



Design and Analysis of a Low-Cost Uninterruptible Power Supply for Domestic Applications

Olamide Khatibullah

Department of Electrical and Computer Engineering, Siam Delta Engineering Institute, Thailand
 olamide.khatibullah@sdei-th.edu

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Abstract

Reliable domestic electricity is important for lighting, communication equipment, fans, routers, computers, and other low-power household loads. Commercial online uninterruptible power supplies (UPSs) offer excellent regulation but are often unnecessarily complex and expensive for homes where the main requirement is short-to-medium duration backup during supply interruptions. This paper presents a methodology for the design and analytical evaluation of a low-cost 600 VA domestic UPS based on an offline/line-interactive architecture. The proposed system uses a 12 V lead-acid battery, a four-switch MOSFET full-bridge inverter, a 12/230 V step-up transformer, sinusoidal pulse-width modulation (SPWM), a 10 A constant-current/constant-voltage charger, a mains-sensing transfer relay, and basic over-current, under-voltage, over-temperature, and short-circuit protection. Component ratings are derived from load power, battery current, transformer volt-ampere capacity, switching stress, and required backup time. An LC output filter is selected to attenuate the switching carrier while preserving the 50 Hz fundamental. Analytical results indicate that, for a 400 W design load, the battery-side current is approximately 38 A at 88% inverter efficiency, and a 12 V, 100 Ah battery can provide about 1.2–1.5 h of practical backup at high load or substantially longer at 200 W. The selected architecture emphasizes low component count, repairability, galvanic isolation through the transformer, and acceptable domestic power quality. The methodology provides a reproducible basis for constructing and testing a cost-conscious household UPS without claiming laboratory measurements that have not yet been performed.

Introduction

Uninterruptible power supplies are power-electronic systems that maintain continuity of supply when the utility source is interrupted or becomes unsuitable. UPS configurations are commonly grouped as passive-standby (offline), line-interactive, and double-conversion (online) systems, each providing a different compromise among cost, transfer time, regulation, efficiency, and component count [1], [2]. For hospitals, data centers, and critical industrial controllers, online conversion is often justified because it isolates

the load from many grid disturbances. For domestic applications, however, the dominant constraints are usually affordability, ease of repair, acceptable efficiency, low standby losses, and sufficient backup for a selected group of essential loads. These considerations motivate a deliberately simpler topology in which the utility feeds the load directly during normal operation, while a battery-fed inverter is activated only when the utility voltage falls outside an acceptable window.

Earlier work has shown that the inverter and output filter strongly influence UPS voltage quality. Multiple-feedback and repetitive-control approaches improve dynamic regulation and harmonic rejection but add sensing and control complexity [3], [4]. Predictive control can also produce low-distortion output from an LC-filtered inverter, although it requires a model-based digital controller and faster computation [5]. For a low-cost household unit, these advanced methods are valuable design references but are not always necessary. A practical alternative is fixed-frequency SPWM implemented with an inexpensive microcontroller, combined with dead-time control, an adequately sized transformer, and a simple LC filter. Transformerless UPS arrangements can reduce weight and conversion stages [6], yet a mains-frequency transformer remains attractive in a repair-oriented domestic product because it simultaneously provides voltage step-up and galvanic isolation.

Energy storage is another major cost and reliability factor. Battery/supercapacitor hybrid arrangements can reduce battery stress and improve transient response [7], but the additional converter, control, and storage cost works against the objective of a basic household UPS. Field-scale evidence also shows that widespread poorly designed domestic UPS use can increase network losses and harmonic burden, underlining the need for reasonable charging current, controlled transfer, and a well-shaped inverter output [8]. Reliability studies further emphasize that component stress, redundancy choices, and protection strategy affect availability [9]. Accordingly, the present methodology focuses on a modest 600 VA rating, a single 12 V battery, controlled charging, and conservative semiconductor and transformer derating.

The objectives are therefore to: define a realistic domestic load envelope; select a low-cost UPS architecture; calculate battery, semiconductor, transformer, and filter ratings; establish a charging and transfer-control strategy; define protection thresholds; and estimate expected output regulation, efficiency, transfer time, and backup duration. The design is intended for loads such as LED lighting, a ceiling fan, a Wi-Fi router, a laptop charger, and small electronics. High-inrush appliances such as refrigerators, pumps, heaters, irons, and air-conditioners are outside the proposed continuous-load envelope unless the inverter and transformer are substantially upgraded.

Literature Review

Bekiarov and Emadi [2] provided a widely cited classification of UPS systems and explained the operating behavior of standby, line-interactive, and online structures. Their framework remains useful because it links topology directly to performance requirements: a standby system minimizes conversion loss and cost but introduces a finite transfer interval, while online systems eliminate normal-mode transfer at the expense of continuous conversion losses and additional power stages. Aamir, Kalwar, and Mekhilef [1] later reviewed UPS circuit configurations and control techniques and highlighted the continuing design trade-off among power quality, efficiency, size, reliability, and price. These findings justify selecting an offline/line-interactive structure when low cost and domestic efficiency are prioritized over zero-transfer operation.

Control of the inverter has been studied extensively. Abdel-Rahim and Quaicoe [3] analyzed a multiple-feedback strategy for single-phase voltage-source UPS inverters with an LC filter, showing that inner current feedback and outer voltage regulation can produce stable sinusoidal output. Escobar et al. [4] developed a repetitive controller that compensates harmonic distortion and load unbalance, while Cortés et al. [5] demonstrated model predictive control for an inverter with an output LC filter. These methods establish the importance of regulating the output waveform under changing loads. Nevertheless, a low-cost domestic implementation can obtain acceptable performance with SPWM, transformer isolation, modest feedback, and adequate filtering, provided that the design does not attempt the same dynamic performance as a high-end online UPS.

Aamir and Kim [6] proposed a non-isolated single-phase UPS, illustrating how topology reduction can decrease power-processing stages and improve compactness. For a household design built around locally serviceable components, transformer isolation was retained despite its mass because it simplifies the 12 V-to-230 V conversion and reduces the risk of exposing the battery-side electronics directly to the mains potential. Lahyani et al. [7] investigated battery/supercapacitor combinations in UPS applications and showed that high-power transients can be shifted away from the battery. The present work does not adopt a supercapacitor bank because the targeted domestic loads and budget favor a single lead-acid storage element, but the study informs the

use of current limits and surge margins to reduce battery stress.

At the system level, Ahmad et al. [8] analyzed the effect of extensive domestic UPS deployment on a national power system and reported concerns associated with charging behavior and power quality. This is especially relevant to low-cost products, where uncontrolled rectifier charging can draw highly distorted current. The proposed charger therefore limits current and avoids unnecessarily high recharge power. Rahmat, Karim, and Salleh [9] examined sensitivity of AC UPS reliability, reinforcing the importance of reliable switching and component selection. The literature collectively supports a design philosophy that does not minimize cost by simply reducing ratings; rather, it minimizes unnecessary stages while retaining protection, derating, isolation, and controlled charging.

Methodology

1. Design requirements and topology selection

The design begins by defining a nominal output of 230 V rms, 50 Hz, with a 600 VA apparent-power rating and a recommended continuous real-power limit of 400 W. The 600 VA rating gives margin for common domestic loads whose power factor is below unity. The preferred topology is offline/line-interactive: utility power is passed to the load through a transfer relay during normal conditions, while a charger maintains the 12 V battery. When the mains voltage is lost or moves outside a 180–260 V acceptance window, the controller disables charging, starts the inverter, verifies an acceptable inverter output, and transfers the load. On utility restoration, the sequence is reversed after a short validation delay to prevent chatter.

Table 1. Proposed design specifications for the low-cost domestic UPS.

Parameter	Selected value	Design reason
Rated output	600 VA / 400 W recommended	Covers essential domestic loads with surge margin
AC output	230 V rms, 50 Hz	Domestic single-phase supply standard
Battery	12 V, 100 Ah lead-acid	Low cost, wide availability, simple charging
Inverter	4-MOSFET full bridge, 20 kHz SPWM	Low switch count and sinusoidal fundamental
Transformer	12-0-12/230 V, 600 VA	Voltage step-up plus galvanic isolation
Charger	10 A CC/CV, 14.4 V absorption, 13.7 V float	Reasonable charge time and battery life
Transfer target	< 12 ms	Acceptable for many domestic electronic loads
Protections	OC, SC, UV, OT, surge	Improves safety and reliability

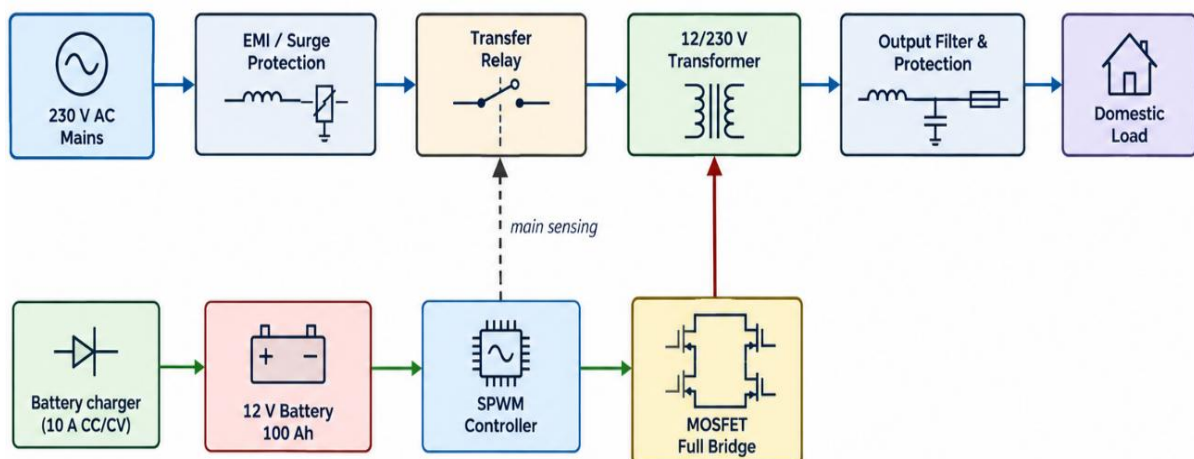


Figure 1. Functional block diagram of the proposed low-cost domestic UPS.

2. Battery and inverter sizing

The battery-side current is determined from the required AC power and expected inverter efficiency. For an output power P_o , battery voltage V_b , and inverter efficiency η , the approximate DC current is $I_b = P_o/(V_b\eta)$. At $P_o = 400$ W, $V_b = 12$ V, and $\eta = 0.88$, $I_b \approx 37.9$ A. A design current of at least 50 A is therefore used for wiring, fuse selection, transformer low-voltage windings, and normal semiconductor conduction. Because motor and capacitive loads can momentarily demand substantially higher current, each MOSFET should have a low on-resistance and a continuous current rating comfortably above the steady-state requirement; a practical design rule is to select devices with at least 75–100 A current capability at an adequate voltage margin, while recognizing that the heat-sink and PCB copper, not the headline device rating alone, determine usable current.

Nominal stored energy of the 12 V, 100 Ah battery is 1.2 kWh. Lead-acid batteries should not be treated as ideal 1.2 kWh sources because available capacity falls at high discharge current and deep discharge shortens life. For first-pass sizing, usable AC energy can be approximated as $E_{ac} = V_b C_b \text{DOD} \eta$, where C_b is ampere-hour capacity and DOD is an allowable depth-of-discharge factor. With DOD = 0.70 and $\eta = 0.88$, $E_{ac} \approx 739$ Wh. The idealized backup time is therefore $739/P_o$ hours; at 200 W it is about 3.7 h and at 400 W about 1.85 h. To account for Peukert effect, wiring loss, aging, and conservative low-voltage cutoff, practical targets of approximately 2.5–3.1 h at 200 W and 1.2–1.5 h at 400 W are more realistic.

3. SPWM generation, transformer and filter

A low-cost microcontroller generates a 50 Hz sinusoidal reference compared with a 20 kHz triangular carrier to produce bipolar or unipolar SPWM gate commands. Complementary switch pairs are separated by dead time to prevent shoot-through. The full bridge applies a high-frequency pulse train of alternating polarity to the 12 V transformer winding; the transformer steps the voltage to the 230 V level while providing isolation. The transformer VA rating is selected at 600 VA rather than 400 VA so that copper heating and transient voltage drop remain acceptable. Low-voltage conductors must be short and thick because a 0.02Ω path would dissipate nearly 29 W at 38 A.

An LC low-pass filter is placed at the transformer secondary/output stage to reduce switching ripple. A practical starting pair is $L = 2.2$ mH and

$C = 2.2 \mu\text{F}$, giving an approximate corner frequency $f_c = 1/(2\pi\sqrt{LC}) \approx 2.29$ kHz. This is far above the 50 Hz fundamental but well below the 20 kHz carrier, allowing substantial attenuation of the switching component. The final inductor current rating and capacitor voltage rating must exceed full-load conditions, and damping may be added if resonance is observed during prototype testing. Output-voltage feedback can adjust the modulation index slowly to compensate battery sag and transformer regulation.

4. Charger, transfer logic and protection

The charger is designed for approximately 10 A, equivalent to a 0.1C charge rate for a 100 Ah battery. A constant-current phase is followed by a constant-voltage absorption stage near 14.4 V, then a float stage around 13.6–13.8 V. Battery temperature compensation is recommended for a final product. The transfer relay must be rated for the full AC load current and selected for sufficiently fast operation; total interruption includes mains-detection time, controller decision time, relay movement, and inverter build-up. A target below 12 ms is used because many switch-mode power supplies can ride through a short interruption, though exact compatibility must be verified.

Protection is incorporated at both DC and AC sides. A battery fuse of roughly 50–60 A is placed close to the positive terminal; over-current sensing shuts down PWM during sustained overload or short circuit; battery under-voltage cutoff is placed near 10.5–11.0 V under load to prevent excessive discharge; heat-sink temperature is monitored to reduce load or shut down near the thermal limit; and the mains input includes a fuse, surge suppressor, and basic EMI filtering. Restart after a fault is delayed and limited to prevent repeated stress. These features are intentionally retained even in a low-cost design because omitting protection shifts cost from components to failures.

5. Analysis procedure

The proposed design is evaluated using hand calculations and expected component characteristics. The procedure is: (i) calculate full-load DC current; (ii) calculate transformer and semiconductor stress; (iii) estimate battery runtime at representative loads; (iv) estimate conduction and transformer losses to obtain inverter efficiency; (v) verify filter corner frequency; (vi) check charger power and recharge time; and (vii) assess transfer timing and protection thresholds. A future hardware validation should record output rms voltage, frequency, waveform THD, transfer interval,

battery current, heat-sink temperature, and efficiency at 25%, 50%, 75%, and 100% of the recommended real-power load. Nonlinear loads such as LED drivers and laptop adapters should be included because they are more representative of domestic use than purely resistive loads.

Results

The analytical design results are summarized in Table 2. These values are design estimates and acceptance targets for a prototype; they are not

presented as measured experimental data. At the 400 W recommended load, the calculated battery current is 37.9 A at 88% inverter efficiency. Allowing for magnetizing current, wiring resistance, battery sag, and device losses, the DC path is therefore rated for 50 A continuous service. At half load, fixed losses become a larger fraction of output power, but absolute thermal stress is lower. The expected peak efficiency region is around 50–75% load, where transformer core loss and control overhead are distributed over useful output power.

Table 2. Analytical performance estimates and prototype acceptance targets.

Load	Est. DC current	Est. efficiency	Output target	Practical backup target
100 W	9.5 A	87–89%	225–235 V, 50 Hz	5.0–6.0 h
200 W	18.9 A	88–90%	225–235 V, 50 Hz	2.5–3.1 h
300 W	28.4 A	87–89%	223–235 V, 50 Hz	1.7–2.0 h
400 W	37.9 A	85–88%	220–235 V, 50 Hz	1.2–1.5 h

The estimated output-voltage band of approximately 220–235 V reflects transformer regulation and battery-voltage variation. Closed-loop modulation-index correction can narrow this range, but the design avoids aggressive control in order to preserve simplicity. With the selected 20 kHz carrier and approximately 2.29 kHz LC corner frequency, switching components should be strongly attenuated while the 50 Hz component experiences negligible attenuation. Achieving a final total harmonic distortion below 5% is a reasonable prototype target for predominantly linear domestic loads, but nonlinear load testing is required before such a value can be reported as measured performance.

Cost reduction results mainly from architectural choices rather than from under-rating components. The proposed unit uses one battery, one transformer, four main MOSFETs, one inexpensive controller, one transfer relay, a simple charger, and discrete protection. Compared with double-conversion UPS structures described in the literature [1], [2], the inverter is not continuously processing load power during healthy mains operation, so standby conversion loss is low and the heat-sink requirement is smaller. Compared with more advanced feedback, predictive, or repetitive-control systems [3]–[5], the SPWM controller requires less computation and fewer high-bandwidth sensors. Compared with battery/supercapacitor systems [7], the storage hardware is simpler. These savings are obtained at the cost of a finite transfer time and less sophisticated disturbance conditioning.

The calculations also identify the main technical risk: the 12 V architecture carries high current. At

400 W, connectors, fuses, PCB tracks, transformer windings, and MOSFET conduction paths must all handle approximately 40 A continuously, so poor mechanical connections can dominate loss and temperature rise. If the design were scaled beyond roughly 600–800 VA, a 24 V battery bus would become more attractive because it approximately halves current for the same power. Thus, the proposed 12 V configuration is economically appropriate only within the intended small domestic power range.

Conclusion and Discussion

This paper developed a step-by-step methodology for a low-cost domestic UPS rated at 600 VA with a recommended 400 W continuous load. The chosen offline/line-interactive architecture is consistent with the cost-performance trade-offs identified in UPS classification and review literature [1], [2]. Instead of continuous double conversion, the utility supplies the load directly in normal operation, while a 12 V battery, MOSFET full bridge, transformer, and SPWM controller provide backup during outages. The resulting topology has a low component count, good serviceability, galvanic isolation, and lower normal-mode conversion loss than an online UPS. The analysis showed that a 400 W load requires about 38 A from a 12 V battery at 88% inverter efficiency, making conductor sizing, MOSFET thermal design, and low-resistance connections critical. A 100 Ah lead-acid battery provides a useful compromise between cost and autonomy, with a practical target of roughly 1.2–1.5 h at 400 W and 2.5–3.1 h at 200 W when conservative depth of discharge and real battery behavior are considered. The 600 VA transformer provides

step-up and isolation, while a 20 kHz SPWM carrier and an LC filter with an approximately 2.29 kHz corner frequency support a near-sinusoidal output. Controlled 10 A charging, transfer-delay logic, battery under-voltage protection, over-current shutdown, and thermal protection are essential parts of the low-cost design rather than optional additions. The proposed system deliberately does not attempt the zero-transfer performance or high-order digital control of premium UPS products. Research on multiple-feedback, repetitive, and predictive inverter control [3]–[5] shows what can be added if lower distortion or faster load response becomes necessary. Similarly, transformerless conversion [6] and hybrid battery/supercapacitor storage [7] can reduce size or battery stress but increase design complexity. System-level studies of domestic UPS use [8] and reliability sensitivity [9] support the emphasis on controlled charging and conservative component selection. The next stage should be hardware implementation followed by instrumented testing of rms voltage, transfer time, THD, efficiency, battery runtime, temperature rise, and short-circuit response. Until those tests are performed, the numerical values reported here should be treated as analytical design targets. Within that scope, the proposed methodology demonstrates that a safe and useful domestic UPS can be developed economically by simplifying topology while retaining the electrical protections and derating needed for reliable operation.

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