A Sub-Two-Second Automatic Transfer Switch for Hybrid PV–Grid Systems Using Arduino Uno and ZMPT101B Voltage Sensing

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Abstract— **A solar photovoltaic (PV) generator converts sunlight into useful electrical energy and operates most effectively when paired with a controller capable of automatically connecting and disconnecting it from the load. A common limitation in existing PV–grid switching systems is the relatively long transition delay between the utility supply and the PV source. To address this issue, the present work develops an Arduino Uno-based automatic transfer controller that performs source switching according to the measured PV output voltage. Two transfer scenarios were evaluated: from grid (PLN) to PV (PLTS) and the reverse direction, with the threshold for activating PV set at 10 V. The acceptable transition delay was specified as no greater than five seconds to prevent voltage spikes that may damage the connected load. Experimental results across ten trials showed an average transfer time of 1.6 s for the PLN-to-PLTS transition and 1.8 s for the reverse transition. Both values comply with the design target, indicating that the proposed controller offers a fast, reliable, and low-cost approach to managing hybrid PV–grid operation.**

Keywords— Arduino Uno; automatic transfer switch; hybrid PV–grid; solar power plant; voltage sensor.

I. Introduction

Reliable access to electrical energy underpins virtually every aspect of contemporary economic and household activity, and the trajectory of demand in Indonesia continues to climb steadily as urbanization and industrial expansion proceed. The country's electricity supply is still dominated by fossil-based generation, which exposes the system to fuel-price volatility, supply-chain risk, and the long-term liability of carbon emissions. Indonesia's National Energy Plan responds to these pressures by targeting up to 443 GW of renewable capacity by 2050, with solar photovoltaic (PV) earmarked as the principal contributor considering the country's abundant equatorial irradiance [1]. Recent techno-economic studies further confirm that, under the latest feed-in-tariff regime, utility-scale PV deployment in Indonesia is approaching financial viability and is expected to constitute a primary lever in the national energy transition [2].

Power electronics has long been recognized as the enabling technology that allows intermittent renewable resources to be integrated into existing networks without compromising service quality [3]. Within that broader context, distributed PV generation offers a particularly attractive pathway for residential and small-commercial consumers, since it converts incident sunlight directly into direct-current electricity through the photovoltaic effect, requires minimal maintenance, and scales gracefully from kilowatt-class rooftops to multi-megawatt arrays [4]. However, the instantaneous output of any PV array fluctuates with irradiance, ambient temperature, and cloud cover, making standalone PV operation unsuitable for loads that demand continuous service. Hybrid configurations that combine a PV source with the utility grid (in Indonesia, the PLN network) have therefore emerged as the dominant practical solution: solar energy is harvested whenever available, and the grid takes over during low-irradiance periods or at night [5].

The reliability of such a hybrid system hinges on its automatic transfer switch (ATS), which is responsible for selecting the active source according to PV availability and for executing the source change without exposing the load to voltage transients. Numerous reviews of grid-connected PV systems have identified power-quality preservation, voltage stability, and source-transition reliability as the central technical concerns that an effective interface controller must address [6]. Conventional ATS designs based on bulky electromechanical contactors are well established but tend to be costly, prone to mechanical wear, and slow in their response. Recent work has therefore turned to microcontroller-driven implementations: Chowdhury et al. demonstrated that an Arduino-based ATS combining a PV array and a standby generator can replace contactor logic at a fraction of the cost while still maintaining sub-second response times [7], and Prastya and Purwahyudi reported a comparable Arduino Uno prototype that transfers a domestic load between PLN and a small PV–battery system upon outage detection, although their study did not quantify the bidirectional transfer time in detail [8].

Despite this progress, two gaps persist in literature. First, most reported designs target grid-to-generator switching rather than the bidirectional grid-to-PV transition, leaving the PV-to-grid direction comparatively unexplored. Second, although the ZMPT101B AC voltage sensor has become a popular sensing element in low-cost energy projects, its measurement performance under field-like conditions is rarely characterized inside an ATS context, even though prior calibration studies have shown that with appropriate scaling its error remains below 2.5% across the 50–250 V AC range [9].

The present study addresses both gaps through the design, construction, and experimental evaluation of a low-cost ATS controller for hybrid PV–grid operation, built around an Arduino Uno microcontroller and a pair of ZMPT101B voltage sensors. The controller continuously monitors the inverter output voltage on the PV side and toggles a pair of relays whenever the measured value crosses a programmable threshold. The contributions of this work are threefold: (i) a compact hardware-software architecture that performs automatic dual-source switching with a minimum component count; (ii) experimental characterization of the transfer delay in *both* transition directions across ten trials each; and (iii) verification that the achieved delays comfortably satisfy the 5-second safety guideline established for transfer operations, together with a quantitative assessment of the on-board voltage-sensing accuracy.

II. Literature Review

A. Solar Photovoltaic Generation and Hybrid Operation

A photovoltaic cell exploits the photovoltaic effect to convert incident photons into a flow of charge carriers across a doped semiconductor junction. In the most common silicon-based architecture, p-type and n-type regions are joined to form an internal electric field that separates photo-generated electron-hole pairs and drives a usable current through an external load [4]. The instantaneous output of a PV module therefore depends on solar irradiance, ambient temperature, panel tilt, and the spectral content of incident light. Because each of these factors fluctuate, isolated PV operation is rarely sufficient for critical loads; pairing the array with a complementary source, most commonly the utility grid or a battery bank, has become standard practice in residential and small-commercial deployments [5].

Comprehensive reviews of inverter topologies for grid-connected PV systems have shown that the dynamic behavior of the inverter following a sudden change at its DC input is one of the principal determinants of source-transition quality [6]. In particular, when the PV-side voltage is removed, residual energy stored in the inverter and in any buffering, capacitance produces a finite decay window during which the inverter output remains non-zero. This phenomenon is directly relevant to the reverse transition (PV-to-grid) examined in this work, since it places a lower bound on the time required for the controller to register a clear under-threshold reading.

B. Arduino Uno Microcontroller and Software Environment

The Arduino Uno is an open-source development board built around the ATmega328P microcontroller. It provides 14 digital input/output pins (six of which support PWM), six analog inputs, a 16 MHz clock, 32 KB of flash memory, and convenient USB-based programming. Code is developed in a C/C++ derivative through the Arduino Integrated Development Environment, which integrates editing, compilation, and serial-monitoring utilities. The combination of accessible programming workflow, sufficient I/O density for typical control tasks, and an extensive community-maintained library ecosystem has made the Uno a frequent choice for prototype work in power electronics, instrumentation, and renewable-energy applications [7].

C. AC Voltage Sensing with the ZMPT101B Module

Sensing the AC voltage on each side of an ATS is the prerequisite for any threshold-based switching decision. The ZMPT101B is a precision AC voltage sensor based on a small step-down current transformer paired with an operational-amplifier conditioning stage. It accepts up to 250 V AC at its primary side and produces a microcontroller-compatible analog output, with a quoted linearity better than 0.2% across the 20%–120% input range. Because each module's on-board trim potentiometer is set during assembly, inter-device variation is significant, and per-unit calibration is therefore necessary for accurate measurement. Abubakar et al. demonstrated that, with a third-order polynomial calibration applied to the raw ADC output, measurement errors below 1% (peak-to-peak method) and 2.5% (instantaneous RMS method) can be achieved across the utility-voltage range [9]. These figures are sufficient for the threshold-comparison logic adopted in the present work, since the trip point of 10 V lies far from the sensor's noise floor.

D. Switching Components and Standby Power Provision

Electromechanical relays remain the dominant choice for small-scale ATS implementations because they provide galvanic isolation, accept low-current control signals from a microcontroller pin, and can switch the high currents typical of residential loads. A relay's energized coil actuates a mechanical contact, allowing a 5 V control output from the Arduino to gate a 220 V AC load circuit [7] [8]. To prevent any momentary supply interruption from reaching the load during the brief transition window, a small uninterruptible power supply (UPS) is incorporated in series with the controller; this practice is widely adopted in microcontroller-based dual-source designs and has been shown to suppress voltage dips that would otherwise propagate to sensitive loads.

Related Work on Automatic Transfer Switches

Automatic transfer switching for backup generation has been studied extensively. PLC-based ATS panels with Android-based remote monitoring have demonstrated that a transfer interval of no more than five seconds is the de facto safety guideline beyond which voltage transients become liable to damage downstream equipment. A growing body of work has subsequently shifted to lower-cost microcontroller realizations: Patil et al. proposed an Arduino-based ATS combining PV with a standby generator and reported sub-second switching transients [7], while Prastya and Purwahyudi developed an Arduino Uno prototype dedicated to PLN–PLTS transfer for residential use [8]. Both studies established the feasibility of solid-state-driven relay logic for dual-source operation but stopped short of a quantitative bidirectional characterization. Source-priority strategies in PV–battery–grid microgrids have also been formalized through hierarchical control schemes; threshold-based switching of the kind adopted here represents the simplest practical realization of such a scheme and provides a baseline against which more sophisticated controllers can be benchmarked [10]. IoT-enabled extensions of Arduino-class platforms, such as the cellular-connected solar-home monitor reported by López-Vargas et al., further illustrate how an ATS controller can be augmented with remote diagnostic and energy-accounting capabilities once the basic switching layer is reliable [11]. The present study contributes to this trajectory by characterizing the transfer time in both directions and by reporting the on-board voltage-sensing accuracy in the same experimental campaign, thereby enabling fair comparison with future implementations.

III. Research Methodology

A. Hardware Components

The components used in the prototype include a polycrystalline solar panel, a PWM solar charge controller, a 12 V VRLA battery, an inverter, an Arduino Uno R3, a ZMPT101B AC voltage sensor, two 5 V relay modules, miniature circuit breakers, an LCD 16×2 display, and a small UPS. A 20 W LED lamp rated at 220 V AC was used as the test load, chosen for its representative profile of typical residential lighting.

B. System Design

Figure 1 illustrates the overall wiring of the prototype. The PV array charges a 12 V battery through a PWM charge controller, and the battery feeds an inverter that produces 220 V AC on the PV side. The grid line provides an alternative 220 V AC supply. Two ZMPT101B sensors monitor the PV-side and grid-side AC voltages and feed analog signals into the Arduino Uno, which executes the switching algorithm and drives two relays that, in turn, connect the active source to the load. An LCD module displays the measured voltages in real time, while the

UPS supplies the controller during the brief transition window.

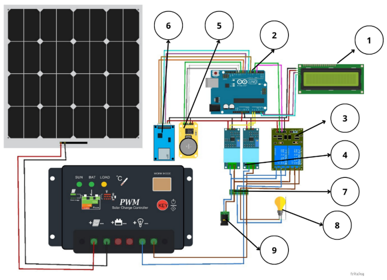

Figure 1. Wiring schematic of the proposed Arduino-based hybrid PV–grid ATS

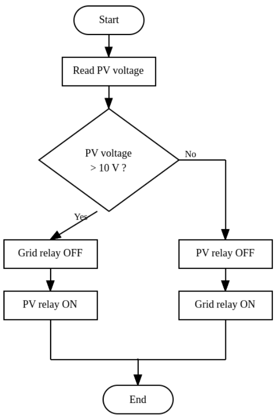

Figure 2. Flowchart of the switching logic executed by the Arduino Uno

The switching strategy is summarized in Figure 2. After initialization, the controller continuously samples the PV-side voltage. If the measured value exceeds the 10 V threshold, the grid relay is opened and the PV relay is closed, supplying the load from the inverter. If the PV voltage falls below the threshold, the polarity of the relays is reversed, and the load is fed from the grid. The 10 V threshold was chosen because it lies safely above the inverter low-input cutoff while still permitting operation under partial irradiance.

C. Testing Procedure

Five categories of tests were carried out: (i) relay actuation under increasing PV voltage (9, 9.5, 10, 10.5, and 11 V); (ii) transfer-time measurement from grid to PV; (iii) transfer-time measurement from PV to grid; (iv) accuracy assessment of the grid-side voltage sensor; and (v) accuracy assessment of the PV-side voltage sensor. For tests (ii) and (iii), the transition was triggered ten times and the elapsed time logged at one-second resolution. For tests (iv) and (v), sensor readings were compared against a calibrated digital voltmeter at ten input levels, and the percentage error was computed for each measurement.

IV. Result and Discussion

A. Prototype Implementation

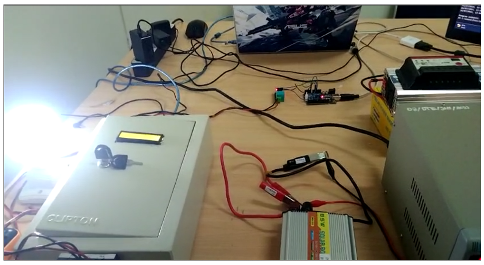

Figure 3. Photograph of the assembled prototype

Figure 3 shows the final prototype mounted in a metal enclosure. During preliminary tests the PV input was emulated using a regulated DC power supply, with its output limited to 15 V to remain within the inverter's permissible input window. This arrangement allowed reproducible voltage sweeps that would otherwise be impractical under naturally varying irradiance.

B. Relay Switching Behavior

Table 1 summarizes the relay actuation results. The relays remained in the open state for input voltages of 9 V and 9.5 V and closed at 10 V and above, in agreement with the programmed threshold. The transition from open to closed occurred sharply, with no observable chattering, confirming that the analog-to-digital comparison and relay-driver section of the controller behave deterministically near the trip point.

Table 1. Relay actuation results

Sensor Voltage (V)	Programmed Criterion	Observed Relay State
9	Off	Off
9.5	Off	Off
10	On	On
10.5	On	On
11	On	On

C. Grid-to-PV Transfer Time

T When the PV input voltage was raised across the 10 V trip point, the system reliably disconnected the grid and engaged the inverter. Across ten trials, the mean transition time was 1.6 s with a maximum of 3 s, as listed in Table 2. All measured values fall well within the 5-second guideline reported in [12] for safe transfer operation, indicating that the controller introduces no unsafe delay between sources.

Table 2. Measured transfer time from grid (PLN) to PV (PLTS)

No.	PLN Time	PLTS Time	Δt (s)
1	13:33:32	13:33:33	1
2	13:33:59	13:34:00	1
3	13:51:11	13:51:14	3
4	14:49:28	14:49:29	1
5	14:50:01	14:50:03	2
6	14:50:57	14:50:58	1
7	14:51:51	14:51:53	2
8	14:53:18	14:53:19	1
9	14:54:33	14:54:35	2
10	14:56:00	14:56:02	2
Mean	-	-	1.6

D. PV-to-Grid Transfer Time

The reverse transition was then triggered by lowering the PV-side voltage below the trip point. As reported in Table 3, the average transfer time was 1.8 s, again with a maximum of 3 s. The slightly longer mean compared with the grid-to-PV direction is plausibly attributed to the additional decay time of the inverter output when the input is removed and to the residual energy stored in the UPS, both of which extend the moment at which the controller registers a clear under-threshold reading.

Table 3. Measured transfer time from PV (PLTS) to grid (PLN)

No.	PLTS Time	PLN Time	Δt (s)
1	13:33:38	13:33:40	2
2	13:53:10	13:53:12	2
3	14:49:41	14:49:42	1
4	14:49:53	14:49:54	1
5	14:53:37	14:53:38	1
6	14:53:44	14:53:46	2
7	14:55:22	14:55:24	2
8	14:55:35	14:55:38	3
9	14:56:24	14:56:27	3
10	14:57:06	14:57:07	1
Mean	-	-	1.8

E. Voltage Sensor Accuracy

The two ZMPT101B sensors were calibrated against a digital voltmeter (Vizard DT9205A) over ten input levels each. The grid-side sensor produced a mean absolute error of 2.82%, while the PV-side sensor exhibited a slightly higher mean error of 4.05%. Both figures are acceptable for the threshold-comparison logic adopted here, since the trip point of 10 V lies far from either sensor's noise floor or the relay action is therefore robust against modest measurement bias. Discrepancies between the sensor and the reference voltmeter are likely to be due to a combination of operator error in reading the analog voltmeter and the limited absolute accuracy of the reference instrument used.

Table 4. Summary of voltage sensor accuracy (mean over 10 readings)

Sensor location	Mean error (%)	Max error (%)
Grid (PLN) side	2.82	5.52
PV (PLTS) side	4.05	5.99

F. Discussion

The combined results confirm that the proposed controller meets all design objectives. Relay actuation occurs precisely at the programmed threshold; the average transition delay is far below the 5-second safety guideline; and the voltage sensors operate with errors small enough not to interfere with the trip decision. The controller can support loads of up to 2,200 VA, which is sufficient for typical residential needs. Practical limitations of the present prototype include the use of a power supply to emulate the PV inverter and the absence of long-term reliability data; both will be addressed in subsequent field deployments. Further work will explore extending the design with current sensing for power-flow logging, integrating an IoT module for remote monitoring, and investigating alternative source-prioritization rules that account for state-of-charge of an attached battery bank.

V. Conclusion

This study has presented an Arduino Uno-based automatic transfer switch for hybrid PV–grid operation, integrating a pair of ZMPT101B voltage sensors, two electromechanical relays, and a small UPS to manage residential-scale loads up to 2,200 VA. Across ten trials in each direction, the controller achieved mean transfer times of 1.6 s for grid-to-PV and 1.8 s for the reverse transition, both well within the 5-second safety guideline. The voltage sensors recorded mean errors of 2.82% and 4.05% on the grid and PV sides respectively, which proved adequate for threshold-based switching at the 10 V trip point.

These results confirm that an Arduino-class microcontroller paired with calibrated AC voltage sensors offers a practical and economical solution for dual-source switching. Future work will focus on field trials with an actual PV array, the addition of current sensing for power-flow logging, and IoT-based remote supervision.

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