Section 5.

5. Stability Analysis of the Closed-Loop System

This section establishes formally that the closed-loop system comprising the converter (8), the observer (16)–(17), and the RPBC law (22) is stable under load disturbances and bounded estimation error.

5.1 Lyapunov Function

Consider the energy-based Lyapunov candidate

$$V(e) = (1/2) e^T A e \quad (25)$$

Differentiating along the error dynamics (24) and using the fact that the interconnection matrix is skew-symmetric, $e^T J(u_{av}) e = 0$, gives

$$\dot{V} = -e^T \bar{R} e - e^T M \tilde{x} \quad (26)$$

5.2 Input-to-State Stability

When the estimation error vanishes, $\tilde{x} = 0$, (26) reduces to $\dot{V} = -e^T \bar{R} e < 0$ for $e \neq 0$, which proves that the tracking error converges to zero exponentially and that the closed-loop system is globally exponentially stable in the ideal (perfectly estimated) case. When $\tilde{x} \neq 0$, a standard ISS argument applies: for any $\theta \in (0,1)$, whenever

$$\|e\| \geq \|M\| \|\tilde{x}\| / [\theta \lambda_{\min}(\bar{R})] \quad (27)$$

it follows that $\dot{V} \leq -(1 - \theta) e^T \bar{R} e < 0$, which confirms that the mapping $\Sigma: \tilde{x} \rightarrow e$ is Input-to-State Stable. In other words, bounded estimation error implies bounded tracking error, and the tracking error converges to zero as $\tilde{x} \rightarrow 0$.

5.3 Stability Proposition and Practical Remarks

Proposition. The Buck–Boost converter in closed loop with the robust passivity-based controller (22) and the adaptive disturbance observer (16)–(17) is globally exponentially stable in the absence of estimation error, and Input-to-State Stable with respect to the estimation error $\tilde{x}$.

Three practical implications follow from this result. First, the ISS property provides a separation-type guarantee: the observer gain R and the damping gains R_d1 , R_d2 can be tuned independently while overall closed-loop stability is preserved. Second, perfect load estimation is not required for stable operation — bounded estimation error simply implies a proportionally bounded tracking error, which explains the small steady-state offsets observed experimentally in Section 7.

Third, the analysis assumes accurate knowledge of L , C , and E ; in practice, small uncertainties in these physical parameters do not invalidate the ISS guarantee but can mildly alter the transient response, an effect that is quantified experimentally in Section 7.5.

6. Simulation Studies

6.1 Simulink Model and Parameters

The proposed RPBC scheme was implemented and validated in MATLAB/Simulink. The model, shown in Fig. 2, contains the averaged power stage, the PWM generation block, the disturbance-observer subsystem, and the passivity-based controller subsystem, connected in a closed feedback loop that allows the input voltage, the load, and the observer gain to be varied independently during a run. The nominal circuit and observer parameters used in all simulation studies are listed in Table 3.

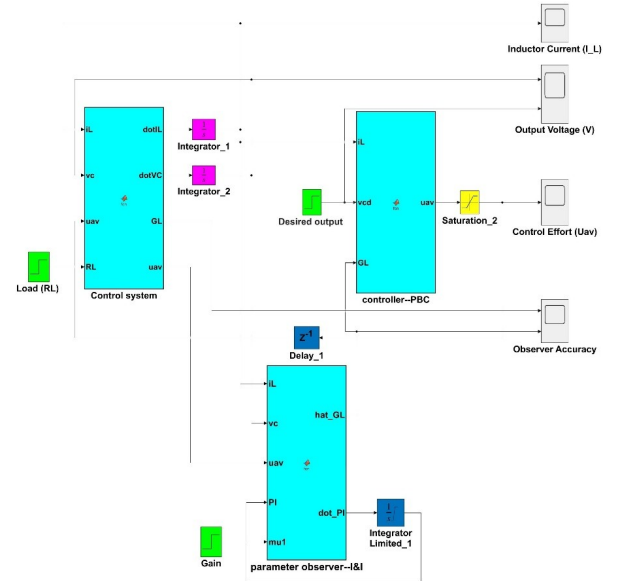


Fig. 2. MATLAB/Simulink implementation of the Buck–Boost converter with the combined PBC–DO control scheme.

TABLE 3

Buck–Boost Converter Parameters Used in Simulation and Experiment

Parameter	Symbol	Value	Remark
Input voltage	E	45 V	Representative industrial supply level
Inductance	L	750 μ H	Limits current ripple to < 10%
Capacitance	C	2200 μ F	Limits voltage ripple to < 2%
Load resistance	RL	20 $\Omega \rightarrow$ 40 Ω	Step used to test disturbance rejection
Observer gain	R (PI)	100 $\rightarrow$ 1000	Swept to study the convergence/noise trade-off

Three complementary case studies were carried out: (i) a step change in the input reference voltage, (ii) a step change in the load resistance, and (iii) a sweep of the observer gain. For each case, the inductor current, the output voltage, the control effort (u_{av}), and the observer estimation error were recorded and analysed in terms of transient response, steady-state error, and robustness to uncertainty.

6.2 Case 1 — Input-Voltage Variation

The reference voltage was stepped from 20 V to 36 V to evaluate the controller's response to a substantial change in the operating point. Fig. 3 shows the resulting inductor-current response: the current exhibits a transient excursion at the instant of the step, but the RPBC scheme rapidly re-establishes a smooth, bounded trajectory with no sustained oscillation, confirming strong disturbance rejection at the current level.

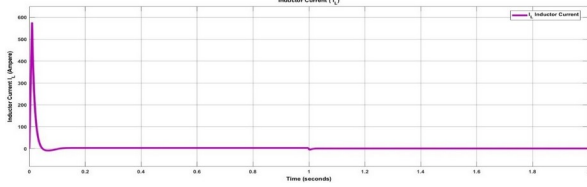


Fig. 3. Inductor current i_L response to a step change in the reference voltage.

Fig. 4 shows the corresponding output-voltage response. The controller tracks the new voltage reference with minimal delay; a small steady-state offset appears after the transient because the feed-forward term in (22) is computed from the nominal parameters and the control law contains no integral action to eliminate a constant bias. Despite this offset, the closed-loop response remains smooth and bounded, which is consistent with the ISS property established in Section 5.2.

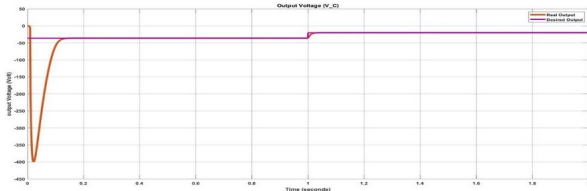


Fig. 4. Output voltage v_C response to a step change in the reference voltage.

6.3 Case 2 — Load Variation

The load resistance was stepped from 20 Ω to 40 Ω to emulate a sudden reduction in power demand, of the kind encountered when a mechanical load is disengaged from the driven DC motor. Fig. 5 shows the inductor-current response: the current settles quickly to the new steady-state value corresponding to the reduced load, with only a brief transient at the switching instant.

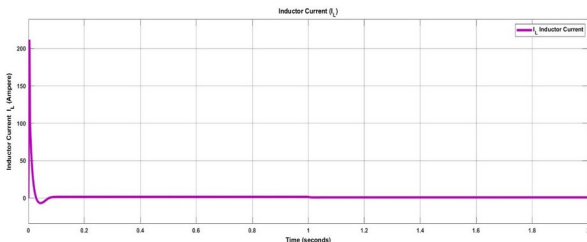


Fig. 5. Inductor current i_L response to a step change in load resistance.

Fig. 6 shows that the output voltage recovers to its regulated value quickly following the load step, with negligible overshoot or undershoot, confirming that the adaptive reference (20) correctly re-computes the steady-state operating point as soon as the observer estimate $\hat{G}_L$ updates. During this transient the control effort exhibited a brief but well-damped correction, and the observer estimate showed a small transient deviation before rapidly reconverging, consistent with the exponential convergence proved in (15).

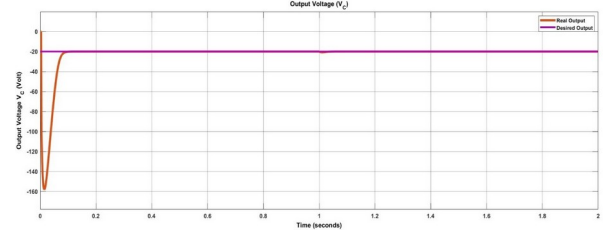


Fig. 6. Output voltage v_C response to a step change in load resistance.

6.4 Case 3 — Observer Gain Sweep

The observer gain R (denoted PI in the implementation) was swept from 100 to 1000 to characterize the trade-off between estimation speed and sensitivity to measurement noise. Increasing R accelerates the convergence of both the inductor-current and output-voltage responses, consistent with the exponential rate predicted by (15), but also increases the sensitivity of the estimate to high-frequency noise and, at the highest gains, introduces mild oscillatory behaviour. Conversely, low gains yield smoother, better-damped trajectories at the cost of slower disturbance rejection. Table 4 summarizes the qualitative system behaviour observed across the three simulation case studies.

TABLE 4

Summary of System Behaviour Under the Three Simulation Case Studies

Case	Observed behaviour
Voltage change	Fast disturbance rejection; smooth current and voltage correction; small steady-state offset due to the absence of integral action.
Load change	Quick re-adjustment of current and voltage following the load step; brief transient deviation in the observer estimate that decays rapidly.
Gain change	Higher gain accelerates convergence but increases sensitivity to noise and, at high values, introduces mild oscillation; lower gain trades speed for smoothness.

Overall, the simulation study confirms that the disturbance observer converges quickly to the true load conductance, that the RPBC law rejects both voltage and load disturbances with fast, well-damped transients, and that the observer gain provides a single, physically meaningful tuning knob for balancing response speed against noise sensitivity — consistent with the separation-type property established analytically in Section 5.3.

7. Experimental Validation

To confirm that the analytical and simulation results carry over to a physical implementation, the proposed RPBC scheme was validated on a hardware-in-the-loop (HIL) test bench built around a modular power-electronics platform (UMI PED01–PED06) that interfaces the digital controller, a programmable DC voltage source, and a programmable resistive load with the physical converter prototype, as shown in Fig. 7. The real-time controller communicates continuously with the hardware through analog and digital I/O channels; at each sampling instant it acquires the inductor current and output-voltage measurements needed by the passivity-based control law and the disturbance observer, computes the control action, and updates the PWM duty cycle.

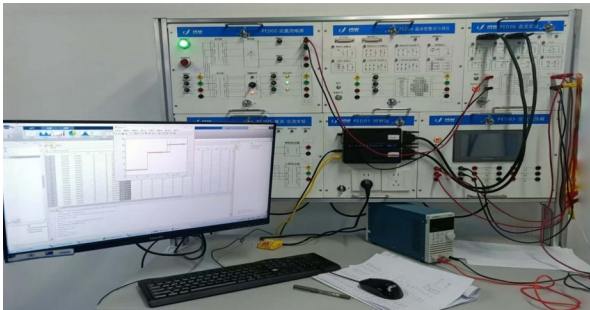


Fig. 7. Real-time hardware-in-the-loop test environment used for experimental validation.

7.1 Hardware Prototype and Test Bench

The prototype is a non-inverting Buck–Boost converter using a single inductor and power MOSFET switching devices, shown in Fig. 8. The embedded RPBC and disturbance-observer algorithms run on a TMS320F28335 digital signal processor combined with an FPGA, selected for its high-speed fixed-point arithmetic and deterministic timing, which together support the sensor-feedback processing, state estimation, and switching-command generation required at the chosen sampling rate. Table 5 summarizes the key hardware components.

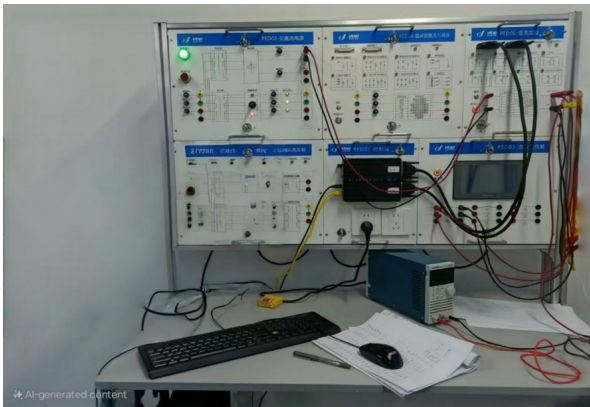


Fig. 8. Experimental hardware prototype of the non-inverting Buck–Boost converter.

TABLE 5

Key Hardware Components and Specifications

Component	Specification
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Microcontroller / DSP	TMS320F28335 + FPGA
Switching device	Power MOSFET
Sensing method	Voltage divider and shunt current sensors
Load type	Programmable resistive load bank
Sampling rate	10 kHz

7.2 Real-Time Implementation Considerations

Moving from simulation to real-time hardware execution raised three practical engineering issues that were addressed prior to data collection: (i) the sampling frequency was chosen to minimize quantization and loop-delay effects while remaining compatible with the switching frequency; (ii) the observer gain R was fine-tuned directly on the hardware to balance fast convergence against sensitivity to sensor noise, since the noise floor on the physical current and voltage sensors differs from the idealized simulation environment; and (iii) the reference-generation logic was adjusted to compensate for small sensor offsets and measurement delays so that the RPBC law tracks the intended set-point accurately. At every sampling instant the measured i_L and v_C are used both by the control law (22) and by the observer update (17), so that the estimated load conductance $\hat{G}_L$ is fed back into the controller in real time, allowing the closed-loop system to adapt automatically to load transients, input-voltage fluctuations, and sensor disturbances.

7.3 Voltage-Change Experiment

The output-voltage reference was stepped in multiple increments from 12 V to 28 V while the load was held constant. Fig. 9 shows the measured inductor current: as expected from the converter physics, the current increases at each voltage step to supply the additional power, and rapidly settles to a new, stable value after each transition without visible fluctuation.

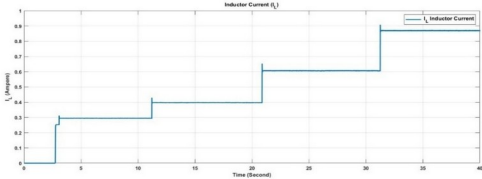


Fig. 9. Measured inductor current i_L response to reference-voltage step changes (experiment).

Fig. 10 shows that the measured output voltage closely tracks the reference through the entire sequence of steps, with low overshoot (on the order of 1.5 V) and fast settling. These results confirm, on physical hardware, the tight regulation predicted by the simulation study of Section 6.2 and demonstrate that the RPBC scheme handles multiple sequential reference changes reliably.

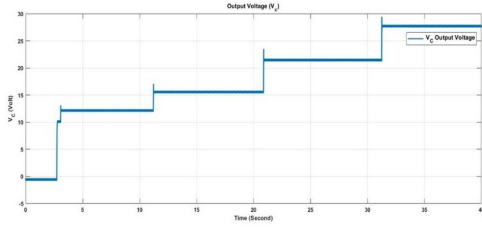


Fig. 10. Measured output voltage v_C tracking multiple reference steps from 12 V to 28 V (experiment).

7.4 Load-Change Experiment

The load resistance was varied stepwise, both increased and decreased, to emulate realistic load fluctuations of the kind seen in battery-powered and industrial equipment. Three quantities were monitored throughout: the observer's real-time load-conductance estimate $\hat{G}_L$, the inductor current i_L , and the output voltage v_C .

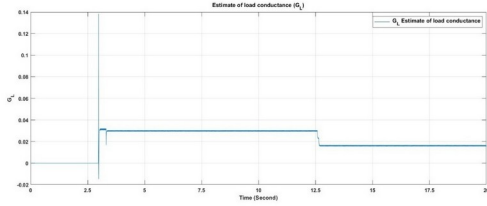


Fig. 11. Estimated load conductance $\hat{G}_L$ during experimental load-step transitions.

Fig. 11 shows that the observer estimate exhibits brief transient spikes at the instant of each load step — a direct consequence of the sudden change in the current and voltage measurements that feed the observer — but reconverges quickly to the correct value, confirming the exponential convergence property of (15) under real sensor noise and quantization. Fig. 12 shows the corresponding output-voltage response: the measured voltage deviates from its set-point by only a few hundred millivolts during each load transient and is rapidly restored, demonstrating that the composite PBC–DO strategy handles load disturbances robustly under real operating conditions.

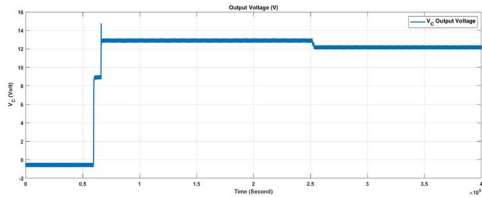


Fig. 12. Measured output voltage v_C during experimental load-step transitions.

7.5 Performance Metrics and Simulation–Experiment Comparison

Table 6 quantifies the closed-loop performance observed experimentally for both the voltage-change and load-change test cases, while Table 7 compares the key simulation and experimental performance indicators directly.

TABLE 6

Experimental Performance Metrics Under Voltage and Load Changes

Metric	Voltage change	Load change
Voltage settling time	≈ 0.3 s	≈ 0.2 s
Overshoot	< 1.5 V	< 0.5 V
Steady-state voltage error	± 0.3 V	± 0.2 V
Observer estimation error (transient)	$\approx 3\%$	$\approx 5\%$

TABLE 7

Comparison of Simulation and Experimental Results

Aspect	Simulation	Experiment	Remark
Voltage settling time	0.2 s	0.3 s	Slight delay attributable to sensor dynamics
Load-estimation accuracy	$< 2\%$ error	$\approx 3\text{--}5\%$ (transient)	Within expected hardware measurement error
Overshoot (voltage change)	< 1.2 V	< 1.5 V	Minimal difference
Current ripple	Medium	Medium	Attributable to hardware switching noise
Controller stability	Excellent	Excellent	Validated under all tested conditions

The close agreement between simulated and measured metrics in Table 7 indicates that the averaged state-space model used for controller and observer design captures the dominant converter dynamics accurately, and that the RPBC scheme retains its predicted transient performance — settling time, overshoot, and estimation accuracy — when deployed on real digital hardware in the presence of sensor noise, parasitic circuit elements, and switching delays that are not represented in the idealized simulation model. Together with the stability results of Section 5, these results support the conclusion that the proposed PBC–DO strategy provides tight output-voltage regulation, fast inductor-current response, and effective real-time disturbance rejection across both simulated and physical implementations.

8. Discussion: Comparison with Existing Control Strategies

The results of Sections 6 and 7 can be placed in context by comparing the proposed RPBC scheme, qualitatively, with the control strategies most commonly reported for DC–DC converter regulation under uncertainty.

Versus PID / PI control. Because the RPBC law compensates directly for the motor back-EMF and adapts its steady-state reference to the estimated load, it removes the systematic bias that a fixed-gain PI controller exhibits once the load departs from its design value, while retaining a comparably simple, low-order feedback structure (Table 8).

Versus sliding-mode control (SMC). SMC offers strong robustness to matched disturbances but is well known to suffer from chattering on the switching surface, which increases switching stress and electromagnetic interference [17], [18]. Because the RPBC law is a smooth function of the state and the observer output, it avoids high-frequency switching in the control signal by construction, while the disturbance observer supplies comparable robustness to load uncertainty without requiring a discontinuous control action.

Versus H^∞ control. H^∞ synthesis can achieve strong disturbance attenuation guarantees but requires an offline linear-matrix-inequality design based on a fixed operating point and a weighting-function selection that is often non-trivial for a nonlinear converter [1]. The proposed RPBC law is designed directly on the nonlinear averaged model and is completely explicit, requiring no offline optimization.

Versus model-predictive control (MPC). MPC can, in principle, achieve near-optimal transient performance but at a computational cost that scales with prediction horizon and constraint set, which limits its use at high switching frequencies on low-cost embedded platforms [13]. In contrast, the observer update (16)–(17) and the control law (22) involve only elementary arithmetic and a single logarithm evaluation per sample, making the proposed scheme substantially cheaper to implement in real time.

TABLE 8

Qualitative Comparison of Control Strategies for Buck–Boost Converters

Strategy	Robustness	Comp. cost	Notable drawback
PID / PI	Low	Low	Steady-state error under load/parameter drift
Sliding-mode control	High	Low–moderate	Chattering, switching stress, EMI
H^∞ control	High	Moderate	Offline LMI design tied to a fixed operating point
Model predictive control	Very high	Very high	Computational burden at high switching frequency
Proposed RPBC (PBC + DO)	High	Low	Requires accurate L, C, E; no integral action

These comparisons should be read as qualitative positioning based on the well-documented properties of each strategy in the cited literature, together with the quantitative results obtained for the proposed scheme in Sections 6 and 7; a direct head-to-head experimental benchmark against SMC, H^∞ , and MPC controllers on the same test bench was outside the scope of the present study and is identified as a natural next step in Section 9.

9. Conclusion and Future Work

9.1 Summary

This paper has presented a Robust Passivity-Based Control (RPBC) strategy for a non-inverting Buck–Boost DC–DC converter feeding a DC-motor load, combining an energy-shaping passivity-based controller with an adaptive, Lyapunov-convergent disturbance observer for the unknown load conductance. Starting from the averaged state-space model, the converter dynamics were recast in port-controlled Hamiltonian form; a logarithmic nonlinear injection function was shown analytically to render the observer's estimation-error dynamics linear and exponentially stable; and a composite control law, combining adaptive feed-forward inversion with damping-injection feedback, was shown to be globally exponentially stable in the absence of estimation error and Input-to-State Stable with respect to bounded estimation error. Simulation studies under input-voltage, load, and observer-gain variation, followed by hardware-in-the-loop experiments on a TMS320F28335 + FPGA test bench, confirmed fast disturbance rejection, low overshoot, and close agreement between simulated and measured transient performance.

9.2 Practical Implications

Because the proposed observer and controller rely only on measurable electrical quantities and require modest computation, the RPBC scheme is well suited to embedded implementation in cost-sensitive applications such as renewable-energy front ends, electric-vehicle powertrains, and industrial DC power supplies, where load and source disturbances are frequent and where a discontinuous or computationally intensive controller would be undesirable. The reduced tuning burden relative to sliding-mode or model-predictive alternatives, together with the physically interpretable structure of the energy-shaping and damping terms, may also lower the engineering effort required to adapt the controller to new converter designs or operating ranges.

9.3 Limitations

Four limitations of the present study should be acknowledged. First, the observer showed measurable sensitivity to high-frequency sensor noise at high gain settings, suggesting that noise-filtering enhancements (e.g., Kalman or H^∞ filtering) merit investigation. Second, the observer and controller gains were tuned manually; an automated or self-tuning gain-selection procedure would reduce the commissioning effort in practice. Third, the experimental validation was carried out over a moderate range of voltage, load, and temperature conditions, and the controller's behaviour at the extremes of its operating envelope has not yet been characterized. Fourth, the study focused on a single-phase, non-inverting topology; extending the analysis to multi-phase or modular converter architectures would require additional treatment of inter-phase coordination and is left for future work.

9.4 Future Work

- 1) *Self-tuning extensions.* Incorporating adaptive or reinforcement-learning-based gain tuning for the observer and controller to reduce manual commissioning effort.
- 2) *Advanced filtering.* Investigating Kalman- or H_∞ -based observer redesigns to further improve robustness to sensor noise and drift.
- 3) *Extended operating envelope.* Systematic testing under wider temperature, voltage, and long-duration operating conditions, including component-aging studies.
- 4) *Multi-phase and modular extensions.* Generalizing the PCH modeling and RPBC design to multi-phase and grid-connected modular Buck–Boost architectures.
- 5) *Direct benchmarking.* Conducting a controlled experimental comparison of the proposed RPBC scheme against sliding-mode, H_∞ , and model-predictive controllers on the same hardware test bench.

Data Availability Statement

The MATLAB/Simulink models and the raw simulation and experimental data (output voltage, inductor current, control signal u_{av} , and observer estimates, in .mat and .csv formats) supporting the findings of this study are openly available at: <https://drive.google.com/drive/folders/1UhiHL8u7UDbrrMIhUIYq00dyij0VYy5?usp=sharing>.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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