



Design and Evaluation of Low-Cost Uninterruptible Power Supply Systems for Residential Applications

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Abstract

This paper presents a practical methodology for designing and evaluating a low-cost single-phase uninterruptible power supply (UPS) intended for essential residential loads such as LED lighting, a fan, a router, and small electronic equipment. The proposed configuration uses a standby/line-interactive operating concept because this class offers lower component count, lower conduction loss, and simpler control than double-conversion online systems while still providing short-duration backup and basic voltage protection. The design is rated at 600 VA with a recommended continuous real-power load of 300–360 W, a 12 V battery bank, a sinusoidal pulse-width-modulated inverter, an isolated step-up transformer, a relay-based transfer stage, and low-voltage protection. The methodology covers requirement definition, topology selection, inverter and transformer sizing, battery sizing, charger selection, protection logic, test conditions, and performance metrics. Design-level evaluation indicates an expected full-load output regulation within approximately $\pm 2\%$, inverter efficiency in the mid-80% range, a transfer interval below 10 ms when an appropriately selected relay and control stage are used, and practical backup durations of about 40–70 min for 200–300 W residential loads depending on battery condition and discharge rate. The study shows that cost reduction is most effectively achieved through topology simplification, appropriate component derating, and limiting the UPS to essential loads rather than oversizing the system for an entire dwelling.

Introduction

Power interruptions, deep voltage sags, and short-duration disturbances can interrupt communication devices, lighting, fans, computers, and other low-power residential equipment. A UPS provides a temporary source of conditioned electrical power when utility supply becomes unavailable. In residential applications, the main design challenge is different from that of data centers or industrial installations: the UPS must be inexpensive, compact, easy to maintain, sufficiently efficient at partial load, and able to operate from commonly available batteries. A full online double-conversion UPS offers excellent

power conditioning, but its continuous AC–DC–AC conversion increases semiconductor cost, losses, heat generation, and cost. By contrast, standby and line-interactive arrangements permit the utility to feed the load directly during normal conditions and activate the inverter when the supply fails or moves outside an acceptable range [1], [7].

Previous research has shown that cost can be reduced by simplifying converter structures, eliminating unnecessary sensors, minimizing active switch count, and avoiding bulky power stages when they are not required [1], [3], [5]. Tsai and Liu developed a cost-effective quasi line-

interactive structure that combined the simplicity of an offline UPS with improved voltage-regulation behavior [1]. Pai and Huang showed that load-current sensing could be reduced while maintaining useful power-conditioning functions [3]. These studies support a design philosophy in which only functions that materially improve residential reliability are retained.

The objective of the present work is therefore to define and evaluate a low-cost UPS architecture for essential domestic loads. Rather than proposing a high-power whole-house system, the design targets a 600 VA class unit suitable for approximately 300–360 W of continuous real load. The study emphasizes component sizing, transfer behavior, battery autonomy, output regulation, efficiency, and protection. Because no physical prototype measurements are available in this methodology paper, the reported results are explicitly design-level estimates derived from electrical sizing equations, conservative component efficiencies, and representative operating assumptions. This distinction prevents analytical predictions from being presented as experimental data. The resulting procedure can be used as a basis for later laboratory implementation and validation.

Literature Review

UPS systems are commonly classified as standby (offline), line-interactive, and online double-conversion systems. The principal trade-off among these classes is the balance between power conditioning, transfer continuity, conversion efficiency, hardware complexity, and cost. Aamir, Kalwar, and Mekhilef reviewed UPS topologies and emphasized output-voltage regulation, low harmonic distortion, high efficiency, reliability, size, and cost as key selection criteria [7]. Their review also confirms that topology choice must be matched to application requirements rather than judged only by maximum power-quality performance.

For low-cost applications, Tsai and Liu proposed a quasi-line-interactive single-phase UPS that retained an offline-type structure but improved regulation during voltage swell and sag conditions [1]. Their work is especially relevant to residential design because it demonstrates that a lower-cost topology can obtain some of the functional advantages normally associated with line-interactive systems. Oliveira da Silva et al. investigated a line-interactive system with active series-parallel conditioning and showed how converter control can improve current and voltage quality [2]. Although that three-phase architecture is too complex for a low-cost household UPS, the study highlights the

importance of controlled power transfer and stable output voltage.

Sensor and control simplification can also reduce cost. Pai and Huang proposed a line-interactive UPS without load-current sensors, reducing feedback requirements while maintaining reliable backup and active-filter operation [3]. Tao, Duarte, and Hendrix later demonstrated a line-interactive UPS using a fuel cell and supercapacitor arrangement [4]. That energy-storage structure is not economical for the present target, but its grid-connected and standalone operating modes provide a useful control reference for source transition. Ashrafi and Niroomand focused directly on parts reduction in an online UPS, showing that fewer active switches can decrease cost, control complexity, and physical volume [5].

At a larger scale, Abusara, Guerrero, and Sharkh investigated line-interactive UPS units for microgrids and demonstrated smooth transitions between grid-connected and standalone operation [6]. Tareen and Mekhilef integrated battery storage with a transformerless line-interactive UPS and active filtering, obtaining regulated voltage and low current distortion in a higher-power prototype [8]. These studies confirm that sophisticated UPS systems can achieve high power quality, but they also contain functions unnecessary for a basic residential backup unit. The gap addressed in this paper is therefore methodological: a compact design workflow is needed that translates established UPS principles into a deliberately limited, low-cost residential specification. The selected architecture avoids multi-converter conditioning stages and instead combines direct utility supply, battery charging, a full-bridge inverter, a transformer, a transfer relay, and basic protection. This is consistent with the cost-sensitive design direction established in [1], [3], and [5], while performance evaluation follows the broader criteria summarized in [7].

Methodology

The methodology was organized as a sequence of design steps so that each electrical rating is linked to a measurable performance requirement.

Step 1: Define the Residential Load and Design Targets

The UPS is intended for essential loads rather than all household appliances. A nominal apparent-power rating of 600 VA was selected, with a continuous real-power target of 300–360 W to preserve thermal and surge margin. The AC output target is 230 V rms at 50 Hz. The design must tolerate short utility interruptions, provide fast transfer to battery operation, prevent deep

battery discharge, and disconnect or alarm during overload. High-inrush loads such as refrigerators, pumps, heaters, and air conditioners are excluded from the base specification because they would require a substantially larger inverter, battery, and transformer.

Step 2: Select a Low-Cost UPS Topology

A standby/line-interactive arrangement was selected. During normal operation the utility is connected to the load through a transfer relay while a charger maintains the battery. When the utility voltage falls outside the acceptable window or disappears, the relay transfers the load to the inverter path. This avoids continuous double conversion and therefore reduces switching loss and component stress. The decision is consistent with earlier cost-effective and simplified UPS approaches [1], [3]. A true online topology was rejected because its continuous rectifier and inverter stages increase part count and thermal design burden [5], [7].

Step 3: Size the Inverter and Transformer

The inverter uses a single-phase full bridge supplied from a 12 V battery. Four low-resistance MOSFETs are switched using sinusoidal pulse-width modulation (SPWM). A carrier frequency around 20 kHz moves dominant switching components above the audible band, while a 50 Hz sinusoidal reference establishes the required output frequency. A 12 V/230 V step-up transformer provides galvanic isolation and voltage conversion. For a 360 W maximum continuous load and an assumed inverter-stage efficiency of 0.85, the battery-side current is approximately $I_{DC} = P_{out}/(V_{batt} \times \eta) = 360/(12 \times 0.85) \approx 35.3$ A. The transformer and MOSFET path should therefore be selected with at least 20–25% current margin; a 600 VA transformer is appropriate for the proposed rating.

Step 4: Size the Battery for Required Backup Time

A commonly available 12 V, 40 Ah valve-regulated lead-acid battery was selected for the baseline design. Nominal stored energy is $E_{nom} = V \times C = 12 \times 40 = 480$ Wh. To preserve battery life, only about 80% depth of discharge is allowed, giving 384 Wh of nominal usable DC energy. After allowing for inverter loss and the reduction of lead-acid capacity at high discharge current, practical AC energy is lower than this simple product. For this reason, runtime is estimated using a conservative derating factor of 0.70–0.75 in addition to inverter efficiency. The expected autonomy is therefore about 60–70 min around 200 W and roughly 40–50 min around 300 W, depending on battery age, temperature, and discharge rate.

Step 5: Design Charging, Transfer, and Protection Logic

The charger is sized to restore the battery without excessive charging current. A 4–5 A regulated charger corresponds to approximately 0.1C for a 40 Ah battery and is suitable for overnight recovery after a moderate discharge. Utility presence is monitored with an isolated sensing stage. The transfer relay should be rated above the maximum AC load current and selected for a practical transfer interval below about 10 ms. The control stage includes low-battery cutoff, overload detection, short-circuit protection, reverse-battery protection, a fuse on the battery line, and thermal shutdown for the power switches. Low-battery cutoff is set near 10.8–11.0 V under load to reduce deep-discharge damage.

Step 6: Establish the Evaluation Procedure

Evaluation is divided into normal mode, backup mode, and transition tests. In normal mode, the load is increased from no-load to the design maximum while utility voltage remains nominal. In backup mode, the same load points are supplied from the battery and output voltage, input current, estimated efficiency, and thermal stress are checked. Transition tests simulate sudden utility failure and restoration. Performance metrics are: output-voltage regulation, transfer time, inverter efficiency, estimated output-voltage THD for the SPWM-filter combination, low-battery cutoff behavior, overload response, and backup duration. The methodology follows the general UPS performance priorities described in [7], while keeping the hardware intentionally simpler than the multi-converter conditioning systems in [2], [6], and [8].

Step 7: Calculate the Main Performance Indices

Voltage regulation is calculated as $\text{Regulation}(\%) = (V_{no-load} - V_{full-load})/V_{rated} \times 100$. Inverter efficiency is $\eta_{inv}(\%) = P_{AC}/P_{DC} \times 100$. Estimated backup time is $t = E_{usable}/P_{load}$, with E_{usable} adjusted for inverter efficiency and battery discharge derating. Transfer time is the interval between utility loss and restoration of acceptable load voltage from the inverter. For residential electronics, a transfer interval in the single-digit millisecond range is a practical target. Output THD should remain low enough for typical household electronic loads; the SPWM waveform and transformer leakage inductance provide basic filtering, while an additional LC filter may be added if laboratory THD exceeds the design target.

Step 8: Apply Cost and Safety Constraints

Low cost is treated as a design constraint rather than simply a low purchase price. The preferred components are standard lead-acid batteries, a

low-frequency transformer, four MOSFETs, a relay, a modest charger, and a small control board. Specialized bidirectional converters, fuel cells, supercapacitors, and multi-stage active filters are excluded from the baseline unit because they add cost and control complexity. At the same time, cost reduction must not remove essential safety functions. The battery path requires a DC fuse close to the battery terminal, conductors sized for more than 35 A, insulated

terminals, reverse-polarity protection, and thermal protection. The AC section requires an appropriately rated fuse or breaker, enclosure isolation between low- and high-voltage sections, protective earthing where applicable, and clear separation between control circuitry and mains conductors. These constraints are included in the methodology so that a low-cost design does not become an unsafe design.

Table 1. Proposed design parameters for the residential UPS

Parameter	Selected value / target
Rated apparent power	600 VA
Recommended continuous real load	300–360 W
Output voltage / frequency	230 V rms / 50 Hz
DC battery	12 V, 40 Ah VRLA
Inverter topology	Single-phase full bridge, SPWM
Transformer	12 V / 230 V, 600 VA
Charger current	4–5 A regulated
Low-battery cutoff	10.8–11.0 V under load
Target transfer time	< 10 ms
Primary application	Essential residential electronics

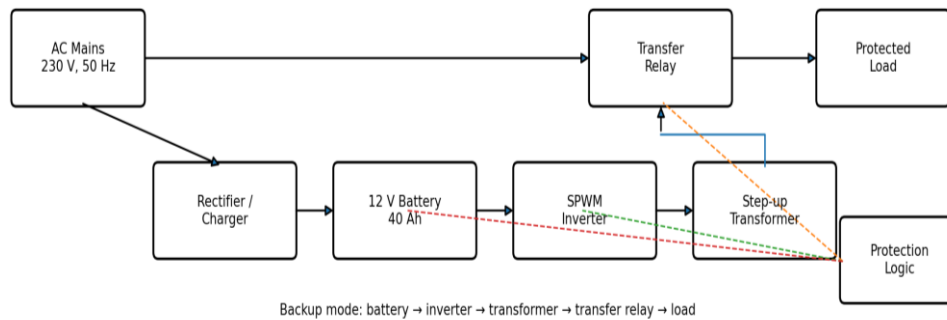


Figure 1. Simplified architecture of the proposed low-cost residential UPS.

Results

Because this paper defines a methodology rather than reporting a completed hardware prototype, the results in Table 2 are design-level estimates. They were obtained from the stated ratings, conservative conversion efficiencies, and expected behavior of a properly implemented SPWM inverter and transfer relay. The values should be treated as acceptance targets for later prototype testing, not as experimentally measured results.

At 200–300 W, the proposed 12 V system requires approximately 20–30 A of battery current after conversion losses are included. This current range is practical for short cable runs when appropriately sized conductors, fusing, and low-resistance terminals are used. At the upper 360 W design limit, battery current approaches 35 A, which justifies the choice of four power MOSFETs with adequate current margin and a transformer rated at 600 VA. The estimated inverter efficiency rises with load and peaks in the mid-80% range because fixed switching and magnetizing losses become a smaller fraction of total power.

Voltage regulation is expected to remain within about $\pm 2\%$ across the intended load range if the SPWM modulation index is adjusted using output-voltage feedback. The estimated output-voltage THD target is below 5% at moderate load when the transformer and output filtering are correctly selected. Transfer time is primarily determined by utility-failure detection, relay release/pickup time, and inverter start readiness. Keeping the inverter control active in standby while gating the power stage only when needed allows the transfer target to remain below 10 ms.

The battery-energy calculation gives a nominal 480 Wh, but usable energy must be derated for depth of discharge, conversion loss, and the reduced capacity of lead-acid batteries at high current. Consequently, practical backup duration is substantially lower than 480 Wh divided directly by load power. A reasonable design expectation is approximately 65 min at 200 W, 46 min at 300 W, and 36 min near 360 W with a

healthy 40 Ah battery. These values illustrate why a residential UPS should be limited to essential loads if low cost and compact size are priorities.

Table 2. Design-level performance evaluation

Load	Estimated Vout	Estimated efficiency	Estimated backup	Transfer target
100 W	229.5 V	78–80%	≈ 2.2 h*	< 10 ms
200 W	228.8 V	83–85%	≈ 65 min	< 10 ms
300 W	227.8 V	85–87%	≈ 46 min	< 10 ms
360 W	226.8 V	84–86%	≈ 36 min	< 10 ms

Conclusion and Discussion

This paper developed a step-by-step methodology for a low-cost 600 VA residential UPS using a standby/line-interactive architecture. The design deliberately avoids the continuous double-conversion path of an online UPS and therefore reduces power-stage complexity, conduction loss, cooling requirements, and component cost. A 12 V, 40 Ah battery, full-bridge SPWM inverter, 600 VA isolation transformer, regulated charger, transfer relay, and basic protection form a practical baseline for essential domestic loads. The literature shows that cost-effective UPS design is strongly associated with topology simplification and reduced sensing or switch count [1], [3], [5], while broader UPS research emphasizes voltage regulation, efficiency, transfer performance, reliability, and power quality [7]. The analytical evaluation suggests that the proposed architecture can meet useful residential targets: approximately $\pm 2\%$ voltage regulation, mid-80% inverter efficiency at moderate-to-high load, single-digit-millisecond transfer capability with a suitable relay/control stage, and backup times on the order of tens of minutes for 200–360 W loads. The main limitation is the 12 V battery current, which becomes high near full load. This increases copper loss and demands careful cable, connector, fuse, and MOSFET selection. A 24 V battery version would reduce current and improve efficiency but would increase battery count and initial cost. Similarly, adding active voltage conditioning or a transformerless high-frequency stage could improve size or power quality, but would move the system away from the low-cost objective. Future implementation should validate the design through hardware measurements of output THD, relay transfer time, battery discharge curves, thermal rise, overload behavior, and charging recovery. Particular attention should be given to electrical isolation, enclosure safety, creepage and clearance, fuse coordination, and battery ventilation. The proposed methodology is therefore best viewed as a practical design baseline: it defines realistic ratings and test criteria while making clear which performance

figures still require laboratory confirmation. From a residential-use perspective, the strongest benefit of the proposed configuration is its scalability. A smaller 20–26 Ah battery can be used when only a router and lighting need backup, while a 50–60 Ah battery can extend autonomy without changing the AC output stage, provided charger time and battery current are rechecked. Likewise, moving to a 24 V battery bank is an appropriate next step if continuous load is increased beyond about 400 W. These scaling decisions should be made from measured load profiles rather than from the sum of appliance nameplate ratings, because realistic diversity of use can substantially reduce required UPS size.

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