
**MULTIPLE INPUT DC–DC CONVERTER FOR HYBRID
RENEWABLE ENERGY APPLICATIONS: DESIGN,
IMPLEMENTATION, AND PERFORMANCE ANALYSIS**

**Pratiksha P. Mirajkar*¹, Mandira D. Pote², Vijay R. Molake³, Asmita S. Salunkhe⁴,
Prof. Dhanyakumar A. Patil⁵**

^{1,2,3,4}Department of Electrical Engineering, D.K.T.E. Society's Textile and Engineering
Institute, Ichalkaranji.

⁵Assistant Professor, Department of Electrical Engineering, D.K.T.E. Society's Textile and
Engineering Institute, Ichalkaranji.

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*Corresponding Author: Pratiksha P. Mirajkar

Department of Electrical Engineering, D.K.T.E. Society's Textile and Engineering Institute, Ichalkaranji.

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ABSTRACT

This paper presents the design, implementation, and experimental evaluation of a Multiple Input DC–DC (MIDC) converter for hybrid renewable energy applications. The proposed topology integrates power from a solar photovoltaic (PV) panel (18 V, 50 W) and a lead-acid battery (12 V, 7 Ah) into a single step-down (buck) converter stage, delivering a regulated 12 V DC output to resistive and motor loads. An Arduino UNO microcontroller generates Pulse Width Modulation (PWM) signals to control power MOSFET switches, enabling automatic source selection, closed-loop voltage regulation, and safe battery charging. Three operating modes solar-dominant, battery-backup, and hybrid are defined and validated experimentally. Measured conversion efficiency ranges from 88% to 93%, output voltage ripple remains below 50 mV, and source transitions are achieved without observable load interruption. The results confirm that the MIDC architecture reduces component count, improves system reliability, and provides a cost-effective platform for off-grid electrification, EV auxiliary charging, and distributed energy management.

KEYWORDS: DC–DC converter; multiple input converter; photovoltaic; battery storage; PWM control; renewable energy; buck converter; hybrid energy system; Arduino UNO; MPPT.

I. INTRODUCTION

The global transition toward sustainable energy has accelerated the deployment of renewable energy sources (RES) such as solar photovoltaic (PV) systems and wind turbines. Despite their environmental benefits, individual RES exhibit intermittent generation profiles that depend heavily on prevailing weather conditions. Solar PV output, for instance, is a function of irradiance and cell temperature, resulting in wide diurnal and seasonal fluctuations. This intermittency compromises supply continuity and limits the standalone applicability of single-source renewable systems [1].

Hybrid energy systems (HES) mitigate these challenges by coupling complementary sources typically a primary RES with an electrochemical storage unit to ensure uninterrupted power delivery. Conventionally, each source in such a system is interfaced through a dedicated power converter, leading to increased hardware complexity, elevated cost, and potential control conflicts at the shared DC bus. A Multiple Input DC–DC Converter (MIDC) addresses these drawbacks by combining two or more source interfaces into a single power-conversion stage, thereby reducing passive component count, simplifying control architecture, and improving overall efficiency [2], [3].

This work presents a dual-input buck converter capable of accepting power simultaneously from a solar PV panel and a 12 V lead-acid battery. An Arduino UNO microcontroller implements PWM-based switching control, real-time voltage and current sensing, automatic source-priority management, and Constant-Current / Constant-Voltage (CC–CV) battery charging logic. The converter was built and tested under variable irradiance and load conditions, with key performance metrics efficiency, voltage regulation, and ripple—recorded and analysed.

The remainder of this paper is organised as follows. Section II reviews prior art on MIDC topologies. Section III describes the system architecture and operating modes. Section IV details hardware implementation. Section V presents the control algorithm. Section VI reports experimental results. Section VII discusses applications and limitations. Section VIII concludes the paper.

II. RELATED WORK

Multiple-input converter research has grown steadily over the past decade. Jiang and Peng [1] proposed a pulsating-source multiple-input converter that processes power from sources with different voltage levels using a common magnetic structure, achieving high efficiency but requiring precise gate timing. Hinago and Koizumi [2] extended this concept to a single-

phase multilevel inverter with a cascaded architecture suitable for photovoltaic sub-module integration.

Benavides and Chapman [3] classified MIDC topologies into three categories: (i) time-shared single-inductor converters, (ii) independent converter banks with power-rail ORing, and (iii) coupled-inductor multi-port converters. They concluded that time-shared approaches offer the lowest passive component count whereas coupled-inductor topologies yield superior dynamic response.

Multi-port converters incorporating fuzzy logic or model-predictive control have been demonstrated for photovoltaic–battery–wind hybrid systems, achieving seamless source transitions and peak efficiencies exceeding 94% [4]. However, the increased algorithmic complexity of such control schemes demands high-performance digital signal processors (DSPs) or field-programmable gate arrays (FPGAs), raising implementation cost.

The present work contributes an accessible, low-cost MIDC implementation using a commodity microcontroller (Arduino UNO / ATmega328P), PWM-based closed-loop regulation, and a modular hardware design suitable for educational prototyping and small-scale off-grid deployment.

III. SYSTEM ARCHITECTURE AND OPERATING MODES

A. Overall Architecture

Fig. 1 (see block diagram in Sec. 2.1 of the project report) depicts the proposed system. Two DC sources a 50 W solar PV panel and a 12 V, 7 Ah lead-acid battery feed a dual-input buck converter. The converter output supplies a 12 V DC load bus shared by a DC motor (12 V, 0.5 A) and an LED lamp (12 V, 10 W). Source-side blocking diodes prevent inter-source reverse current. A voltage-divider feedback network feeds scaled signals to the ADC channels of an Arduino UNO, which closes the voltage-regulation loop via PWM duty-cycle adjustment.

B. Operating Modes

The converter operates in three well-defined modes:

- Mode 1 – Solar-Dominant: Solar irradiance is sufficient ($V_{PV} \geq 15$ V). The PV panel supplies the load and simultaneously charges the battery via CC–CV control. The battery acts as an energy sink. PWM duty cycle is adjusted to maintain $V_{out} = 12$ V.

- Mode 2 – Battery-Backup: Solar voltage drops below 15 V (cloud, night). The battery discharges through the converter to maintain uninterrupted 12 V output. The solar-side blocking diode prevents back-feed into the PV panel.
- Mode 3 – Hybrid: During high load demand or transitional irradiance both sources share load current. The controller prioritises solar power and supplements with battery current only when solar power alone cannot satisfy the load.

IV. HARDWARE IMPLEMENTATION

A. Solar PV Module

A monocrystalline PV panel rated 18 V open-circuit voltage (V_{oc}), 50 W peak power (P_{max}), short-circuit current $I_{sc} = 3.0$ A, and maximum-power-point voltage $V_{mp} \approx 17$ V was used. MC4 connectors and UV-resistant 4 mm² cables were employed for field wiring. A 1N5822 Schottky blocking diode (D1, 40 V / 3 A) suppresses reverse current into the panel under low-irradiance conditions.

B. Energy Storage

A 12 V, 7 Ah sealed lead-acid (SLA) battery serves as the secondary source and energy buffer. Battery voltage thresholds are: lower discharge cut-off $V_{min} = 11.5$ V; upper charge cut-off $V_{max} = 13.8$ V. A 15 A automotive blade fuse protects the battery branch.

C. Power-Conversion Stage

The converter core is a non-synchronous step-down (buck) topology implemented with: IRFZ44N power MOSFET (S1, $V_{ds} = 55$ V, $I_d = 49$ A, $R_{ds(on)} = 28$ m Ω), SR560 Schottky freewheeling diode (60 V / 5 A), 220 μ H toroidal ferrite inductor (DCR = 0.15 Ω , $I_{sat} = 5$ A), and 470 μ F / 50 V electrolytic output capacitor paralleled with 10 μ F ceramic for high-frequency decoupling. Switching frequency is set to 31.25 kHz by Arduino Timer1 in phase-correct PWM mode.

D. Gate Driver and Control Electronics

An IR2110 half-bridge gate driver translates the 5 V Arduino PWM output to a 12 V gate drive signal, ensuring adequate gate voltage swing and sub-microsecond rise/fall times. ACS712-20A Hall-effect current sensors monitor inductor and battery branch currents. Resistive voltage dividers (ratio 1:5.7) scale bus voltages into the 0–5 V ADC range of the Arduino.

V. CONTROL ALGORITHM

A. Initialisation

At power-on the microcontroller resets all PWM outputs to zero, initialises ADC references, and sets Timer1 for 31.25 kHz phase-correct PWM on pin D9 (MOSFET gate). An LCD display is initialised for real-time monitoring.

B. Sensing and Source Selection

Every 10 ms the firmware samples V_{solar} , V_{batt} , I_{solar} , I_{load} , and V_{out} . Threshold comparisons determine the active mode. Hysteresis bands of ± 0.5 V around switching thresholds prevent mode chattering during boundary conditions.

C. Voltage Regulation Loop

A proportional-integral (PI) controller computes the error $e = V_{\text{ref}} - V_{\text{out}}$ ($V_{\text{ref}} = 12.0$ V) and updates the PWM duty cycle D every 10 ms:

$$D[n] = D[n-1] + K_p \cdot e[n] + K_i \cdot \int e \, dt$$

Empirically tuned gains $K_p = 0.05$ and $K_i = 0.002$ yield a settling time of approximately 15 ms for a 50% load step with less than 2% steady-state error.

D. Battery Charging (CC–CV)

When $V_{\text{batt}} < 13.8$ V and solar power is available, a separate PWM channel controls charging current. In the constant-current (CC) phase I_{charge} is regulated to 0.7 A (0.1C for a 7 Ah battery); once V_{batt} reaches 13.8 V the controller transitions to constant-voltage (CV) mode, tapering current until $I_{\text{charge}} < 50$ mA, at which point charging terminates.

E. Protection

Software over-voltage (>14.5 V), under-voltage (<10 V), and over-current (>4 A) faults immediately latch PWM output to zero and display a fault code on the LCD. Hardware fast-blow fuses provide failsafe protection independent of firmware.

VI. EXPERIMENTAL RESULTS AND DISCUSSION

A. Test Setup

Experiments were performed under clear-sky conditions (irradiance ≈ 850 – 1000 W/m²), partial cloud (300–600 W/m²), and simulated night (covered panel). Load conditions ranged from no-load to full rated load (27.6 W). An oscilloscope (Rigol DS1054Z), a bench multimeter (Fluke 87V), and a clamp ammeter were used for measurements.

B. Output Voltage Regulation

Table I summarises steady-state output voltage for three representative operating conditions. The converter maintained V_{out} within $\pm 1.5\%$ of the 12 V set-point across all tested conditions, confirming robust PI regulation.

TABLE I: Output Voltage Under Different Operating Conditions

Operating Mode	V_{in} (V)	Load (W)	V_{out} (V)	Error (%)
Solar-Dominant	17.8	27.6	11.94	0.5
Battery-Backup	12.0	27.6	11.88	1.0
Hybrid	17.8 / 12.0	27.6	11.97	0.25

C. Conversion Efficiency

Fig. 2 (efficiency vs. output power) shows that peak efficiency of 92.4% is achieved at approximately 20 W output (72% of rated load). At light load (5 W) efficiency drops to 81% due to fixed switching and gate-charge losses. Table II lists efficiency at selected load points.

TABLE II: Measured Converter Efficiency.

P_{out} (W)	P_{in} (W)	Efficiency (%)
5	6.17	81.0
10	11.36	88.0
20	21.65	92.4
27.6	29.89	92.3

D. Output Voltage Ripple

Peak-to-peak output ripple voltage measured with the oscilloscope at full load was 42 mV (0.35% of V_{out}), well within the 50 mV specification. Ripple frequency matched the 31.25 kHz switching frequency, confirming satisfactory inductor-capacitor filter design.

E. Dynamic Response

A 50% load step (13.8 W \rightarrow 27.6 W) resulted in a transient voltage undershoot of 380 mV, recovering to within 1% of set-point in 14.8 ms. Source-mode transitions (solar to battery and vice versa) produced transient deviations below 250 mV, imperceptible to the connected DC motor and lamp.

F. Battery Charging Performance

In solar-dominant mode the battery (initially at 11.8 V) was fully charged to 13.8 V in approximately 4.5 hours at 0.7 A constant current, consistent with the expected C/10 charge

rate for the 7 Ah battery. The CV phase tapered current to below 50 mA within 30 minutes before charging was terminated automatically.

VII. APPLICATIONS AND LIMITATIONS

A. Applications

The proposed MIDC converter is well suited for: (i) standalone off-grid residential lighting and small appliance supply; (ii) solar street-lighting systems with battery backup; (iii) auxiliary power supply for electric vehicle (EV) control electronics; (iv) distributed energy management in DC microgrids; (v) educational prototyping for renewable energy and power electronics courses.

B. Limitations

The current prototype has several limitations that motivate future research:

- Power capacity is constrained to approximately 30 W by the passive component ratings. Scaling to higher power levels requires upgraded inductors, MOSFETs, and heat sinks.
- Only two input ports are supported; integrating additional sources (wind, fuel cell) requires circuit and firmware modifications.
- No full Battery Management System (BMS) is implemented; advanced functions such as cell balancing, state-of-health estimation, and thermal monitoring are absent.
- The buck topology limits output voltage to values below the minimum input voltage. Loads requiring boosted voltage necessitate a different or additional converter stage.
- Perturb-and-Observe (P&O) MPPT was not implemented in the final prototype, leaving potential solar harvest gains unrealised.

VIII. CONCLUSION

This paper has demonstrated the feasibility of a dual-input buck DC–DC converter for hybrid solar–battery renewable energy applications. The converter was designed around commodity power electronics components and an Arduino UNO microcontroller, keeping the bill-of-materials cost accessible for small-scale deployments. Experimental evaluation confirmed three fully automatic operating modes, steady-state output voltage regulation within $\pm 1.5\%$, peak efficiency of 92.4%, output ripple below 50 mV, and load-step recovery within 15 ms. Battery charging followed the CC–CV profile, reaching full charge without overcharge events.

Future work will incorporate: (a) an Incremental-Conductance MPPT algorithm to maximise solar harvest; (b) synchronous rectification to reduce freewheeling diode conduction losses;

(c) a full BMS with state-of-charge estimation; (d) extension to a three-port topology accommodating a wind turbine rectifier; and (e) a higher-power prototype (200–500 W) validated against IEC 62109 safety standards.

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