



Hybrid AC/DC Microgrid with Bidirectional Power Flow

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ABSTRACT—

Hybrid AC/DC microgrids bring solar generation, battery storage and utility supply together, but fluctuating generation and load can leave either bus short of power. This paper describes a low-cost laboratory prototype that moves energy in both directions between an AC bus and a 12 V DC bus without a purpose-built interlinking converter. A 200 W transformer-based inverter carries energy from the battery to the AC side, while a 14 V, 1.2 A SMPS charger carries it from the AC side back into the battery. An ESP32 board reads isolated voltage (ZMPT101B), current (ACS712) and mains-presence signals, then drives a two-channel relay module according to a small set of rules, using a break-before-make delay of about 2 s so that the grid and inverter are never joined. A 16×2 PC LCD and a buzzer report the active mode. Staged bench tests confirmed correct grid detection, automatic grid-to-inverter and inverter-to-grid changeover, and calibrated voltage sensing (grid sensitivity 500→561, inverter 271→606). The prototype is intended for teaching and demonstration, and the paper closes with a route toward a true closed-loop bidirectional converter.

Index Terms—hybrid microgrid, bidirectional power flow, ESP32, inverter, SMPS charger, battery storage, break-before-make changeover, renewable energy.

I. Introduction

A microgrid is a small, locally controlled power system that groups generation, storage and loads, and that can run alone or alongside the main utility network [1]. Early work compared purely AC and purely DC microgrids and found that each is attractive for a different class of source and load [2], [3]. Alternating current suits the utility grid and most household appliances, whereas photovoltaic panels, batteries and electronic loads are natively direct-current devices. Forcing everything onto one bus therefore adds conversion stages, and every stage costs efficiency.

The hybrid AC/DC microgrid answers this by keeping an AC subgrid and a DC subgrid and connecting them through an interlinking converter [4], [5]. Power can then travel in whichever direction the situation calls for: from the DC side to feed AC loads when sunlight is poor, or from the AC side to recharge the battery when the grid is healthy [6]. Published designs usually rely on fully controlled bidirectional converters with sophisticated modulation and droop-based sharing, which is hard for a student laboratory to build and difficult to explain step by step.

This work takes a deliberately simpler route. Instead of a single bidirectional converter, two commercially available stages are combined: a battery-fed inverter for the DC→AC direction and a mains-fed SMPS charger for the AC→DC direction. An ESP32 microcontroller decides which path is active from measured and sensed conditions. The aim is not to compete with research-grade interlinking converters but to give students a transparent, safe and inexpensive platform on which the ideas of source selection, storage, power conversion and monitoring can be seen working.

The main contributions are: (i) a complete hardware architecture for two-direction energy transfer built from off-the-shelf modules; (ii) a state-based, break-before-make control scheme implemented on the ESP32; (iii) a calibration procedure for isolated voltage and current sensing; and (iv) test evidence for each subsystem and for the integrated changeover sequence.

II. Related Work

Several surveys frame the field in which this prototype sits. Saponara et al. discuss how renewable sources, battery storage and bidirectional converters can be combined in hybrid micro-grids, and the same ideas underpin the power-transfer concept used here [7]. Khan et al. review interlinking converters, control strategies and protection schemes for hybrid AC/DC microgrids and show how converter control allocates power between buses according to load and generation [8]. A more recent systematic review by Fiuza and Oliveira examines converter topologies, stability, efficiency, power sharing and hardware difficulties of interlinking converters [9].

On the control side, hierarchical schemes built on droop characteristics are the accepted route for sharing power among distributed units in both AC and DC microgrids [10], [11]. Rocabert et al. summarise how power converters are controlled in AC microgrids, including grid-forming and grid-following behaviour [12], and Meng et al. survey supervisory controllers and energy management systems [13]. Connecting an inverter to a live utility requires phase-locked synchronisation and anti-islanding protection [14]; this is a major reason the present prototype never parallels the two AC sources and uses

sequential switching instead.

The gap this paper targets is practical rather than theoretical. Most published systems assume expensive laboratory converters and real-time controllers. There are comparatively few documented, reproducible low-power setups that show AC→DC and DC→AC power paths working under one coordinated, easily understood controller. The prototype reported here fills that teaching niche.

III. System Architecture and Design

A. Overall Architecture

The prototype has an AC section and a DC section. The AC section contains the utility supply, voltage and current sensing, the relay-based source selector and the AC load. The DC section contains a PV panel with a PWM charge controller, a 12 V, 7 Ah sealed lead-acid battery, the SMPS charger and the inverter. The ESP32 sits above both sections as the monitoring and decision unit. Fig. 1 is reserved for the block diagram of the complete system.

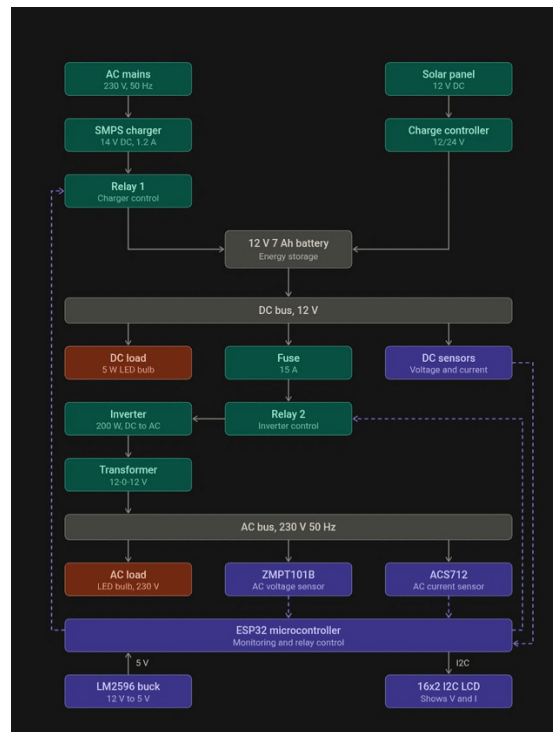


Fig. 1. Block diagram of the proposed hybrid AC/DC microgrid prototype.

B. Principle of Bidirectional Transfer

Two energy paths exist. In the AC→DC path, mains power feeds the SMPS charger, which delivers a regulated 14 V to the battery, so surplus utility energy is stored on the DC bus. In the DC→AC path, the battery supplies the inverter, whose output is stepped up by a 12-0-12 V / 230 V transformer to supply the AC load when the utility fails. The controller labels the first condition “AC→DC, mains available” and the second “DC→AC, backup mode”, and the label is shown on the LCD.

C. Battery and Conversion Choices

A 12 V, 7 Ah lead-acid battery was selected because it is inexpensive, tolerant of abuse and simple to charge; its usable energy is, however, lower than the nominal value because of depth-of-discharge limits and discharge-rate effects [15]. The inverter uses a push-pull style stage with a centre-tapped transformer, a topology whose operation and losses are standard textbook material [16]. Because the inverter is not synchronised to the grid, the two AC outputs must stay electrically separate, in line with accepted grid-connection practice [17].

D. Component Specifications

TABLE I
Principal components of the prototype

Component	Rating / type	Role
ESP32 DevKit V1	3.3 V logic, 12-bit ADC, Wi-Fi/BT	Controller
Lead-acid battery	12 V, 7 Ah	Energy storage
Inverter board	12 V DC in, 200 W	DC→AC conversion
Transformer	12-0-12 V / 230 V	Step-up, isolation
PWM charge controller	12/24 V, 10 A	PV charging
SMPS charger	230 V AC in, 14 V, 1.2 A out	AC→DC charging
ZMPT101B (×2)	Isolated AC voltage sensor	Grid & inverter voltage
ACS712-5A (×2)	Hall-effect, ≈185 mV/A	Grid & inverter current
Relay module	2-channel, 5 V, active-LOW	Source selection
LM2596 buck	Adjustable step-down	5 V control supply
16×2 I ² C LCD, buzzer	Status display, alerts	User interface
AC test load	9 W LED lamp	Load
Solar Panel	30W,12V	Converts sunlight into DC electrical energy for the microgrid.

IV. Hardware Implementation

A. Power Wiring

The PV panel feeds the PV terminals of the charge controller, and the battery is wired to the controller's battery terminals with correct polarity. The battery positive lead passes through a fuse and an isolating switch to the 12 V DC bus, from which the inverter is fed. The SMPS charger is connected to the battery through the switched charging path. The controller load terminals are not used to feed the AC load. The 5 V rail for the electronics comes from an LM2596 module that is adjusted and checked with a multimeter before the ESP32 is connected [21].

B. Sensing and Control Interface

Two ZMPT101B modules provide galvanically isolated voltage signals, one on the grid side and one on the inverter side. Two ACS712 sensors measure the corresponding currents. Because the ESP32 ADC accepts only low-voltage signals and shows non-linear behaviour that varies from chip to chip, readings are averaged over many samples and calibrated against a reference meter [18], [19]. An isolated AC-detection module gives a clean logic level for the presence of mains and is active-LOW: LOW means mains present, HIGH means mains absent. TABLE II lists the pin allocation.

TABLE II
ESP32 pin allocation

Function	GPIO	Function	GPIO
LCD SDA	21	Inverter ACS712	34
LCD SCL	22	Inverter ZMPT101B	35
Grid ACS712	32	AC detection	25
Grid ZMPT101B	33	Relay 1 (grid/charge)	26
Buzzer	18	Relay 2 (inverter)	27

C. Switching and Display

The two-channel relay module controls the grid/charging path (channel 1) and the inverter path (channel 2). Both channels are driven with active-LOW logic. The LCD alternates between a status screen (mode and mains availability) and a measurement screen (active source, voltage and current), which makes good use of the limited 16×2 character area. The buzzer sounds distinct patterns for start-up, mains failure, mains restoration and completion of changeover.

D. Assembly and Safety

The prototype was assembled in stages: battery and DC distribution, PV charging, charger, inverter and transformer, sensors, detection module, relays, LCD and buzzer, and finally software. Each stage was tested before the next was added. Since mains voltage is present, all AC wiring is insulated and enclosed, work is performed with the supply isolated, and the control board only ever receives low-voltage signals through isolation devices. The grid and inverter outputs are never connected together at any time.

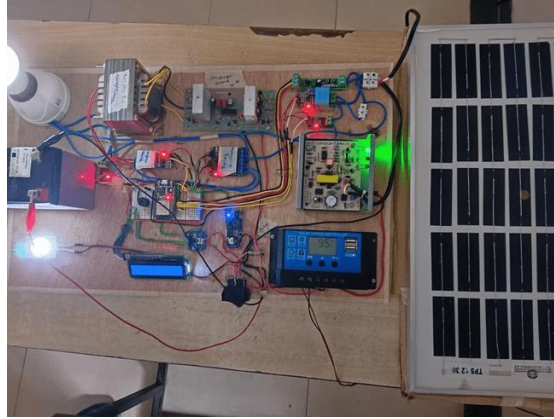


Fig. 2. Photograph of the assembled hybrid AC/DC microgrid prototype (hardware setup).

V. Control Algorithm and Mathematical Model

A. State-Based Control

The firmware is organised around five states: STARTING, MAINS_MODE, BACKUP_MODE, CHANGE_TO_BACKUP and CHANGE_TO_MAINS. After initialising the serial port, ADC, I²C bus, LCD, sensors, relays and buzzer, the ESP32 switches both relays OFF and reads the detection pin to choose its first mode. The loop then follows the rules below.

Rule 1: mains present → grid relay ON, inverter relay OFF; measure and display grid voltage and current.

Rule 2: mains lost → switch both relays OFF, wait 2 s, then switch the inverter relay ON; measure and display inverter values.

Rule 3: mains restored → switch both relays OFF, wait 2 s, then switch the grid relay ON.

Because both outputs are open during the 2 s interval, the break-before-make condition is satisfied. The interval also stops relays from chattering when the supply flickers.

B. Power and Energy Relations

For a resistive AC load the real power is

$$P = V_{rms} \times I_{rms} \times PF(1)$$

and the apparent power is $S = V_{rms} \times I_{rms}$. At the measured inverter operating point of 190 V and 0.09 A this gives $S = 190 \times 0.09 = 17.1$ VA. The nominal energy of the battery is

$$E = V \times Ah = 12 \times 7 = 84 \text{ Wh}(2)$$

and the inverter efficiency is defined as

$$\eta = (P_{AC} / P_{DC}) \times 100 \%(3)$$

The charging supply delivers $P = 14 \times 1.2 = 16.8$ W, so the theoretical time to recharge a 7 Ah battery at 1.2 A is

$$t_{ch} = C / I_{ch} = 7 / 1.2 \approx 5.83 \text{ h}(4)$$

which is an optimistic lower bound because charging current falls as the battery fills.

C. Sensor Processing

The ESP32 converts a raw 12-bit ADC count to volts using

$$V_{ADC} = (N / 4095) \times V_{ref}(5)$$

with $V_{ref} \approx 3.3$ V. For the ACS712, many samples are collected, their mean is taken as the zero-current level, and the RMS deviation is computed:

$$V_{rms} = \sqrt{\sum (V_i - V_{avg})^2 / n}(6)$$

$$I_{rms} = V_{rms} / 0.185(7)$$

Values below a small threshold are shown as zero so that noise does not appear as load current. For the ZMPT101B the software sensitivity is rescaled after comparison with a reference meter:

$$S_{new} = S_{old} \times V_{ref} / V_{meas}(8)$$

VI. Results and Discussion

A. Subsystem Tests

Each block was verified on its own before integration. The DC bus supplied the correct voltage to the inverter and, through the LM2596 module, a stable 5 V to the control electronics. The PV charging section behaved correctly with sunlight available, although charging current followed irradiance. The SMPS charger gave an output close to 14 V. The inverter and transformer supplied the AC test load in stand-alone mode, and the output varied with battery voltage and load, as expected. Both relay channels followed ESP32 commands, and the LCD and buzzer responded as programmed.

B. Hardware Connections

The ESP32 wiring used for sensing, switching and display is shown in Fig. 3, which corresponds to the pin map in TABLE II.

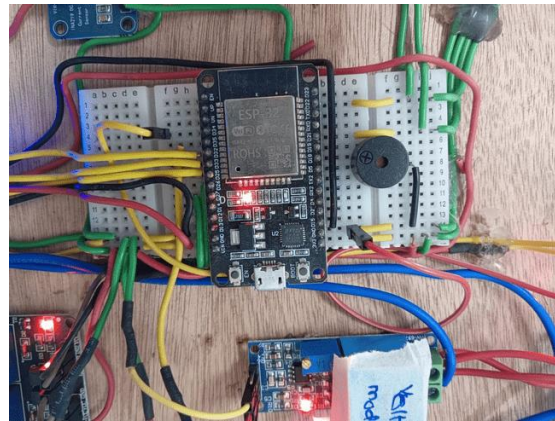


Fig. 3. ESP32 connection diagram showing sensors, relay module, LCD and AC-detection interface.

C. Bidirectional Power Flow

Fig. 4 shows the hybrid microgrid arrangement and the two directions of power flow, and Fig. 5 shows the AC-to-DC and DC-to-AC conversion paths. With mains available, power flows from the AC bus through the SMPS charger to the battery (AC→DC). When the mains fails, power flows from the battery through the inverter and transformer to the AC load (DC→AC), so the load continues without interruption beyond the changeover interval.



Fig. 4. LCD display photographs: (a) AC→DC mains-available screen; (b) DC→AC backup-mode screen.

D. Sensor Calibration

On the grid side the reference meter read about 257 V whereas the uncalibrated ZMPT101B indicated 229 V. Applying (8) with an initial sensitivity of 500 gave $500 \times 257 / 229 \approx 561$. On the inverter side the reference was about 190 V against an initial reading of 85 V; with an initial value of 271, (8) gave $271 \times 190 / 85 \approx 606$. The two sensors need different values because the inverter waveform is not the same as the sinusoidal grid waveform. These values are starting points and should be rechecked at stable battery voltage and load.

E. Changeover Performance

When the grid was removed, the detection output went HIGH, the ESP32 opened both relays, waited roughly 2 s and then closed the inverter relay; the LCD changed to “DC→AC / BACKUP MODE”. On restoration the same sequence ran in reverse and the load returned to the grid with the display showing “AC→DC / MAINS AVAILABLE”. Monitoring of the relay states showed that the two sources were separated during every transfer.

TABLE III summarises the outcomes.

TABLE III
Summary of test results

Test	Expected	Observed
Detector, grid ON	LOW	Detected
Detector, grid OFF	HIGH	Detected
Grid V (ref./raw)	257 V / 229 V	Sens. 500→561
Inverter V (ref./raw)	190 V / 85 V	Sens. 271→606
Apparent power	190 V × 0.09 A	17.1 VA
Changeover delay	≈2 s	≈2 s
Grid → inverter	Auto transfer	Successful
Inverter → grid	Auto transfer	Successful
LCD / relay / buzzer	Correct operation	Successful

F. Discussion

The results show that rule-based coordination of two ordinary conversion stages is enough to demonstrate bidirectional energy transfer at laboratory scale. The weakest part of the measurement chain is the sensing: the ZMPT101B depends strongly on calibration and waveform quality, and the ACS712 carries a zero offset and noise that call for sampling and thresholding. Theoretical figures such as 84 Wh of stored energy and a 5.83 h charge time should be read as reference values, since battery condition, inverter losses, transformer losses and power factor all reduce practical performance.

VII. Limitations

The prototype is a teaching device and should not be treated as a commercial transfer switch. Power transfer is sequential and not simultaneous or controlled continuously; there is no closed-loop current or voltage control, no grid synchronisation and no state-of-charge estimation. Relay operating time and contact ratings limit the load that can be handled, inverter output voltage drops as the battery discharges, and solar charging depends on weather. These limits are consistent with the low-power, low-cost design aim.

VIII. Conclusion and Future Scope

A low-cost hybrid AC/DC microgrid prototype was designed, built and tested in which an inverter and an SMPS charger provide the DC→AC and

AC→DC directions of energy flow, coordinated by an ESP32. The controller detected grid loss and recovery reliably, executed a break-before-make changeover of about 2 s in both directions, and presented the operating mode and electrical measurements on an LCD. Calibration of the voltage sensors against a reference meter was essential for meaningful readings.

Future work includes replacing the two separate stages with a true bidirectional interlinking converter under closed-loop control and grid synchronisation [8], [9], adding MPPT in place of the PWM controller [22], battery state-of-charge estimation, load prioritisation, Wi-Fi telemetry with data logging, stronger protection functions, and higher-power semiconductor stages. Intelligent energy management using forecasting of solar output and load demand could then be layered on top [13].

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