Investigate Power Efficiency in PLECS and MATLAB Software by Designing USB 5-Watt Charger

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Abstract

In power electronics, accurately assessing simulation tools is key for precise, reliable electronic system designs. This study compares MATLAB Simulink and PLECS in modeling a 5W USB charger's power characteristic. The charger, using an AC-DC full bridge rectifier and DC-DC flyback topology, delivers a stable 5VDC at 1A. The analysis focuses on power efficiency and thermal characteristics, incorporating real-life components for detailed insights. Results show PLECS, specialized in power electronics, surpasses MATLAB in accuracy and consistency. This research aids in understanding simulation tools' effectiveness, guiding engineers and researchers in power efficiency evaluations for electronic systems.

Keywords: Power electronics conversion, MATLAB Simulink, PLECS, USB charger, simulation, power efficiency, thermal analysis.

1. Introduction

Power electronics conversion is an essential technology utilized in the landscape of modern technology, permeating various aspects of daily life applications. Power electronics converters serve as a transformative agent in the regulation and control of electric energy flow.

A static power converter is a converter made up with the architecture of electrical components such as transformers, diodes, capacitors, and inductors. Electrical components work together transforming electrical energy from one form to another. From Fig. 1, notable ideal power converter can be observed, controlling the flow of power between two sources aiming to enhance the power efficiency [1]. Power conversion can delve into four categories which are DC to DC converter, AC to AC converter, DC to AC converter and AC to DC converter.

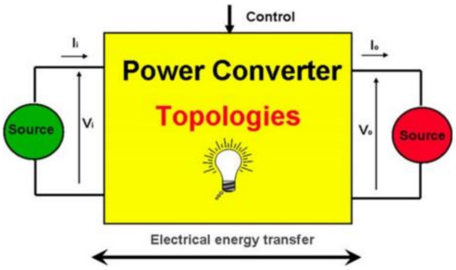


Fig. 1 Power converter topologies.

In recent years, significant improvements in power electronics technology. These advances include breakthroughs in converter topologies, control strategies, and power semiconductor devices, which together have contributed to the continuous improvement and widespread application of modern power conversion systems [2].

USB chargers are one of the illustrations of daily life, where the fundamental principles of power conversion. USB chargers are ubiquitous for charging electronics devices such as laptops and smartphones. In contemporary times, USB chargers are designed with emphasis on fast charging of electronics devices [3]. However, this design of faster charging rates can lead to increased energy loss and heat generated, potentially diminishing the performance of power efficiency.

This paper focuses on using a USB 5-Watt charger as an evaluation method to evaluate the performance of MATLAB Simulink and PLECS software in accurately modeling and predicting the power characteristics of the charger. By conducting a detailed comparative analysis, this study aims to elucidate the disparities in results obtained from each software, shedding light on the strengths and limitations of MATLAB Simulink and PLECS in the context of power efficiency simulations.

The outcomes of this research will not only contribute to a better understanding of the capabilities of these simulation tools but will also assist engineers and researchers in making informed decisions when assessing power efficiency in various electronic systems.

2. Related Work

In the pursuit of advancing understanding of power electronics and simulation tools, a comprehensive review of related work lays the groundwork for our exploration. This section begins by exploring the AC-DC bridge converters, and DC-DC Flyback converter, essential components in designing the 5-Watt USB charger. By continuously adjusting the Proportional-Integral value to fine-tune and achieve the desired output voltage in the 5-Watt USB charger. Understanding converters is crucial for operating and evaluating their role in enhancing power efficiency, and thermal analysis.

2.1. *AC-DC Bridge Converter*

The AC-DC bridge converter, also known as the dual active bridge (DAB) converter, is a power electronic device used for converting alternating current (AC) to direct current (DC) and vice versa and the process known as rectification. The DAB converter, as outlined in Fig. 2 utilizes a bidirectional power flow and high-frequency isolation with a bridge topology featuring two sets of switches and a transformer [4].

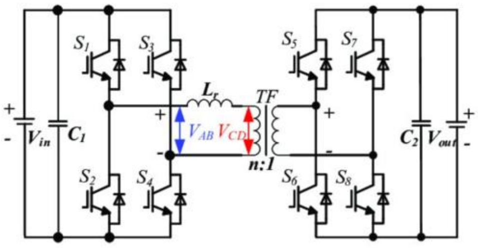


Fig. 2 DAB Converter Topology.

The DAB converter operates by modulating the phase-shift of the switches to control the power flow and achieve AC-DC or DC-AC conversion. It implements both frequency and time-domain analysis to capture the transient behavior of the converter, offering the advantages of steady-state frequency-domain analysis [5]. The converter can be configured to achieve full soft-switching operation, high efficiency, minimize distortion in input current, and provide output short-circuit protection [6]. One notably advantage of DAB is seamless four-quadrant operation [6], [7], [8], [9].

2.2. *DC- DC Flyback Converter*

A Flyback converter, specifically DC-DC converter is a type of power converter that uses a transformer to transfer energy from the input to the output.

The working principles of flyback converter is storing energy in the transformer during on time switching transistor, and then releasing it to the output during off time of switching transistor, as outlined in Fig. 3. This allows for voltage conversion and isolation between the input and output. The flyback converter can be used in various applications, such as AC-DC power supplies, power factor correction circuits, and active-clamp flyback converters [10].

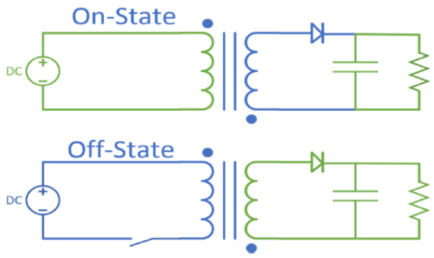


Fig. 3 The Operation of Two States of Flyback Converter.

2.3. *Proportional-Integral*

A Proportional-Integral (PI) controller is a type of feedback control system commonly used in power electronics to regulate the output of the power converters. It combines proportional (P) and integral (I) control actions to achieve the desired output.

The P value generates an output proportional to the current error, while the I value aids eliminating any residual steady-state error by integrating the error over time. In this project, the PI controller is implemented in the DC-DC Flyback converter in regulation to achieve desired output of USB charger.

2.4. *Thermal Analysis*

Thermal analysis is an important aspect of power USB charger configuration, due to it bringing effect on the reliability and safety of the system. The proper working of the charger's thermal considerations is a basic part of power electronics design. Several studies have been conducted on the thermal design of wireless chargers for electric vehicles [11], miniaturization and thermal design of battery chargers [12], and thermal analysis of transformers in on-board chargers for electric vehicles [13]. These studies use simulation tools to predict losses and temperature and establish thermal networks of heating components to calculate hotspot temperatures.

2.5. *Power Efficiency*

Power efficiency in USB chargers can be described as the charger's ability to convert electrical power from the source to the device, allowing it to be charged with minimal loss. It is a critical factor in determining the charging time and energy conservation.

Achieving high conversion efficiency is essential for optimal operation and robustness under varying conditions, as seen in the context of mobile battery charger ICs, where techniques like zero current switching (ZCS) are employed [14]. Therefore, power efficiency in USB chargers is essential for improving device charging, energy conservation, and the development of innovative charging technologies.

3. Materials and Methods

Overview of 5-Watt USB charger described overall input AC voltage to output DC voltage, as outlined in Fig. 4. The process begins with an input of 141/325 VAC with a frequency of 50/60Hz. This input voltage is directed through the AC-DC bridge converter. In this stage, the AC input voltage undergoes rectification, transforming it into a pulsating DC voltage. Subsequently, the pulsating DC voltage undergoes filtering and smoothing to ensure a stable waveform. The smoothed DC voltage then progresses through the DC-DC flyback converter, where it is stepped down to the desired level, providing isolation and regulation in the transformation process. To fine-tune and optimize the output results, a PI controller is applied, ensuring that the output voltage remains regulated at 5V DC with a current capacity of 1A.

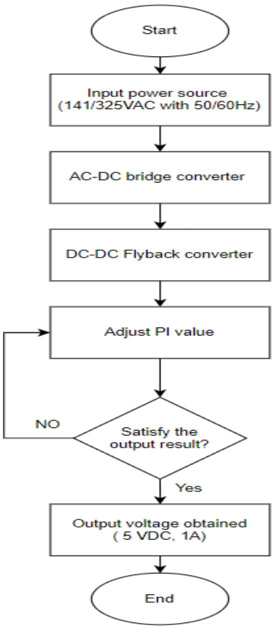


Fig. 4 Overview of 5-Watt USB Charger.

3.1. *The Design Procedure of 5-Watt USB Charger*

The design and implementation of a 5-Watt USB power charger involves the integration of an AC-DC full bridge rectifier employing a DC-DC flyback topology.

The primary objective of this charger is to deliver a maximum output current of 1A with a consistent output voltage of 5VDC. Achieving this goal requires the inclusion of a 5-ohm load resistor in the circuit.

To ensure the charger's adaptability for global use, it accepts two AC input voltages (V_{in}), as outlined in Table 1, providing corresponding output DC voltage, (V_{out}). The switching frequency, (f_{sw}) is set at 40kHz to optimize the performance of the charger.

Table 1. The Calculation of AC Voltage Input with Frequency.

AC Voltage	Input Voltage	Frequency
100V	$100 \times \sqrt{2} = 141.42$V	50/60Hz
230V	$230 \times \sqrt{2} = 325.26$V	50/60Hz

The Flyback equation was employed to calculate the winding ratio (n), critical inductance (Lc), and critical capacitance (Cc) for component selection in the high-frequency transformer and Flyback circuit capacitor. This calculation involves utilising known variables such as resistance (R), duty cycle (D) and output ripple voltage (ΔVo).

Number of turns ratio of transformer in flyback converter to calculate the value of Lc and Cc.

$$n = \frac{N2}{N1} = \frac{V_{out}(1 - D)}{V_{in} * D} \tag{1}$$

Critical Inductance and critical capacitor for Flyback circuit.

$$L_c = \frac{(1 - D)^2 * R}{2 * f_{sw}} (\frac{N2}{N1})^2 \tag{2}$$

$$C_c = \frac{D * V_{out}}{R * \Delta Vo * f_{sw}} \tag{3}$$

Following the calculation of Lc and Cc using the Flyback equation, the appropriate high-frequency transformer, and inductor was selected.

To mitigate ripple voltage and ensure converter stability, a higher capacitor value was subsequently chosen in accordance with the formula. The selection of a higher capacitor value is essential for reducing ripple voltage, even though it may result in a higher peak current at the input. These components specifications are outlined in Table 2.

Table 2. The Specification of the Converter.

Converter Type	AC-DC Bridge Rectifier, DC-DC Flyback Topology
Switching Device	MOSFET (C3M0120065J by CREE was used)
Switching Frequency	20kHz -100kHz
HF Transformer	EE Series (EE16 74091 Flyback Transformer by MYRRA was used)
AC to DC Diode	IN5819
Capacitor	250uF
Inductor	6000uH
Controller Type	PWM PI Feedback Control (No overshoot and 0,1 Second Settling)
Input Voltage	Region Independent (230/100 VAC at 50/60Hz)
Output Voltage	5 VDC
Output Current	1A
Load Type	Resistor (5-ohm)

The proportional-integral (PI) value was tuned for a settling time within 0.1 seconds without overshooting.

For diode selection, the circuit's maximum current was observed on an oscilloscope, guiding the choice of a diode capable of withstanding the surge forward current. Finally, measurements were conducted to assess metal-oxide-semiconductor field-effect transistor (MOSFET) temperature and power efficiency.

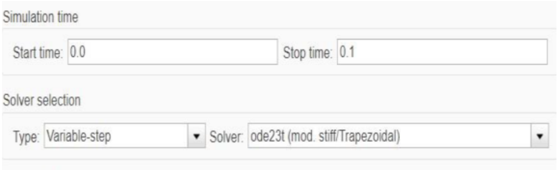
3.2. *The Simulation on MATLAB Simulink and PLECS*

MATLAB Simulink and PLECS were utilized for running simulations, which play a significant role in the selection of components for the power converter. The design overview of the AC-DC 5-Watt USB charger on MATLAB Simulink and PLECS software are shown on Fig. 6 and Fig. 7. Additionally, the PWM PI feedback control was implemented to address steady-state error, requiring lower forward gain.

The PI controller ensures a stable 5V output under varying input voltages by generating a corrective signal to address system faults. Manual adjustments to the proportional and integral values of the PI controller were made until the desired output was stabilized without overshooting.

The flyback capacitor is adjusted to 250 microfarads during PI value tweaking to prevent excessive ripple. The PI value should be at P=0.06 and I=16, it was subsequently found.

The MATLAB Simulink environment is configured with the solver ode23t (modified Stiff/Trapezoidal), as outlined in Fig. 5 to facilitate analysis before conducting performance tests.



Simulation time

Start time: 0.0 Stop time: 0.1

Solver selection

Type: Variable-step Solver: ode23t (mod. stiff/Trapezoidal)

Fig. 5 The Configuration Parameters of the Simulink Solver.

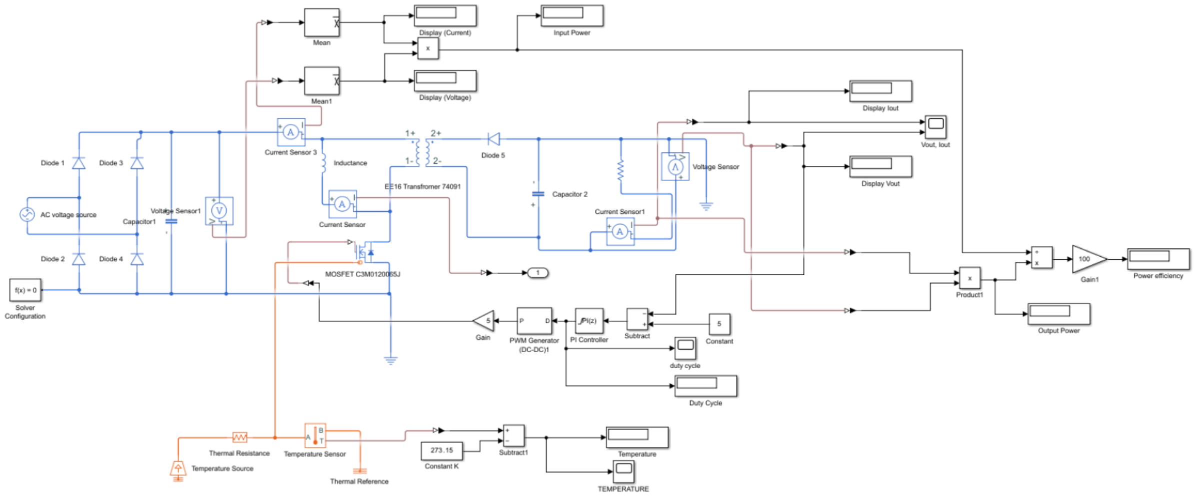


Fig. 6 The MATLAB Model of the AC – DC 5-Watt USB Charger.

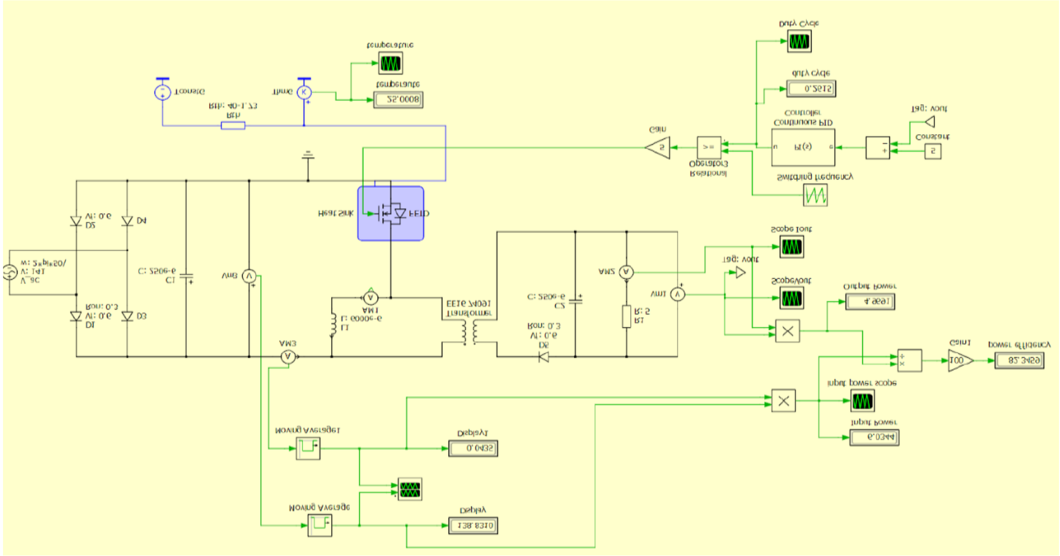


Fig. 7 The PLECS Model of the AC – DC 5-Watt USB Charger.

4. Results and Discussion

The 5-Watt USB Charger simulation results, as detailed in Table 3, are presented utilizing both MATLAB Simulink and PLECS. The simulations were conducted using a f_{sw} value of 40kHz and a PI value of P=0.06 and I=16. The results from both simulations are tabulated and compared to each other.

Table 3. Comparison of the Simulation Results of the AC – DC 5-Watt USB Charger.

Voltage Region	**Frequency**	**Input Voltage** **Input Current** **Input Power**		**Output Voltage** **Output Current** **Output Power**	
		MATLAB	PLECS	MATLAB	PLECS
141V	50Hz	138.9V 45mA 6.31W	138.83V 43.5mA 6.03W	5.002V 1.00A 5.003W	4.985V 997mA 4.969W
	60Hz	138.9V 45mA 6.307W	138.9V 43.4mA 6.034W	5.002V 1.00A 5.004W	4.985V 997mA 4.970W
325V	50Hz	323.1V 22.6mA 7.307W	323.23V 18.5mA 5.989W	4.996V 999mA 4.992W	4.987V 997mA 4.973W
	60Hz	323.2V 22.5mA 7.302W	323.25V 18.5mA 5.989W	4.996V 999mA 4.992W	4.987V 997mA 4.974W

4.1. *The Output Voltage, Current and Power*

The result indicates that the USB charger produces an output voltage of 5VDC and an output current of 1A and shown in Fig. 8.

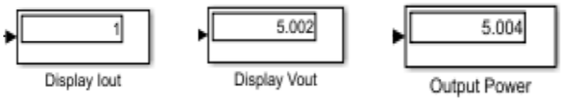
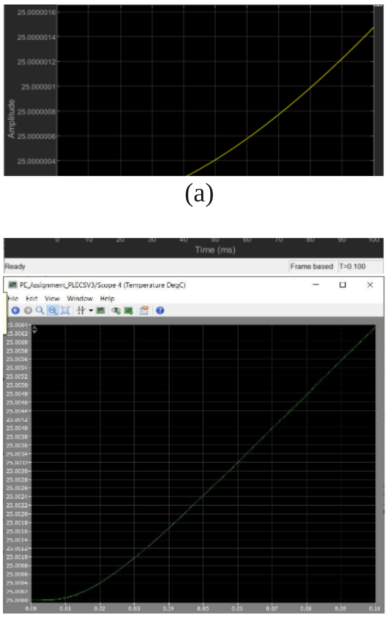


Fig. 8 The Scope of Voltage, Current, and Power Output at 325/100V AC with 50/60Hz.



(a)

(b)

Fig. 9 The scope thermal analysis at 230/100VAC at MATLAB Simulink (a) and PLECS (b).

4.2. *Thermal Analysis*

Fig. 9 performs the scope thermal analysis of the input voltage at 230/100 VAC in MATLAB Simulink (a) and PLECS (b). The result of MOSFET temperature reaches a steady-state value of 25 °C in MATLAB Simulink and 25.06 °C in PLECS, after a simulation time of 0.1 seconds.

Table 4 performs detail comparison on the MOSFET temperature after simulation at different voltage regions and frequencies.

The MOSFET temperature is slightly higher in PLECS than in MATLAB Simulink. This is consistent with the results of the simulation setup, which showed that PLECS software utilized a more detailed thermal model of the MOSFET. As can be seen from Fig. 9 (a) and (b), the MOSFET temperature is slightly higher in PLECS than in MATLAB Simulink.

Table 4. The MOSFET Temperature After Simulation

Voltage Region	**Frequency**	**MOSFET Temperature**	
		MATLAB	PLECS
141V	50Hz	25 °C	25.06 °C
	60Hz	25 °C	25.06 °C
325V	50Hz	25 °C	25.01 °C
	60Hz	25 °C	25.01 °C

4.3. *Power Efficiency*

Power efficiency results can be observed on differences input voltages and frequencies in Table 5. The table showed power efficiency was also compared with using MATLAB and PLECS software. The results in the MATLAB are between 68% and 79%. On the other hand, the power efficiency in PLECS is more consistent at 82.35% to 83.04%. It is notably underscoring the difference in the power efficiency in both software.

Table 5. Power Efficiency After Simulation.

Voltage Region	**Frequency**	**Power Efficiency**	
		MATLAB	PLECS
141V	50Hz	79.29%	82.35%
	60Hz	79.35%	82.37%
325V	50Hz	68.31%	83.04%
	60Hz	68.37%	83.04%

Comparing to MATLAB Simulink, the performance of PLECS on simulation power efficiency USB charger exhibits a 3.06% improvement at 141 VAC with 50/60Hz. Moreover, PLECS further outperforms, demonstrating a significant 14.73% increase in power efficiency with a 325V AC input voltage at 50/60Hz frequency.

MATLAB is a general-purpose software used in engineering fields for numerical analysis, data visualization, and simulation of complex systems, using a discrete-time simulation method. MATLAB's general approach to simulation may not be as accurate in modelling power electronics components, resulting in less consistent power efficiency results.

PLECS is designed specifically for simulating power electronics systems, using a continuous-time simulation method with specialized models for simulating power electronic components. The different simulation methods and models used by these two software tools could result in variations in simulation outcomes, including power efficiency.

PLECS specialized models accurately represent the behaviour of power electronic components leading to more precise simulations and consistent power efficiency results.

While the same datasheet was implemented, this does not demonstrate that the MATLAB Simulink software is superior for simulating the circuit because the MOSFET's specific parameter differs from that of the PLECS Software. This is because the MOSFET in the PLECS Software is based on the characteristics of the actual MOSFET that have been implemented by the manufacturer, CREE. On the other hand, the parameters for the MOSFET in the MATLAB/Simulink Software are manually entered based on the datasheet.

When simulated in 0.1 seconds, the MOSFET temperature of each software is slightly comparable. Nevertheless, the temperature of the simulation in PLECS Software is slightly higher than that of the simulation in MATLAB Simulink Software. This is because MOSFET's specific parameter varies depending on the software.

In MATLAB Simulink software, the MOSFET is manually inserted based on the datasheet, which may result in less precision than the model used in the PLECS software. Whereas in PLECS software, MOSFET is based on the manufacturer, CREE. The parameters and thermal model of MOSFET are needed to add into PLECS thermal library.

The ways to solve the numerical methods involved to solve the system of equations also can impact the outcome of simulations in both MATLAB Simulink and PLECS Software, which might result in some degree of error throughout the simulation results.

Step size, solver parameters, and the accuracy of the used models are only a few of the variables that affect how accurate the simulation is. It is advised to decrease the step size or raise the solver accuracy in both MATLAB and PLECS software and evaluate if the simulation results converge to improve the accuracy of the simulation results.

5. Conclusion

This paper successfully constructs a 5-Watt USB power charger, exploring AC to DC full bridge rectifier and DC-to-DC Flyback converters. Each circuit component's parameter adjustments produce the 5VDC, 1A output, necessitating a PI controller for stability. This controller manages P = 0.06 and I=16, minimizing the difference between reference and actual voltage. Two simulation software were compared for their performance and outcomes. PLECS excels, designed specifically for power electronics, offering greater accuracy and faster, memory-efficient, showing a 3.06% advantage at 141V and 50/60Hz. Moreover, at 325V AC input voltage with 50/60Hz frequency, PLECS excels further, exhibiting 14.73% increase in power efficiency compared to MATLAB Simulink. The simulation study provides a comprehensive understanding of converter interactions and highlights PLECS Software advantages in power electronics simulations over MATLAB Simulink Software.

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References

1. F. Bordry and D. Aguglia, "Definition of Power Converters," CAS - CERN Accelerator School: Power Converters, Baden, Switzerland, pp. 15–43, Jun. 2015.
2. M. G. Simões and F. A. Farret, Modeling Power Electronics and Interfacing Energy Conversion Systems. Wiley, 2016.
3. C.-J. Chen, C.-H. Cheng, P.-S. Wu, and S.-S. Wang, "Unified Small-Signal Model and Compensator Design of Flyback Converter With Peak-Current Control at Variable Frequency for USB Power Delivery," IEEE Trans Power Electron, vol. 34, no. 1, pp. 783–793, Jan. 2019.
4. J. Zhai, F. Wang, L. Ye, and R. Li, "Optimal Strategy of Triple Phase Shift Transient DC Bias for Dual Active Bridge DC-DC Converter," E3S Web of Conferences, vol. 185, p. 01088, Sep. 2020.
5. A. Singh, A. K. Yadav, and A. Khaligh, "Steady-State Modeling of a Dual-Active Bridge AC–DC Converter Considering Circuit Nonidealities and Intracycle Transient Effects," IEEE Trans Power Electron, vol. 36, no. 10, pp. 11276–11287, Oct. 2021.
6. C. S. Wong, K. H. Loo, and L. Cao, "A Single-stage Three-phase Bidirectional AC-DC IPT Converter based on SWISS-Rectifier for EV Charging Applications," in IECON 2022 – 48th Annual Conference of the IEEE Industrial Electronics Society, IEEE, Oct. 2022, pp. 1–6.
7. Filho, "Predictive Control Applied to a Single-Stage, Single-Phase Bidirectional AC-DC Converter," IEEE Access, vol. 10, pp. 34984–34995, 2022.
8. S. Bagawade, I. Askarian, M. Pahlevani, and P. Jain, "A New Discrete Four-Quadrant Control Technique for Grid-Connected Full-Bridge AC–DC Converters," IEEE J Emerg Sel Top Power Electron, vol. 10, no. 2, pp. 2362–2379, Apr. 2022.
9. J. Liu, Y. Cheng, Y. Jia, and H. Wu, "Optimal Design of a Constant Frequency Series-Resonant DC/DC Converter with Wide Voltage Gain Range for Single-Stage Isolated AC/DC Power Conversion," in 2022 International Power Electronics Conference (IPEC-Himeji 2022- ECCE Asia), IEEE, May 2022, pp. 1036–1043
10. C. Wang, D. Sun, X. Zhang, W. Gu, and S. Gui, "A Constant Current Digital Control Method for Primary-Side Regulation Active-Clamp Flyback Converter in CCM Mode," in 2021 IEEE Energy Conversion Congress and Exposition (ECCE), IEEE, Oct. 2021, pp. 3501–3506.
11. B. Zhang, J. Deng, L. Li, Z. Wang, S. Wang, and G. Guidi, "Thermal Analysis and Design of a 30kW EV Wireless Charger with Liquid-Cooled Shell for Magnetic Coupler and Integrated Power Converter," in 2021 IEEE Applied Power Electronics Conference and Exposition (APEC), IEEE, Jun. 2021, pp. 426–431.
12. J. Weimer, D. Koch, M. Nitzsche, J. Haarer, J. Roth-Stielow, and I. Kallfass, "Miniaturization and Thermal Design of a 170 W AC/DC Battery Charger Utilizing GaN Power Devices," IEEE Open Journal of Power Electronics, vol. 3, pp. 13–25, 2022.
13. B. K. Kushwaha, R. R., S. Jadhav, and S. T. S., "Thermal Analysis of 2.2kW Transformer of On-Board Charger for Electric Vehicles," in 2023 Second International Conference on Electronics and Renewable Systems (ICEARS), IEEE, Mar. 2023, pp. 311–314.
14. Y. D. Kuan, S. R. Lee, S. M. Lee, M. F. Sung, and H. S. Chiou, "The Performance Analysis of a Portable Charger System Using Direct Methanol Fuel Cells," in Proceedings of the 35th International MATADOR Conference, London: Springer London, 2007, pp. 129–132.

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