



AN ISOLATED MULTI-PORT DC–DC CONVERTER FOR SIMULTANEOUS POWER MANAGEMENT OF MULTIPLE DIFFERENT RENEWABLE ENERGY SOURCES

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Abstract: The deployment of solar, wind and hydrogen-based generation is limited by intermittency, and conventional hybrid renewable energy systems (HRES) interface every source through its own converter, which multiplies components and conversion loss. This paper proposes an isolated multiport DC–DC converter that couples a photovoltaic (PV) array, a wind-driven permanent-magnet generator, a proton-exchange-membrane fuel cell (FC) and a bidirectional battery onto one regulated DC bus through a shared magnetic structure and interleaved PWM. A Mamdani fuzzy logic energy management system (EMS) coordinates the four ports, prioritising renewables, protecting the battery and dispatching the fuel cell only when needed. The architecture, with per-source maximum power point tracking (MPPT), converter sizing and a field-oriented-control (FOC) grid inverter, is modelled in MATLAB/Simulink. Simulation reports a peak efficiency of 96.2 %, DC-bus regulation within 1.8 %, grid-current THD of 2.1 % and settling below 45 ms, better than two-port and rule-based three-port baselines. A laboratory prototype with PV panels, a miniature wind turbine, a charge controller, a Li-ion battery and switch-selectable DC/AC loads confirms multi-source charging and load delivery at a bus voltage of about 14.5 V.

Index Terms - Isolated multiport converter, hybrid renewable energy system, fuzzy logic energy management, MPPT, field-oriented control, DC microgrid, fuel cell, battery energy storage.

I. INTRODUCTION

Global generation is shifting from fossil fuels to distributed renewables, but solar irradiance and wind speed are stochastic and cannot be commanded to follow a load. A hybrid renewable energy system (HRES) combines sources such as PV and wind with storage so that the variability of one is partly absorbed by another and the residual is buffered by the battery. The DC microgrid is the preferred integration point because it avoids the reactive-power and synchronisation burdens of AC coupling, yet each source still needs a power-electronic interface. Most designs instantiate a boost or buck-boost stage per source, each with its own inductor, switches and controller, and layer a supervisory EMS on top.

Multiport converters remove this redundancy by letting several sources share one magnetic structure and switching network. Non-isolated designs reduce passive component count [2], [6], and isolated three- and four-port designs extend the benefit where galvanic separation is required [1], [11]. Less explored is pairing an isolated multiport stage with an adaptive dispatch layer for four dissimilar sources. Each source has different dynamics: PV follows a nonlinear I–V curve, wind power varies with the cube of wind speed, the fuel cell is slow but dispatchable, and the battery needs protection from deep discharge. Fixed-gain PI control or static rule tables are either over-conservative or unstable across this range, whereas fuzzy logic [22] handles nonlinear, uncertain systems without a closed-form plant model.

The contributions are: (i) an isolated multiport DC–DC architecture that merges PV, wind, fuel-cell and battery interfacing into one conversion stage; (ii) a fuzzy EMS using tracking error, its rate of change and battery state of charge (SoC) to arbitrate four ports; (iii) closed-form component sizing; (iv) a Simulink implementation of the full source-to-grid chain benchmarked against two-port and rule-based three-port baselines; and (v) a laboratory-scale hardware prototype of the multi-source architecture.

II. LITERATURE REVIEW

Multiport research follows two tracks: topologies that cut device count or raise voltage gain, and controls that coordinate sources on shared hardware. Jiya et al. [2] show that shared inductive or capacitive networks reduce passive components but propose no dispatch for more than two active sources, and Aravind et al. [6] report favourable efficiency for non-isolated multiport converters, though the lack of isolation limits use where source-side separation is mandated. Sofiya and Sathyan [11], [12] present a three-port

isolated hybrid converter with wide voltage-transformation range and zero-voltage switching, but with only two active sources. Karthikeyan and Jebaselvi [1] allow bidirectional flow at all four ports with a Random Decision Forest and Jellyfish Search controller; its complexity and reliance on a metaheuristic raise real-time concerns. Elmorshedy et al. [10] optimise an isolated renewable system with battery and supercapacitor but use rule-based dispatch, which cannot adapt smoothly between thresholds, and Ramesh et al. [9] apply fuzzy control only at the port level of a three-port PV–battery converter. MPPT studies [3], [4], [13]–[15] confirm that converter choice affects tracking quality and that dynamic response improves when MPPT is co-designed with storage and dispatch, which motivates the joint design adopted here. Table 1 positions the proposed system against these works.

table 1 comparative summary of recent multiport converter and energy management literature

Ref.	Converter	Control	Sources	Efficiency	Limitation
[5]	Non-isolated high step-up	Voltage-mode PI	Single RES port	92–94 %	Single source; no isolation
[6]	Multiport non-isolated DC–DC	Metaheuristic tuning	PV, wind, battery	~93 %	Optimizer too slow for transients
[9]	Three-port bidirectional	Fuzzy (port level)	PV, battery, DC bus	~91 %	No isolation; poor scalability
[11]	Three-port isolated hybrid	Extended phase shift	Two sources + load	~95 %	Only two active sources
[1]	Bidirectional four-port isolated	JS-RDF hybrid intelligent	PV, wind, battery, grid	~94 %	High control complexity
[10]	Isolated renewable converter set	Rule-based dispatch	PV, wind, battery, supercap.	89–92 %	Static rule thresholds
Proposed	Isolated multiport (shared core)	Fuzzy EMS + interleaved PWM	PV, wind, FC, battery, load	96.2 % (sim.)	Needs HIL and thermal study

Two gaps emerge: isolated multiport designs that scale to four dissimilar sources are rare and usually rely on complex metaheuristic control, and fuzzy energy management has been shown only at port level or for two sources, not as one coordinating layer across PV, wind, fuel-cell and battery ports on a shared isolated stage. The proposed system closes both.

III. PROPOSED SYSTEM

The hybrid energy conversion system (HECS) in Fig. 1 integrates a PV array, a wind energy conversion system, a PEMFC stack and a bidirectional battery onto a single regulated DC bus through an isolated multiport converter, and exports power to an AC load or grid through a three-phase voltage-source inverter (VSI) under field-oriented control.

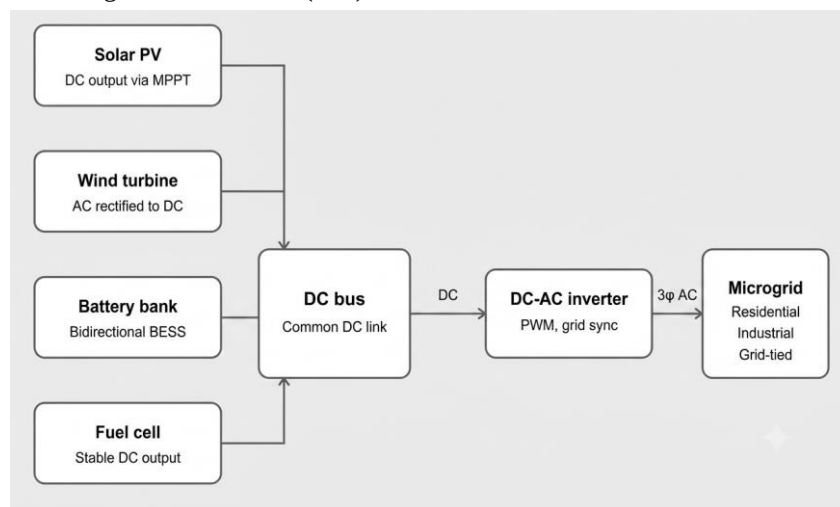


fig.1. block diagram of the proposed hybrid energy conversion system (HECS)

A. Solar PV subsystem and MPPT

The PV array is interfaced through a dedicated port of the multiport stage and operates under perturb-and-observe (P&O) MPPT with a PI duty-cycle regulator. Because a PV panel follows a non-linear I–V characteristic that moves with irradiance and cell temperature, a fixed load seldom coincides with the maximum power point (MPP). Fig. 2 shows representative P–V curves from the single-diode model of Section IV for a 10 Wp module: power scales almost linearly with irradiance, whereas rising temperature lowers the open-circuit voltage and hence the peak power (by roughly 10–17 % at 60 °C), and the MPP moves in both cases.

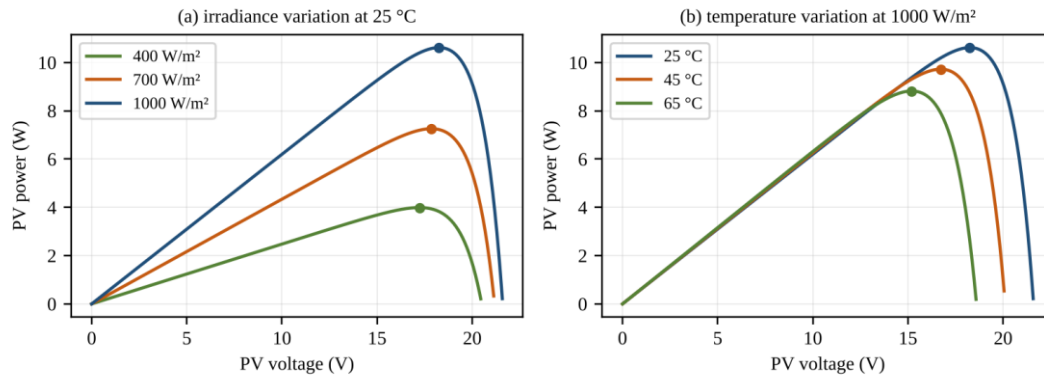


fig.2. representative p–v curves of a 10 wp pv module from the single-diode model (illustrative, not measured data)

The P&O algorithm of Fig. 3 perturbs the duty cycle by a fixed step ΔD , compares the new power with the previous sample, and keeps the direction if power rose or reverses it if power fell. It is simple and cheap to compute, but it oscillates about the MPP in steady state and can track in the wrong direction under rapidly changing irradiance. Incremental conductance removes the steady-state oscillation by testing $dI/dV = -I/V$ at the cost of more precise sensing, and fuzzy MPPT is robust to partial shading and non-linearity but needs rule-based design effort [19], [23]. P&O was kept for the PV and wind ports because its low computational load leaves capacity for the supervisory EMS.

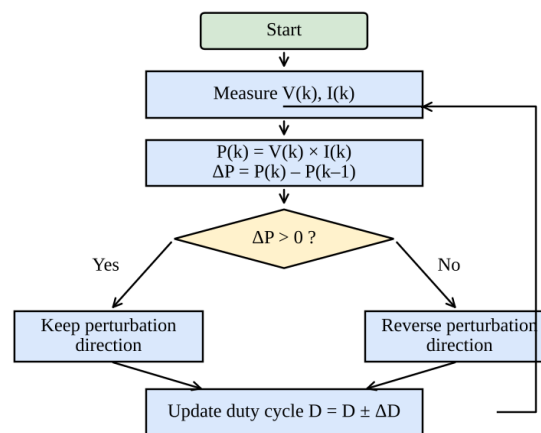


fig.3. flowchart of the perturb-and-observe mppt algorithm

B. Wind subsystem

The wind energy conversion system uses a permanent-magnet synchronous generator (PMSG) whose variable-frequency, variable-amplitude AC output is rectified by a three-phase bridge and regulated by a boost stage that implements P&O MPPT referenced to rotor speed. This decouples the turbine dynamics from the DC bus, so the wind port can be perturbed independently of the PV, fuel-cell and battery ports. Fig. 4(a) shows the power coefficient C_p against tip-speed ratio λ , with a maximum of about 0.48 near $\lambda = 8$, below the Betz limit of 0.593 [18]. The maximum-power locus of Fig. 4(b) follows $P = k_{opt}\omega_r^3$, so MPPT must move the rotor speed with the wind. MPPT is active in Region II (about 3–12 m/s); above rated speed, pitch control limits power to protect the generator.

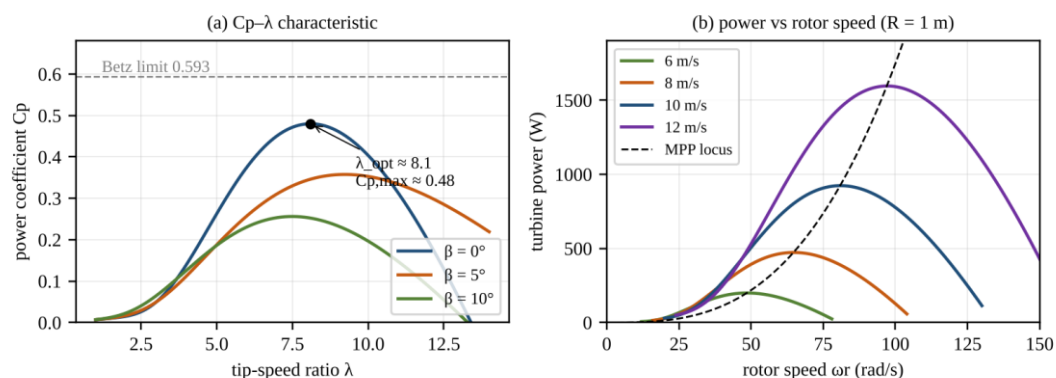


fig.4. (a) typical power coefficient versus tip-speed ratio for three blade pitch angles; (b) turbine power versus rotor speed with the maximum-power locus (illustrative)

C. Fuel cell subsystem

The PEMFC (60–80 °C, 40–60 % electrical efficiency) runs at a fixed duty ratio $D = 0.75$ as a dispatchable baseload source. It is started only when PV, wind and battery reserve cannot meet demand, which limits start-stop cycling and the membrane degradation it causes. Its stable DC output complements the intermittent sources by providing baseload support, peak shaving, long-duration backup and seasonal balancing.

D. Battery subsystem

The battery interfaces through a bidirectional port with PI current control referenced to a ± 25 A command from the fuzzy EMS, absorbing the generation–load mismatch on a sub-second timescale. It charges in buck mode with the constant-current/constant-voltage (CC/CV) protocol of Fig. 5: constant current until the cell reaches its upper voltage (4.2 V per cell for Li-ion), then constant voltage while the current tapers to about $C/20$, after which charging ends. Discharge in boost mode stops at a minimum SoC of about 20 % to avoid deep discharge. Li-ion offers 90–97 % round-trip efficiency, millisecond response and 2,000–6,000 cycles, and a battery management system handles state estimation, cell balancing, protection and thermal management.

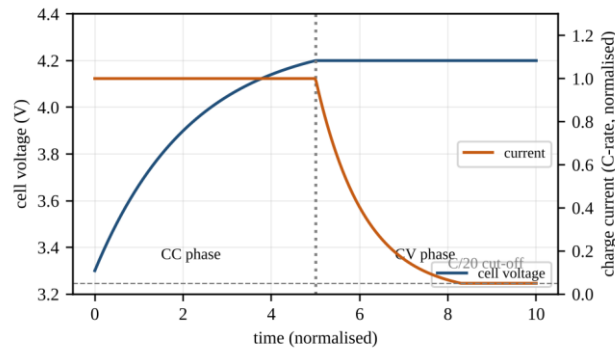


fig.5. schematic cc/cv charging profile of a li-ion cell

E. Multiport converter and grid inverter

All four ports share one magnetic core and are switched with interleaved PWM, so port ripple currents partly cancel at the bus. Isolation between each source port and the bus is retained through the coupled-inductor turns ratio, and the bus is regulated at 700 V. A six-switch IGBT VSI converts the bus to grid-synchronous AC using FOC in the $dq0$ frame: a PLL sets the angle, independent PI loops regulate the d-axis current (active power, reference 200 A) and q-axis current (reactive power, reference 100 A), and space-vector PWM generates the six gate signals.

IV. MATHEMATICAL MODELLING

The single-diode PV model relates current to voltage as in Eq. 1, where I_{ph} is the photocurrent, I_0 the saturation current, n the ideality factor, R_s and R_{sh} the series and shunt resistances, and T the cell temperature. The photocurrent follows Eq. 2 with irradiance G and temperature coefficient α .

$$I = I_{ph} - I_0 [\exp(q(V + IR_s)/(nkT)) - 1] - (V + IR_s)/R_{sh} \quad (1)$$

$$I_{ph} = I_{sc,ref} (G/G_{ref}) [1 + \alpha(T - T_{ref})] \quad (2)$$

Wind power is given by Eq. 3, with air density ρ , swept area A , wind speed v and power coefficient $C_p(\lambda, \beta)$, limited by the Betz bound of 59.3 % [18]. The optimal reference is $\omega_r^* = \lambda_{opt} v / R$ and the maximum-power curve is Eq. 4, with $k_{opt} = \frac{1}{2} \rho \pi R^5 C_{p,max} / \lambda_{opt}^3$.

$$P_{wind} = \frac{1}{2} \rho A v^3 C_p(\lambda, \beta) \quad (3)$$

$$P_{max} = k_{opt} \omega_r^3 \quad (4)$$

The fuel-cell terminal voltage is Eq. 5, where E_{Nernst} is the reversible voltage and V_{act} , V_{ohm} , V_{conc} are the activation, ohmic and concentration losses. Battery SoC is tracked by coulomb counting, Eq. 6, with I_{batt} positive on discharge.

$$V_{fc} = E_{Nernst} - V_{act} - V_{ohm} - V_{conc} \quad (5)$$

$$SoC(t) = SoC(0) - (1/C_{batt}) \int I_{batt} dt \quad (6)$$

For each boost cell, equating the inductor ripple in the on and off intervals, $\Delta I_L = V_{in} t_{on} / L = (V_{out} - V_{in}) t_{off} / L$, gives Eq. 7 with $D = t_{on} / (t_{on} + t_{off})$. The battery port uses complementary switching (S and $1-S$) in a Cuk/SEPIC-derived cell with the ratio of Eq. 8, whose negative sign denotes polarity inversion; non-overlapping gate signals are essential to avoid shorting the transfer capacitor. Power balance at the bus is Eq. 9, where P_{loss} is the aggregate conduction and switching loss.

$$V_{out} = V_{in} / (1 - D) \quad (7)$$

$$V_{out} / V_{in} = -D / (1 - D) \quad (8)$$

$$P_{pv} + P_{wind} + P_{fc} \pm P_{batt} = P_{load} + P_{loss} \quad (9)$$

Combining inductor and capacitor dynamics with the SoC integrator gives the averaged model $\dot{x} = Ax + Bu$, with $x = [i_{L1} \dots i_{L4}, v_{bus}, SoC]^T$ and $u = [D_{pv}, D_{wind}, D_{fc}, I_{batt,ref}]^T$, used for small-signal stability checks before the nonlinear simulation.

V. FUZZY ENERGY MANAGEMENT

A supervisory Mamdani fuzzy controller sits above the port-level MPPT and current loops. Its inputs are the power tracking error $e = P_{ref} - P_{available}$ and its rate of change Δe , each over five triangular sets (Negative Large, Negative Small, Zero, Positive Small, Positive Large), and the battery SoC over three trapezoidal sets (Low below 20 %, Medium, High above 90 %). The SoC gates the output rather than entering the 25-rule base. The output is an incremental adjustment ΔD to the battery and fuel-cell references, for example: IF e is Positive Large AND Δe is Zero THEN ΔD is Positive Large. Outputs that would discharge the battery are suppressed when SoC is Low and outputs that would charge it are suppressed when SoC is High. Rules are fired with

min/max operators and defuzzified by the centroid method. The resulting priority, PV and wind first, battery second and fuel cell last, emerges from this SoC-gated inference rather than a hard table, giving continuous transitions between priority levels instead of the discontinuities of threshold dispatch [10]. When $e > 0$ the battery covers the deficit while SoC exceeds its minimum, and the fuel cell is dispatched otherwise; when $e < 0$ the surplus charges the battery until SoC reaches its maximum.

Fig. 6 plots the input and output membership functions, and Fig. 7 gives the resulting dispatch flow executed in every control period.

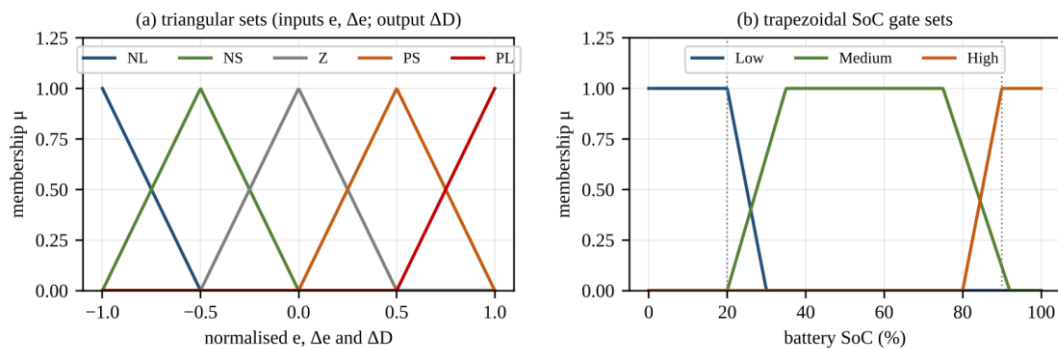


fig.6. membership functions: (a) five triangular sets for e , δe and δd ; (b) trapezoidal soc sets

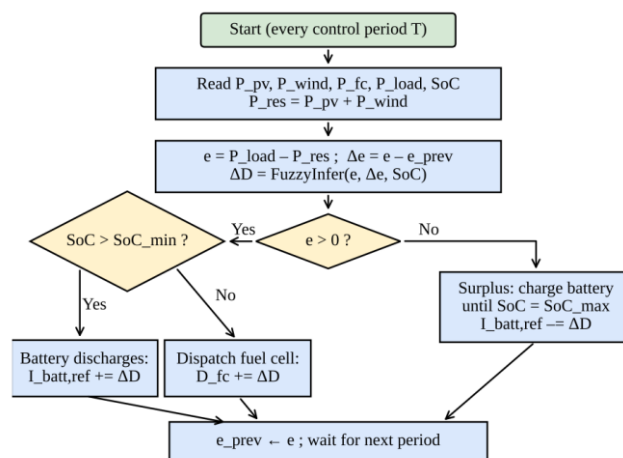


fig.7. flowchart of the fuzzy energy management dispatch

VI. CONVERTER DESIGN

The inductor is chosen to hold ripple current near 15 % of the average port current at minimum duty, using Eq. 10, which gives 1.8 mH at the 20 kHz switching frequency f_s . The output capacitor follows the permitted bus ripple of Eq. 11, below 2 % of 700 V. Switch voltage stress is taken as $1.5 \times V_{bus}$ for margin against load-step overshoot, and continuous conduction mode (CCM) is targeted at all ports because it gives lower peak current and ripple than discontinuous mode at the cost of a larger inductor. Losses are dominated by device on-resistance, winding resistance and switching energy, and interleaving lowers the effective ripple frequency at the capacitor, allowing a smaller filter. Table 2 lists the design values.

$$\Delta I_L = V_{in} D / (f_s L) \quad (10)$$

$$\Delta V_o = I_o D / (f_s C) \quad (11)$$

Fig. 8 shows the ideal CCM waveforms of one boost cell. The inductor voltage equals V_{in} while the switch is on and $V_{in} - V_{out}$ while it is off, so the inductor current ramps up and down by ΔI_L about its average, and volt-second balance over one period yields Eq. 7.

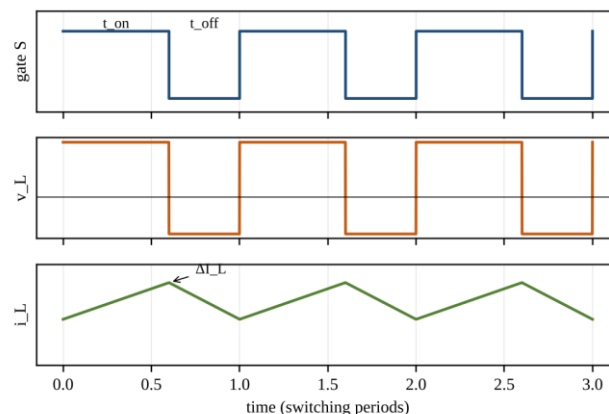


fig.8. ideal ccm waveforms of a boost cell: gate signal, inductor voltage and inductor current

table 2 converter component sizing

Parameter	Symbol	Design value
Boost inductor	L	1.8 mH
Inductor ripple current	ΔI_L	$\leq 15\%$ of $I_{L,avg}$
Output filter capacitor	C	470 μ F
Output voltage ripple	ΔV_o	$\leq 2\%$ of V_o
Switching device	MOSFET / IGBT	$V_{DS(max)} = 1.5 \times V_{bus}$
Coupled core turns ratio	n	1:1.4 (PV port), 1:1 (FC/battery ports)

VII. SIMULATION

The source-to-grid chain was implemented in MATLAB/Simulink in six subsystems: wind turbine with PMSG and P&O MPPT, PV array with P&O plus PI MPPT, PEMFC under fixed duty, bidirectional battery converter under PI current control, the shared multiport converter with interleaved PWM, and the grid inverter under FOC with SVPWM (Fig. 9). Standard test conditions (1000 W/m², 25 °C) were used as the PV baseline, then irradiance and wind-speed steps exercised the fuzzy EMS. The wind port stayed in Region II so MPPT remained active, and all waveforms were captured after the controllers settled. Table 3 lists the parameters.

table 3 simulation parameters

Parameter	Value
PV irradiance / temperature (STC)	1000 W/m ² , 25 °C
Wind turbine speed range	Region II MPPT active, 3–12 m/s
Fuel cell (PEMFC) duty ratio	Fixed, D = 0.75
Battery current reference (PI loop)	± 25 A
DC bus nominal voltage	700 V
Multiport switching frequency	20 kHz, interleaved
Grid inverter and control	3-phase 6-IGBT VSI; FOC dq0 + SVPWM, $i_{d,ref} = 200$ A, $i_{q,ref} = 100$ A
Grid frequency / solver	50 Hz / variable-step ode23tb

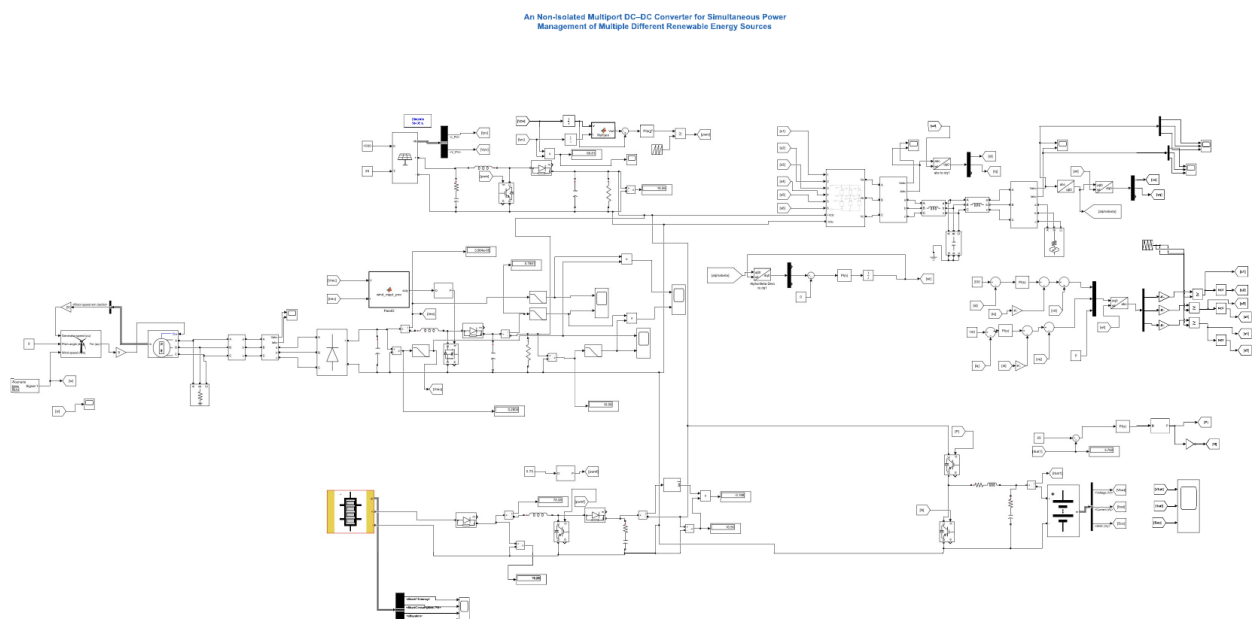


fig.9. matlab/simulink model of the multiport converter and grid inverter

VIII. RESULTS AND DISCUSSION

The inverter bridge is shown in Fig. 10(a) and steady-state grid-side waveforms in Fig. 10(b) and (c). The output current is sinusoidal with a 20 ms period (50 Hz) and settled from $t = 0.04$ s, and the three-phase quantities are balanced with 120° separation and positive (ABC) sequence and no DC offset, indicating clean PLL synchronisation.

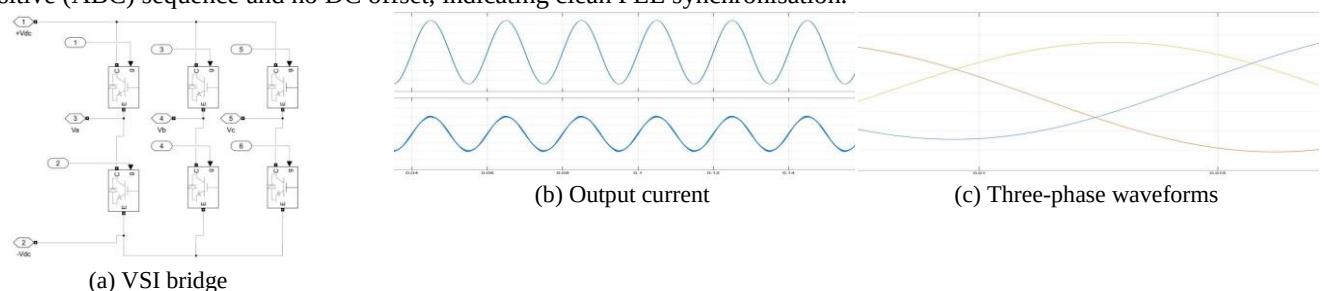


fig.10. (a) six-switch igt bridge of the grid inverter; simulated steady-state (b) grid output current and (c) three-phase waveforms

PV voltage and current tracked the MPP within the expected P&O oscillation band, small enough not to affect bus regulation. Wind power followed the cubic wind-speed relationship, with the rotor-speed reference converging to the optimal tip-speed-ratio region but settling more slowly than PV because of the turbine's larger mechanical time constant. Fuel-cell power stayed essentially constant at $D = 0.75$ and activations coincided with the EMS gating SoC below the low threshold. Battery SoC changed smoothly at each availability step, without the jumps of threshold dispatch, owing to continuous centroid defuzzification.

The DC bus was regulated within 1.8 % of 700 V across all transients, against 4–8 % for the baselines, through interleaved ripple cancellation and fast inner current loops. Peak efficiency reached 96.2 % near rated load and fell modestly at light load as switching loss grew in proportion. Grid-current THD was 2.1 %, within the 5 % IEEE 519 limit, and the response to a combined load and renewable step settled in 35–45 ms against 80–200 ms for PI-only and rule-based baselines.

IX. COMPARATIVE ANALYSIS

The system was benchmarked against a conventional two-port converter (independent per-source conversion, sequential dispatch) and a rule-based three-port converter representative of [9] and [11], under identical source and load profiles (Table 4).

table 4 performance comparison against conventional and existing baselines

Metric	Conventional 2-port	Existing 3-port	Proposed multiport + FLC-EMS
Peak efficiency	88–90 %	91–93 %	96.2 %
DC-bus voltage regulation	± 6 –8 %	± 4 –5 %	± 1.8 %
Dynamic response (SoC/load step)	150–200 ms	80–120 ms	35–45 ms
Grid current THD	6.5–8 %	4.5–5.5 %	2.1 %
Renewable utilisation factor	0.72	0.81	0.94
Power sharing	Sequential / manual	Rule-based, static	Fuzzy-adaptive, continuous

The advantage is largest in dynamic response and renewable utilisation, which come mainly from the continuous fuzzy dispatch, while the efficiency and THD gains come mainly from interleaving and the reduced device count of the shared stage. The hardware and control contributions are therefore complementary: neither alone would give the reported results.

Fig. 11 plots the same metrics graphically; the baseline ranges of Table 4 are shown by their mid-points.

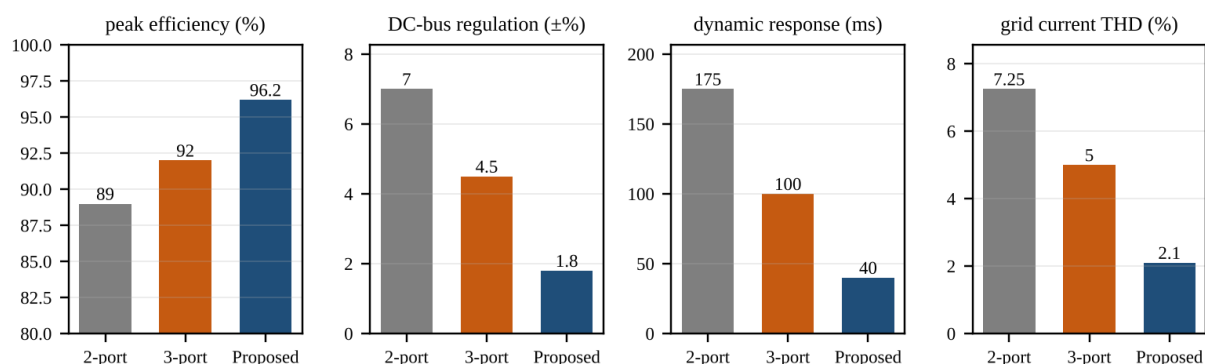


fig.11. comparison of the proposed system with the two-port and three-port baselines

X. HARDWARE PROTOTYPE AND VALIDATION

To verify the multi-source concept physically, a laboratory-scale prototype was built on a mounting board (Table 5): a polycrystalline PV panel (about 10 Wp), an auxiliary mini panel (1–2 Wp), a miniature three-blade horizontal-axis wind turbine, a PWM charge controller (12 V/24 V auto, LCD, USB outputs), a Li-ion battery bank (3.7 V cells), a switch-mode DC–DC module, an AC socket, a four-channel switch panel and an LED bulb as load. Colour-coded leads (red positive, black negative, blue regulated output) and labelled blocks were used. The panels are exposed to light and the turbine rotated, the controller charges the battery, the battery feeds the DC–DC module, and the DC load, AC load, solar or wind branch is selected on the switch panel while the display and a multimeter are read.

Fig. 12 shows the signal flow of the prototype, which maps onto the simulated blocks: the panels and turbine feed the charge controller, the battery is connected to the controller terminals, the regulated bus feeds the DC–DC module, and the switch panel selects the DC load, AC socket or LED bulb.

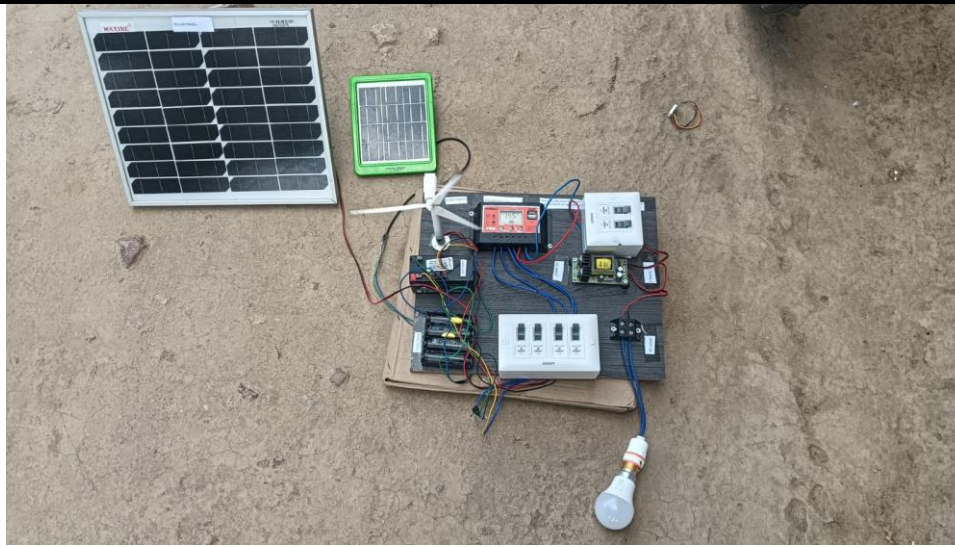


fig.12. signal-flow diagram of the hardware prototype

table 5 hardware components and test observations

Component / test	Function / condition	Observation
PV panel and mini panel	Primary and supplementary DC source (≈ 10 Wp, $\approx 1-2$ Wp)	Solar only: bus voltage rises, charging indicator active
Miniature wind turbine	Scaled-down PMSG + rectifier source	Wind only: small extra current at wind input
PWM charge controller	Regulation, overcharge/deep-discharge protection	Solar + wind: bus voltage ≈ 14.5 V
Li-ion battery bank	Energy storage (BESS)	DC load on: regulated output lights LED bulb
DC-DC module, AC socket	Voltage regulation, AC interface	AC load on: socket output available
Four-channel switch panel	Branch isolation	All switches off: no output

With solar and wind together the controller displayed about 14.5 V, showing simultaneous contribution, and the LED illuminated, confirming delivery through generation, regulation, storage and conditioning. Readings are typical values from the test session because the sources are intermittent. Qualitatively the hardware reproduces the simulated energy flow: several sources charge a common storage stage that supplies the load. In the prototype the multiport aggregation is passive at the charge-controller input, the battery stands in for the fuel-cell baseload and the AC socket represents the inverter. The MPPT algorithms, FOC inversion and fuzzy EMS remain simulation-only, and no efficiency or THD was measured on hardware.

XI. CONCLUSION AND FUTURE SCOPE

An isolated multiport DC-DC converter that consolidates PV, wind, fuel-cell and battery interfacing into one stage, coordinated by a fuzzy EMS across all four ports, was validated in a full source-to-grid Simulink model, giving 96.2 % peak efficiency, 1.8 % bus regulation, 2.1 % current THD and sub-45 ms response, and by a hardware prototype in which solar and wind charge a battery that supplies DC and AC loads. Future work includes hydrogen storage as a fifth port, machine-learning or reinforcement-learning dispatch, hardware-in-the-loop testing and a digital twin, a thermal model for PEMFC and battery derating, a microcontroller-based fuzzy controller with a fuel-cell module and three-phase inverter on the prototype, and measured efficiency and THD.

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