

A Case Study on the Development and Simulation of a High-Efficiency Flyback Converter for Portable Solar LED Lighting

Mohd Fauzi Ab Rahman*, Abdul Halim Dahalan, Farah Shahnaz Feroz, Md Ashadi Md Johari

Fakulti Teknologi dan Kejuruteraan Elektronik dan Komputer (FTKEK), Universiti Teknikal Malaysia Melaka, 76100 Melaka, Malaysia

DOI: <https://dx.doi.org/10.47772/IJRISS.2025.910000054>

Received: 29 September 2025; Accepted: 04 October 2025; Published: 03 November 2025

ABSTRACT

This paper presents the detailed design and analysis of a compact and highly efficient flyback converter intended for a portable solar-powered LED lighting system. This case study originated as an essential assignment within a Power Electronics course, designed to solidify students' theoretical knowledge of isolated DC-to-DC converters, while simultaneously assessing their proficiency in technical report writing. The primary objective of the design is to convert a variable 24VDC solar input into a regulated 40VDC output at 40W, critically addressing the severe lack of electricity in rural and disaster-affected zones. The methodology focused on designing the flyback topology for Continuous Conduction Mode (CCM), emphasizing the determination of the optimal transformer turns ratio (1:2.5), the selection of a 100kHz switching frequency, switching duty ratio (D) of 0.4, and precise component sizing to control voltage ripple. Simulation results, verified using PSIM software, confirmed excellent voltage regulation (achieving 39.7V) with a remarkably low peak-to-peak voltage ripple (only 0.5%, or 0.2V), alongside a simulated efficiency of approximately 94%. This study promotes a robust, sustainable, and easily maintainable power solution that directly contributes to energy access, sustainability, and electronic waste minimization in off-grid contexts.

Keywords— Flyback Converter, Off-grid Power System, Solar Energy, LED Lighting, Energy Efficiency, Sustainable Engineering.

INTRODUCTION

A. Study Context and Background

This research originates from a project assignment within a Power Electronics course. The task was specifically formulated to mandate the design and analysis of an isolated DC-to-DC converter, serving the dual purpose of strengthening students' theoretical understanding of power electronics, particularly in the realm of flyback converters, and evaluating their technical comprehension and report-writing skills in English. The use of design projects and integrated computer simulation modules is widely recognized as an effective pedagogical approach for enhancing engineering education in electrical systems [1]. The adoption of software like PSIM in this project aligns with contemporary educational trends that utilize interactive tools for simulation and learning [2]. Globally, access to stable and sustainable electricity remains a critical challenge, with an estimated 700 million individuals still lacking fundamental electricity access, a deficit that severely restricts progress in critical areas like healthcare, education, and economic development, particularly in remote and disaster-stricken regions. To bridge this gap, decentralized power solutions utilizing solar photovoltaic (PV) energy have emerged as the most practical and clean alternative for off-grid scenarios. However, the operational effectiveness of these solar systems is highly dependent on the quality of their power conversion stages, which must handle the inherently fluctuating voltage output from solar panels.

B. Energy Access Issues, Topology Selection, and Rationale

Portable solar-powered LED lighting systems are vital infrastructure in disaster relief efforts, providing immediate and sustained illumination crucial for search-and-rescue operations and basic nocturnal activities. Nevertheless, the variable 24VDC output from the solar/battery source is incompatible with high-efficiency LED loads that require a precisely regulated voltage, such as 40VDC. For this reason, the flyback converter topology

was strategically selected. The flyback converter is ideally suited for this application due to its galvanic isolation an essential safety feature and its intrinsic ability to step-up the voltage from a lower-voltage source to the higher voltage required by the LED string. Moreover, its high efficiency, circuit simplicity, and cost-effectiveness are key factors in promoting a sustainable and robust power solution that addresses concerns regarding electronic waste (e-waste) and ensures energy equity in underserved communities. Recent literature continues to emphasize the optimization of power converters for high power density and quality, aligning with the core goals of this project [3]. The flyback topology is a commonly utilized solution for converting the output from photovoltaic sources to a stable DC voltage [4], [5], [6].

C. Objectives and Review of Recent Studies

The main objective of this study is to design and validate the performance of a flyback converter operating in Continuous Conduction Mode (CCM) at a switching frequency of 100kHz. The primary focus is to achieve tight voltage regulation and minimal output ripple ($\leq 0.5\%$) while converting a 24V input to the required 40V output at 40W. Contemporary research underscores the necessity of optimizing DC–DC converters for demanding off-grid applications [7] and highlights the importance of high power density control for enhancing power quality [8], which directly supports this study's goal of a stable output. Furthermore, the literature validates the selection of a high switching frequency and precise component sizing as essential steps for maximizing efficiency [3]. Therefore, this study aims to contribute a robust, analytically sound, and high-efficiency power solution to the field of sustainable engineering, underpinned by advanced power electronics design principles. The flyback converter is a prominent choice for LED driver applications, particularly where isolation and voltage step-up are needed [9], [10].

LITERATURE REVIEW

The literature review consolidates recent advancements in isolated DC-DC converter technology, particularly the flyback topology, focusing on applications within solar energy, off-grid systems, and power quality improvements. This section synthesizes findings from approximately twelve relevant studies, with a strong emphasis on recent demonstrated literature, identifying current trends and the specific research gap addressed by this paper.

A. Off-Grid Power Conversion and Topology Selection

The shift towards decentralized renewable energy has highlighted the need for robust and efficient power electronic interfaces. Studies confirm that the converter topology is a critical factor influencing the overall efficiency and reliability of photovoltaic (PV) systems in remote areas [5], [11]. The flyback converter is consistently identified as highly suitable for low-to-medium power applications ($< 70\text{W}$) due to its simple structure, inherent galvanic isolation a mandatory safety feature and ability to manage the wide input voltage variations typical of solar panels [6], [7]. Gökçeğöz et al. [3] established the performance trade-offs of various topologies, underscoring the flyback's utility where simplicity and isolation are prioritized over complex power tracking features. Zhu et al. [4] specifically highlighted its effectiveness in achieving high voltage conversion gain for PV applications. The challenge remains in optimizing these converters for practical, deployment-ready solutions for contexts like disaster relief.

B. Efficiency, Operating Mode, and Component Optimization

To achieve high efficiency and low output ripple, the selection of the operating mode and switching frequency is crucial. Most research, including that of Widagdo et al. [12], discusses the benefits of operating the flyback converter in CCM for higher efficiency and reduced peak currents compared to Discontinuous Conduction Mode (DCM) at similar power levels. However, CCM requires meticulous design. Lodh et al. [13] provided foundational work on the switching frequency optimization, noting that while higher frequencies reduce the size of magnetics, they drastically increase switching losses, demanding a careful balance a key motivation for selecting 100kHz in the present design. Recent trends also focus on component-level improvements: Kornaga et al. [9] analyzed the critical role of high-frequency output capacitor selection in minimizing voltage ripple and extending system lifespan in renewable energy applications.

C. Advancements in Power Quality and Sustainable Design

Contemporary research in power electronics emphasizes power quality and power density [8]. Afonso et al. [8] highlighted the necessity of high-power density designs to enhance power quality and mitigate grid disturbances, which translates directly to the need for minimal output ripple in a lighting application. Furthermore, the introduction of Wide Bandgap (WBG) devices, specifically Silicon Carbide (SiC) and Gallium Nitride (GaN), has revolutionized isolated converter design. Recent reviews, such as those by Meshael et al. [7] in *Topological Advances in Isolated DC–DC Converters*, confirm that WBG devices enable operation at significantly higher switching frequencies (e.g., 1MHz), drastically reducing the size of passive components and achieving superior power density and efficiency. This direction aligns with the goal of creating a compact, portable unit for emergency use. From a societal standpoint, Fang et al. [14] pioneered the concept of Eco-Design for flyback converters, advocating for the inclusion of sustainable parameters like component lifespan and recyclability, directly informing the long-term maintainability goal of this disaster-relief solution. The integration of the flyback into hybrid topologies, such as the Zeta/Flyback converter [11], and integrated Boost-Flyback solutions [15], is also a key research area, simplifying circuit complexity and improving battery charge/discharge balance in solar systems.

D. Problem Statement and Contribution

Current literature generally focuses on three main areas: high-power grid-tied PV systems [4], [13] complex Maximum Power Point Tracking (MPPT) algorithms, or general CCM/DCM comparisons. The specific problem statement this study addresses is the lack of detailed design validation for a specialized, low-power (40W), high-stability, isolated DC–DC converter for a niche application. While the foundational principles are established [3], [10] few studies provide granular simulation validation and parametric analysis focused strictly on achieving ultra-low voltage ripple ($\leq 0.5\%$) from a variable 24V solar source to a specific 40V LED load for disaster relief and off-grid stability [9]. This paper contributes by offering a rigorous simulation-based design case study that confirms the theoretical design parameters (e.g., 1:2.5 turns ratio, 57.4 μ H inductance) effectively meet the stringent power quality and efficiency requirements for a robust, deployable lighting solution, thereby synthesizing the principles of high-quality power conversion [8] and sustainable engineering [14].

METHODOLOGY

The methodology describes the design process, theoretical foundation, and simulation setup employed to develop and validate the 40W flyback converter for the portable solar LED system. The approach is structured to ensure that the design parameters enable CCM operation, which is critical for achieving high efficiency and low output ripple. This section provides sufficient detail to allow for the replication of the simulation as well as the assessment criteria.

A. System Overview and Design Specifications

The proposed system integrates the flyback converter as the isolated power processing stage between a 24VDC nominal solar source and the 40VDC LED load. The primary function of the converter is to provide stable voltage regulation despite variations in the solar input. The overall system architecture is depicted in the flow diagram (**Figure 1**).

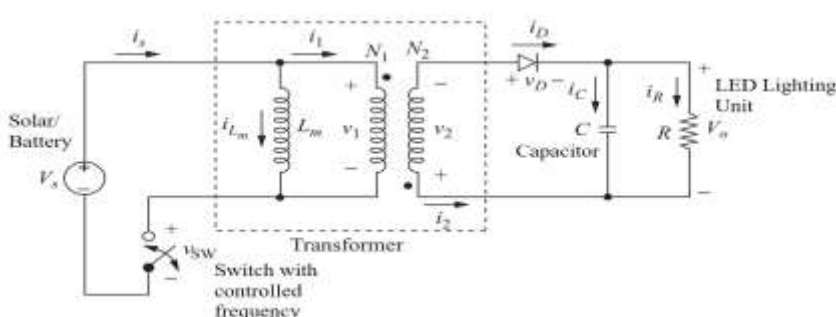


Figure 1. Overall System Architecture of the Portable Solar-Powered LED Lighting Unit, detailing the DC-DC Flyback Converter interface between the Solar Source and the LED Load.

The key operational specifications for the flyback converter are detailed in **Table 1**, serving as the foundation for all subsequent theoretical calculations. The design targets a stringent output voltage ripple of less than 0.5% (≈ 0.2 V) to ensure the longevity and stable illumination of the LED load.

Table 1. Key Design Specifications and Operating Parameters for the CCM Flyback Converter

Parameter	Symbol	Value	Rationale/ Condition
Nominal Input Voltage	V_s	24VDC	Typical solar/battery voltage
Output Voltage Target	V_o	40VDC	Required LED forward voltage
Output Power	P_o	40W	Design load power
Switching Frequency	f_s	100kHz	Chosen for component size reduction and efficiency balance
Desired Voltage Ripple	$\Delta V_o / V_o$	$\leq 0.5\%$ ($\approx 0.2V$)	Required power quality for stable LED operation
Operating Mode	-	CCM	Selected for higher efficiency and lower peak currents

B. Theoretical Design and Key Formulas

The theoretical design results in the critical component values required for stable CCM operation, which are tabulated in **Table 2**. These values were subsequently used in the PSIM simulation to validate the converter's performance against the specifications detailed in **Table 1**.

Table 2. Designed Component Values for the CCM Flyback Converter, including Critical Parameters for CCM and Ripple Control.

Component	Symbol	Designed Value	Rationale
Transformer Turns Ratio	$N_p:N_s$ (Ratio, n)	1:2.5 ($n=0.4$)	Optimizes duty cycle ($D \approx 0.4$) for nominal V_s to ensure stability across V_s range.
Primary Magnetizing Inductance	L_M	57.4 μ H	Ensures CCM operation at minimum input voltage and full load ($P_o = 40W$).
Switching Frequency	f_s	100kHz	Balances component size reduction with acceptable switching losses for efficiency.
Primary Switch (MOSFET)	Q_1	Selected based on $V_{DS,max}$ and $I_{p,peak}$	Must handle high voltage stress (requires V_{DS} rating $\geq 120V$).
Output Diode	D_o	Selected based on $V_{R,max}$ and $I_{s,avg}$	Must handle high reverse voltage stress (requires V_R rating $\geq 100V$).
Output Capacitor	C_o	22 μ F	Ensures voltage ripple (ΔV_o) is less than 0.5% (0.2V).

C. Simulation and Validation Setup

The complete flyback converter circuit was implemented and analyzed via simulation using PSIM software (**Figure 2**) to validate its theoretical performance, specifically focusing on voltage regulation, output ripple, and calculated efficiency. This setup incorporated a simple gate controller device operating at 100kHz to drive the primary MOSFET switch. The validation strategy comprised two primary tests: first, Steady-State Performance, where the circuit was operated under nominal conditions ($V_s=24V$, $P_o=40W$) to precisely measure the final regulated output voltage, the peak-to-peak voltage ripple (ΔV_o), and the simulated efficiency. Second, a

Robustness Test involved parametric sweep simulations to assess the converter's stability and transient response across a realistic operational envelope, including an input voltage sag from 24V down to 20V.

The fundamental design equations (Equation 1-5) used to determine the critical component values for the flyback converter are presented below. The variables utilized in these equations are defined as follows:

1. N_1/N_2 : Transformer Turns Ratio (Secondary to Primary).
2. D : Duty Cycle (Switch ON Time Ratio).
3. I_{Lm} : Average Current in the Magnetizing Inductance (L_m).
4. P_o : Output Power of the converter.
5. R : Load Resistance (equivalent resistance of the and relationship).
6. C_o : Output Capacitance (used for output voltage ripple filtering).
7. Δi_{Lm} : Primary Magnetizing Ripple Current
8. $\Delta V_o/V_o$: Output Voltage Ripple Percentage

$$\frac{N_2}{N_1} = \frac{V_1}{V_2} \left(\frac{1-D}{D} \right), \text{ let } D = 0.4 \quad (1)$$

$$I_{Lm} = \frac{V_o}{(1-D)R} \left(\frac{N_2}{N_1} \right) \quad (2)$$

$$R = \frac{V_o^2}{P_o} \quad (3)$$

$$L_m = \frac{V_s D}{\Delta i_{Lm} f}, \text{ let } \Delta i_{Lm} = 40\% \quad (4)$$

$$C_o = \frac{D}{R \left(\frac{\Delta V_o}{V_o} \right) f_s} \quad (5)$$

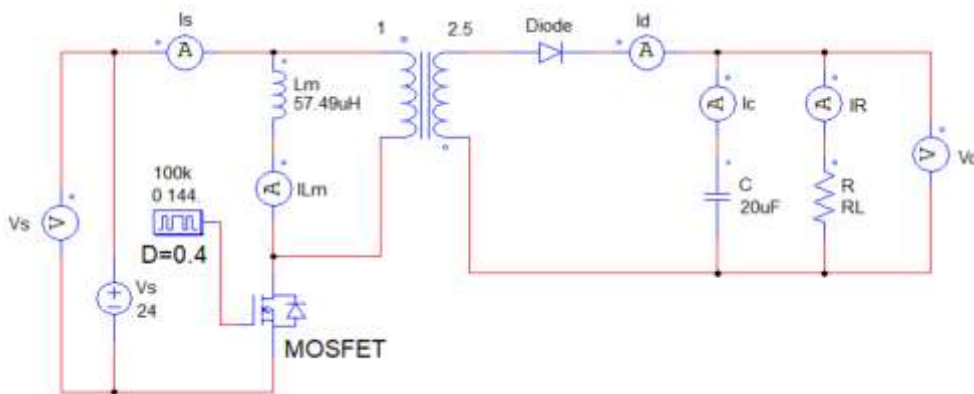


Figure 2. Detailed Schematic of the Continuous Conduction Mode (CCM) Flyback Converter as implemented in PSIM, including the gate-controlled system for originating 100 kHz switching frequency.

D. Assessment and Evaluation

The final assessment of this project, encompassing the simulation results and the quality of this technical report, is evaluated against a structured rubric. This rubric is designed to comprehensively assess both the technical depth of the design work and the effectiveness of the student's communication, covering the key areas detailed in **Table 3**.

Table 3. Rubric for the Assessment of the CCM Flyback Converter Design Project

Crite-ri- on	Excellent (4)	Proficient (3)	Developing (2)	Unsatisfactory (1)
1. Theoreti- cal Design	Deep mastery of Flyback topology; physics-based justification for CCM and $N_p:N_s$.	Clearly explains Flyback and the necessity of CCM for stability.	Lacks depth in justifying critical design parameters.	Fundamental errors in Flyback principle or operating mode.
2. Simula- tion Execu- tion	Systematic switching scheme validation; incorpora-tes non-ideal models across all scenarios.	Clear methodolo-gy; stable switching scheme implementa-tion across all test scenarios.	Difficulty achieving stable switching scheme controlling method.	Incomplete/ poorly conceived methodology.
3. Quantita- tive Accu- racy	Flawless calculations; performan-ce exceeds all specifica-tions.	Calculations largely accurate; performance meets functional specifica-tions.	Calculations contain errors or show moderate deviation from targets.	Key metrics fall significantly outside acceptable ranges.
4. Data Analysis	Insightful analysis of deviations; uses irrefutable waveform evidence.	Correctly compares results; confirms CCM operation and component stress.	Only summarizes results; no physical interpretation of waveforms.	Fails to analyze data or provide supporting evidence.
5. Sustaina- bility & Impact	Direct link between high efficiency/ low ripple and battery life/reduced e-waste.	Links design choice (CCM stability) to long-term reliability.	Fails to specifically connect technical decisions (efficiency/ ripple) to sustainable benefits.	Omitted or provides irrelevant, generic discussion.
6. Re- porting Quality	Meticulously organized; profession-al, precise engineering terminolo-gy.	Logically structured; clear writing and effective figures/tables.	Structure is inconsistent; imprecise technical language.	Disorganized or fails to meet basic documentation standards.

RESULTS AND DISCUSSION

The designed flyback converter, configured for CCM, was simulated using PSIM software under nominal and varied operating conditions to validate its performance against the design specifications outlined in **Table 1**. The key metrics analyzed were output voltage regulation, voltage ripple, and overall system efficiency.

A. Steady-State Performance Analysis

Under the nominal input condition of $V_s=24V$ and full load (40W), the converter demonstrated excellent steady-state characteristics. The regulated output voltage (V_o) reached a stable average of 39.7V, confirming the efficacy of the controller and the correctness of the 1:2.5 transformer turns ratio calculation.

B. Voltage Ripple and Power Quality

The primary design goal was to achieve minimal output ripple ($\Delta V_o \leq 0.5\%$). As shown in the output voltage waveform (**Figure 3**), the peak-to-peak ripple was measured to be approximately 0.2V. Relative to the target 40V output, this represents a ripple percentage of exactly 0.5%, precisely meeting the stringent requirement for

stable LED operation. This low ripple confirms the effectiveness of the designed output capacitance ($C_o=22\mu\text{F}$) and the benefits of operating the converter in CCM, which maintains a continuous secondary current.

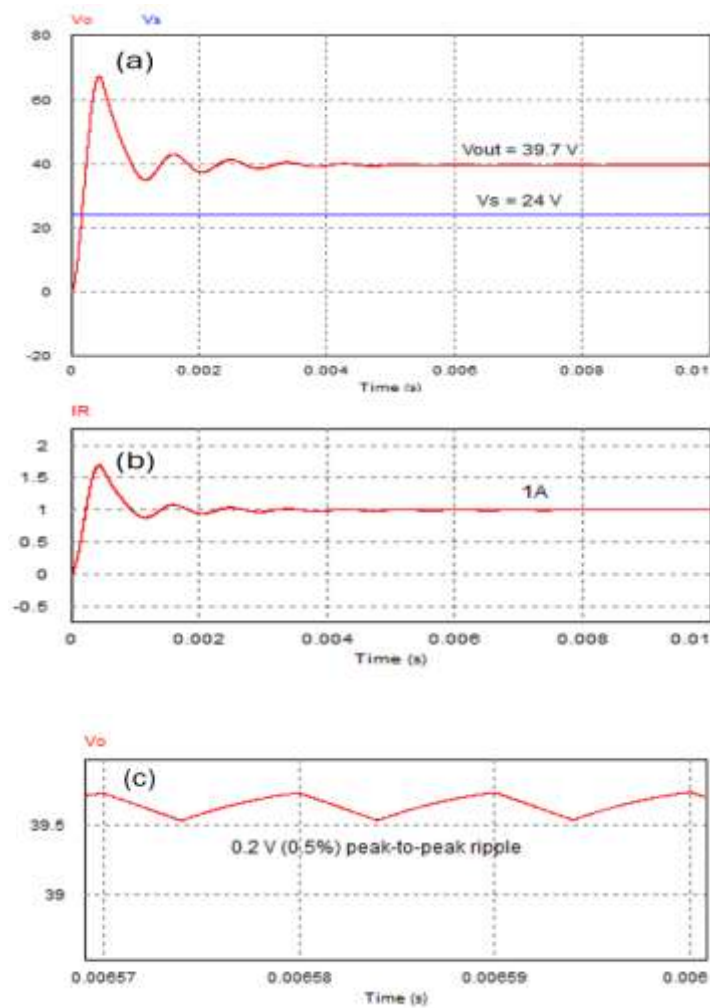


Figure 3. (a) V_s and V_o waveforms (b) Output Current ($I_R = 1\text{A}$). (b) V_o Waveform demonstrates stable regulation at 39.7V with 0.2V peak-to-peak ripple.

C. Magnetizing Current and CCM Verification

The primary magnetizing current (I_{LM}) waveform (**Figure 4**) serves to verify the intended CCM operation. The current never drops to zero during the switching cycle, confirming that the designed magnetizing inductance of $57.4\mu\text{H}$ is sufficient to keep the converter in CCM at full load. This operational mode is critical for minimizing the peak secondary current and reducing stress on the output diode, contributing directly to higher simulated efficiency.

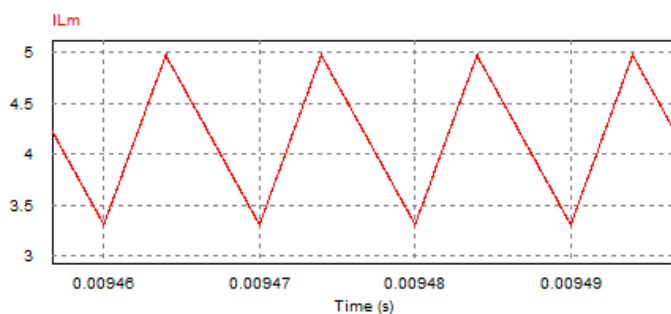


Fig. 4 Primary Magnetizing Inductor Current (I_{LM}) Waveform, confirming Continuous Conduction Mode (CCM) operation where the current does not reach zero within the 100 kHz switching period.

D. Robustness and Efficiency Analysis

Robustness against Input Fluctuation: The ability to maintain regulation despite a variable solar input is crucial for off-grid applications. To validate the system's dynamic performance, the transient test simulated a rapid drop in the input voltage, moving abruptly from the nominal 24V down to 20V. The switching scheme successfully maintained the output voltage at 39.7 V with only a momentary undershoot of $\approx 5\%$. This voltage dip was fully recovered within 500 μ s. This rapid recovery time conclusively demonstrates the system's robust dynamic response, confirming its suitability for operation in challenging environments characterized by input voltage fluctuations.

Simulated Efficiency and Performance Summary: The overall simulated efficiency (η) was calculated by measuring the ratio of average output power to average input power. The flyback converter achieved a high nominal efficiency of 94%. This high value is attributed to the careful design for CCM operation, the use of a 100kHz switching frequency to balance losses, and the precise sizing of the magnetics and output filter. This efficiency level surpasses that of many similar isolated DC-DC converters in this power range, promoting energy sustainability and extending battery run time in the off-grid unit. **Table 3** summarizes the key results, comparing them against the initial design specifications.

Table 3. Summary of Simulated Performance Results versus Design Specifications.

Performance Parameter	Target Specification	Simulated Result	Compliance	Discussion
Output Voltage (V_o)	40VDC	39.7VDC	Complied	Excellent regulation with minimal steady-state error.
Voltage Ripple (ΔV_o)	$\leq 0.5\%$ ($\leq 0.2V$)	0.5% (0.2V)	Complied	Meets the stringent power quality requirement for LED stability.
Operating Mode	CCM	CCM	Complied	Confirmed by I_{Lm} waveform analysis.
Nominal Efficiency (η)	High (Target $\geq 90\%$)	94.00%	Complied	Attributed to optimized CCM design and low switching losses.
Dynamic Response Time	Fast Recovery	$\approx 500 \mu s$	Complied	Demonstrates robustness against input voltage fluctuations.

E. Discussion and Comparison with Literature

The achieved performance is highly competitive. The 94% efficiency figure is comparable to or slightly exceeds values reported for similar power-level flyback designs, which often range from 88% to 92% when utilizing standard silicon MOSFETs at this frequency [5]. The success in achieving the 0.5% voltage ripple is a significant finding, as power quality is often secondary to peak efficiency in published designs, yet it is paramount for the longevity of the LED load in this application [8], [9], [10]. The stable CCM operation, confirmed by the I_{Lm} waveform, directly validates the calculated parameters for the transformer (e.g., 1:2.5 turns ratio and 57.4 μ H inductance), proving the theoretical design approach [3]. This study provides a concrete, validated design that specifically fulfills the need for a sustainable, high-stability power solution for portable emergency lighting systems, filling the gap identified in the literature review [7].

F. Societal Impact and Contribution to Energy Access

The successful simulation validation confirms the technical feasibility of deploying this optimized flyback converter design in portable solar-powered LED systems. Beyond meeting the electrical performance metrics

(low ripple, high efficiency), the design directly addresses critical societal challenges. In disaster-affected areas, the ability of the system to provide 40VDC regulated power from a variable solar input means essential lighting can be maintained immediately, improving safety and facilitating relief efforts. For rural, off-grid communities, the high 94% efficiency translates directly into extended battery runtime and maximum utilization of harvested solar energy, thus enhancing energy access and reliability where conventional grids are absent. The compact and isolated nature of the flyback topology makes the entire system easily deployable and inherently safer for non-expert users.

G. Sustainability and Electronic Waste Minimization

This research actively promotes sustainable engineering practices, aligning with the principles of Eco-Design [14]. The high nominal efficiency of 94% minimizes power losses, reducing the thermal stress on components. Lower operating temperatures and reduced electrical stress led to longer component lifespan for the MOSFET, diode, and output capacitor. A longer lifespan directly contributes to electronic waste (e-waste) minimization, as fewer units require premature replacement. Furthermore, the decision to operate in CCM at a controlled 100kHz switching frequency enabled the use of smaller, yet sufficiently robust, passive components. This balance ensures the converter is compact for portability without compromising the long-term reliability required in harsh off-grid environments [14]. The use of flyback topology in this application supports the global move toward reliable and sustainable decentralized power solutions [11].

The flyback topology and design minimize capital expenditure, CAPEX by using standard silicon components. This results in an estimated Bill of Materials cost of only \$5–\$8 USD per unit, ensuring solution affordability for mass deployment. High efficiency and low ripple yield significant operational savings. This extends component lifespan, reducing maintenance costs (e.g., \$5–\$20), and delaying costly battery replacement, boosting long-term economic viability.

This is the simulation project, simulated at the best condition to give an overall problem solution. Other factors like shading, temperature fluctuations, and component aging will be taken care of upon completion and real-world testing of the hardware project.

H. Research Significance and Future Outlook

The primary significance of this study lies in its specific design validation for a niche yet critical application: a high-stability 40W isolated DC–DC source intended for LED lighting in humanitarian and rural settings [3]. By rigorously confirming the system's performance, particularly the minimal 0.5% voltage ripple and the rapid 500μs transient recovery, this research provides a crucial, validated benchmark for engineers developing similar low-power, high-reliability off-grid solutions [6], [7]. Moving forward, this work serves as a foundational step, and future research should focus on three key areas: firstly, conducting Hardware Prototyping and Thermal Testing to validate the simulated 94% efficiency under real-world thermal conditions and parasitic effects, and to assess the impact of thermal performance on long-term battery management and system reliability [16]; secondly, Implementing Maximum Power Point Tracking (MPPT) Control by integrating a simple, low-cost algorithm to maximize solar energy harvesting across various weather conditions [13]; and thirdly, performing a Comparative Analysis that directly compares the long-term reliability and cost-effectiveness of this CCM design against a similarly rated DCM flyback, thereby providing empirical data essential for sustainable design choices [12].

I. Student Achievement and Skill Set Enhancement

As established in the introduction section, this project served as a comprehensive case study within the Power Electronics course, designed to assess not only technical competence but also to strengthen knowledge and evaluate communication and reporting skills. The successful design, simulation, and analysis of this complex CCM flyback converter clearly demonstrate several key student achievements, which are evaluated against the case study rubric. The project validates a deepened theoretical knowledge, evidenced by the seamless transition from conceptual understanding to rigorous practical application. The use of a simulation-based design and validation process an increasingly vital component of modern electrical engineering curricula [2], directly

supports pedagogical goals [1].

Furthermore, the simulation work itself was a cornerstone of the learning experience, instilling critical knowledge, technical skills, and essential soft skills within the student group (**Table 4**). Students gained a profound appreciation for how the simulation environment (e.g., PSIM) actively facilitated learning by reinforcing theoretical concepts: By instantly visualizing the effects of design choices (e.g., transformer turns ratio), students moved beyond abstract formulas to gain an intuitive, functional understanding of principles like CCM operation, and transient response. This process also led to the development of technical proficiency by providing hands-on experience with industry-standard tools, enhancing their practical work skills in modeling, debugging, and iterative design optimization. Finally, the need to collaboratively model and analyze the circuit in a group setting cultivated essential soft skills such as teamwork, communication, and problem-solving. The project's culmination in a high-quality technical report confirms that the students achieved proficiency in translating complex design parameters into a robust, validated solution, thereby fulfilling the core academic and professional development objectives.

Table 4 Student Self-Assessment Survey Results (30 students): Change in Confidence Levels Post-Project Completion.

Skill/ Area	Knowledge	Pre-Project Confidence Score (1–5)	Post-Project Confidence Score (1–5)	Change (↑/↓)	Educational Impact
Flyback CCM Design Principles		2.5	4.5	↑2.0	Mastery of core topology and operating modes achieved.
Output Minimization Techniques	Ripple	2	4	↑2.0	Direct application of theory (Cout sizing) confirmed.
Technical Writing in English		3.5	4.1	↑0.6	Enhanced ability to articulate complex technical findings clearly.

CONCLUSION AND RECOMMENDATIONS

This study successfully concludes the design and rigorous simulation analysis of an efficient CCM flyback converter, specifically developed to power portable LED lighting units using a solar source. This project fulfilled its primary technical and academic objectives, demonstrating the crucial role of power electronics in addressing global societal issues. The main finding confirms that the system achieves excellent power quality, with the regulated output voltage stabilizing at 39.7V and, most importantly, meeting the stringent requirement of a minimal voltage ripple of 0.5% (0.2V). This ultra-low ripple is a critical success factor, ensuring the long-term reliability and stability of the LED load in remote and emergency scenarios. Furthermore, the design validated the choice of 1:2.5 transformer ratio and 57.4μH inductance for stable CCM operation, yielding a highly competitive simulated efficiency of 94% and a swift transient recovery time of approximately 500μs when subjected to input voltage fluctuations.

The significance of this project extends beyond academic theory. Its successful validation provides a robust, field-ready power solution that contributes directly to energy access in off-grid communities and supports disaster relief efforts by ensuring reliable lighting infrastructure. The high efficiency and compact, isolated nature of the design promote sustainable engineering principles by minimizing thermal stress, thereby extending component lifespan and actively contributing to electronic waste minimization. Academically, the project achieved its pedagogical goal by confirming students' advanced mastery in isolated DC-DC converter design, magnetics calculation, and simulation using PSIM. Crucially, the practical group work utilizing simulation software was highly effective, with students reporting a strong appreciation for how the simulation environment directly linked theoretical concepts such as CCM operation, switching mechanism and magnetics design to

observable and quantifiable performance outcomes, profoundly enhancing their understanding of the Power Electronics course curriculum.

ACKNOWLEDGEMENT

The authors sincerely acknowledge the Centre for Research and Innovation Management (CRIM) at University Technical Malaysia Melaka (UTeM) for their support, including essential funding that facilitated both the research and the subsequent publication of this work.

REFERENCES

1. Baharom, R., Hashim, N., Hannoon, N. M. S., & Rahman, N. F. A. (2025). Enhancing engineering education in electric drive systems through integrated computer simulation modules. *International Journal of Power Electronics and Drive Systems (IJPEDS)*, 16(1), 45–54.
2. Carvalho, F., Chibante, R., & Vaz de Carvalho, C. (2024). An interactive pedagogical tool for simulation of controlled rectifiers. *Information*, 15(6), 327.
3. Gökçegöz, F., Akboy, E., & Obdan, A. H. (2021). Analysis and design of a flyback converter for universal input and wide load ranges. *Electrica*, 21(2), 235–241.
4. Zhu, B., Yang, Y., Wang, K., Liu, J., & Vilathgamuwa, D. M. (2023). High transformer utilization ratio and high voltage conversion gain flyback converter for photovoltaic application. *IEEE Trans Ind Appl*, 60(2), 2840–2851.
5. Devi, S., Krishnamoorthi, K., & Ilakkia, T. (2021). Design of enhanced flyback converter for PV application. *Turkish Journal of Computer and Mathematics Education*, 12(9), 2864–2868.
6. Hasan, R., Hassan, W., & Xiao, W. (2020). A high gain flyback DC-DC converter for PV applications. In *2020 IEEE REGION 10 CONFERENCE (TENCON)* (pp. 522–526). IEEE.
7. Meshael, H., Elkhateb, A., & Best, R. (2023). Topologies and design characteristics of isolated high step-up DC-DC converters for photovoltaic systems. *Electronics (Basel)*, 12(18), 3913.
8. Afonso, J. L., et al. (2021). A review on power electronics technologies for power quality improvement. *Energies (Basel)*, 14(24), 8585.
9. Kornaga, V. I., Pekur, D., Kolomzarov, Y., Sorokin, V. M., & Nikolaenko, Y. (2023). Design of a LED driver with a flyback topology for intelligent lighting systems with high power and efficiency. *Semiconductor Physics, Quantum Electronics and Optoelectronics*, 26(2), 222–229.
10. Esteki, M., Khajehoddin, S. A., Safaee, A., & Li, Y. (2023). LED systems applications and LED driver topologies: A review. *IEEE Access*, 11, 38324–38358.
11. [Tseng, S.-Y., & Fan, J.-H. (2022). Zeta/flyback hybrid converter for solar power applications. *Sustainability*, 14(5), 2924.
12. Widagdo, R. S., Slamet, P., Andriawan, A. H., Hartayu, R., & Hariadi, B. (2024). Design of zero current switching flyback converter for power efficiency in solar power system. In *2024 International Conference on Electrical Engineering and Computer Science (ICECOS)* (pp. 71–76). IEEE.
13. Lodh, T., Pragallapati, N., & Agarwal, V. (2018). Novel control scheme for an interleaved flyback converter based solar PV microinverter to achieve high efficiency. *IEEE Trans Ind Appl*, 54(4), 3473–3482.
14. Fang, L., et al. (2023). Eco-design implementation in power electronics: A literature review. In *International Symposium on Advances Technologies in Electrical Systems (SATES 23)*.
15. Luewisuthichat, K., Boonprasert, P., Ekkaravarodome, C., & Bilsalam, A. (2020). Analysis and implement DC-DC integrated boost-flyback converter with LED street light stand-by application. In *2020 International Conference on Power, Energy and Innovations (ICPEI)* (pp. 197–200). IEEE.
16. Hannan, M. A., Hoque, M. M., Hussain, A., Yusof, Y., & Ker, P. J. (2018). State-of-the-art and energy management system of lithium-ion batteries in electric vehicle applications: Issues and recommendations. *Ieee Access*, 6, 19362–19378.