Half Bridge LLC Resonant Converter Design

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Abstract—**The growing demand for efficient and reliable power conversion systems in various applications, such as renewable energy integration, telecommunications, and industrial automa- tion, has driven innovation in resonant converter technologies. This paper presents the design, development, and testing of firmware for a 1.2kW Half- Bridge LLC Resonant Converter system. The main objective is to achieve compact design, ef- ficiency optimization, loss minimization, operational versatility, and reliability enhancement, which can be achieved through ad- vanced control algorithms and hardware optimization. Rigorous testing validates the system's ability to achieve high efficiency across varying loads. Insights into resonant tank design, mode transition, and control strategies are discussed. The importance of this project lies in its potential to replace less efficient conventional power conversion methods that suffer from high energy losses, thermal inefficiencies, and limited adaptability to dynamic load conditions. By leveraging MATLAB simulink for comprehensive design validation, this project demonstrates the practical feasibility of achieving zero-voltage switching and precise control over voltage and current, and reliable operation under diverse load scenarios. Furthermore, the study investi- gates the role of advanced components like Oring diode and MOSFETs, alongside control strategies such as dynamic load sharing and parallel operation, to enhance system performance. This research contributes to the advancement of cost-effective, high-performance power converters, with applications spanning energy-critical systems in both urban and rural settings.**

Index Terms—**Half-Bridge LLC Resonant Converter, Soft Switching, Zero Voltage Switching (ZVS), Resonant Tank Cir- cuit, Proportional-Integral (PI) Controller, MATLAB Simulink, Dynamic Load Handling, Constant Voltage Mode (CV), Con- stant Current Mode (CC), MOSFETs, ORing Diodes, Frequency Scaling.**

I. INTRODUCTION

Efficient and reliable power conversion systems are essential in modern industries, where scalability, and adaptability are critical [1, 2]. Due to this, LLC resonant converters have emerged as highly efficient solution for their ability to achieve soft switching techniques, and improving overall efficiency. This paper centres on the design and simulation of Half Bridge LLC resonant converter, tailored to deliver high ef- ficiency power while addressing real-world operational chal- lenges. Their compact size and adaptability to varying loads make them ideal for high performance power delivery. Using MATLAB Simulink model this study evaluates the system's performance under dynamic load conditions using advanced algorithm such as proportional- integral (PI) controller. This simulation investigates key factors, such as efficiency of the resonant tank, the responsive control system, the system's abil- ity to maintain stability during load variations. Challenges such as tuning resonant tank parameters, frequency optimization are done through iterative design and analysis. The results validate the proposed design's efficiency and scalabilty, offering a reliable foundation for energy-efficient applications.

II. PROBLEM STATEMENT

Traditional systems struggles with energy losses, poor adaptability, and inefficiency under dynamic loads. While LLC resonant converters offers soft-switching and high efficiency. This paper tackles challenges by designing and simulating a 1.2kW Half-Bridge LLC resonant converters focusing on resonant tank optimization, seamless mode transitions, and performance under varying load conditions using MATLAB Simulink.

III. LITERATURE REVIEW

LLC resonant converters have witnessed significant ad- vancements, particularly in topologies, control

strategies, application-specific designs, and loss minimization. Recent innovations in topology have focused on improving efficiency and adaptability. [1] introduced a half-bridge LLC resonant converter with a variable resonant inductor, dynamically ad- justing inductance to enhance efficiency under light-load con- ditions and voltage fluctuations. Similarly, [2] proposed a hy- brid design integrating a partial-power auxiliary unit, achieving higher voltage gain and optimized power distribution, suitable for EV onboard chargers. [3] developed a three-phase series resonant DC-DC boost converter using double LLC resonant tanks, enabling soft-switching across a wide load range for reduced thermal stress and high power density. Furthermore,
[17] addressed heat dissipation issues by incorporating planar
transformers, significantly improving thermal performance and reliability.

In terms of control strategies, [4] presented a wide voltage range control mechanism that combines PWM and feedback, ensuring efficient voltage regulation. [5] introduced a boost PWM scheme for hold-up state operations, stabilizing per- formance and reducing ripple. [13] implemented a CCCV control strategy, optimizing battery charging efficiency while minimizing thermal losses. For high-precision applications,
[12] developed an AC-DC converter with cable and inductance compensation schemes for accurate voltage regulation.

Applications in battery charging have also been a focal point. [6] outlined a comprehensive design methodology em- phasizing ZVS operation to enhance efficiency and reliability in EV chargers. [7] proposed a design approach that prioritizes time-weighted average efficiency, ensuring consistent perfor- mance across varying loads. Additionally, [9, 11] highlighted control strategies that enable LLC converters to maintain high efficiency over wide voltage ranges in practical charging scenarios.

Efforts to minimize losses and improve reliability include [15], who introduced an on/off resonant capacitor control technique to reduce switching losses and enhance server power supply efficiency. [16] provided a detailed thermal loss analysis, offering valuable insights for high-power operations.
[18] proposed a dual transformer configuration to address challenges associated with wide input voltage ranges, ensuring stable and efficient operations.

IV. RESEARCH ON COMPONENTS

A. ORing Diodes vs. MOSFETs

Traditional ORing diodes are often used for fault-tolerant power paths, but their efficiency is limited by the forward voltage drop. MOSFETs offer an alternative with lower con- duction losses, especially in high-current applications.

MOSFETs offer significant advantages in terms of effi- ciency, thermal management, and switching speed when used in power converters. These benefits align with innovations such as planar transformers to improve heat dissipation and reliability [17]. Their low Rds (on) minimizes power losses during conduction, making them highly efficient compared to conventional diodes. Additionally, MOSFETs generate less heat as a result of reduced energy dissipation, simplifying thermal management, and enhancing reliability. Their fast switching speed ensures a quick response to dynamic load conditions, making them ideal for applications requiring high performance and adaptability. Furthermore, MOSFETs enable seamless integration with advanced digital control techniques, allowing for precise fault detection and load balancing. Their scalability and compatibility with modern power management systems make them a preferred choice for optimizing power density and system performance in both industrial and con- sumer applications.

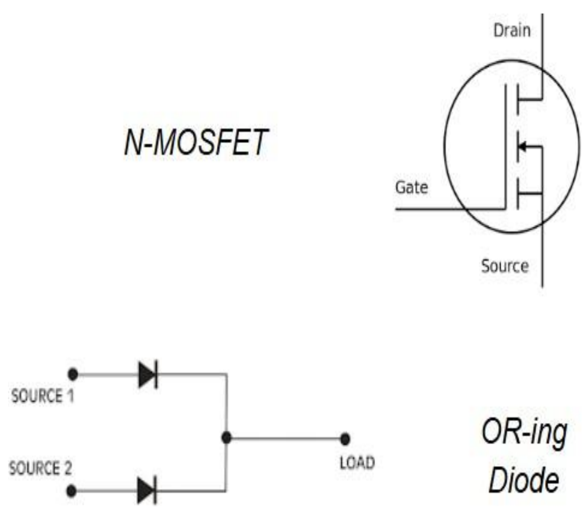


Fig. 1. ORing Diode and n- channel MOSFET

B. Types of Control Systems

1) Centralized Control: A single controller regulates all converters, ensuring unified operation but introducing a single point of failure, which may demand redundancy strategies for critical applications.

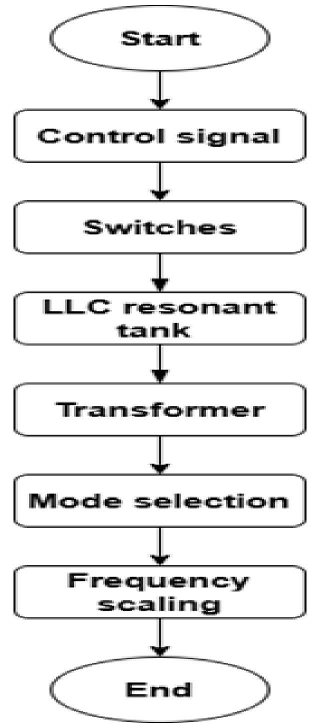
2) Master-Slave Configuration: One converter serves as the master, dictating operations for the slaves, offering scalability but requiring synchronization and robust communication to prevent instability during transient conditions.

3) Parallel Operation with Current Sharing: Distributes load among multiple converters, enhancing reliability and efficiency, while necessitating precise current-sharing mecha- nisms to avoid component overloading or thermal imbalance.

The proposed system employs a parallel operation approach, allowing dynamic sharing of load current across components. Dynamic load sharing approaches [4] further optimize effi- ciency under varying conditions by balancing the workload in real-time, minimizing stress on individual converters, and improving overall system longevity.

V. PROPOSED SYSTEM

The proposed system is a 1.2kW Half-Bridge LLC Resonant Converter, designed to efficiently regulate power delivery and ensure reliable operation across varying load conditions. The system integrates a Resonant Tank Circuit, Control Strategy, and Dynamic Load Handling features to achieve high ef- ficiency, low losses, and stable output. Figure 2 illustrates the fundamental flow of the system. The process begins with a control signal sent to the switches, which operate in synchronization by turning on and off simultaneously to generate waveforms. These waveforms are then passed through the LLC converter and subsequently through the transformer. The circuit monitors the output, and based on varying load conditions (light, medium, or heavy load), the frequency scaler dynamically adjusts the frequency to maintain a stable output.



A. Resonant Tank Circuit

The resonant tank circuit is a vital component in the system, composed of two inductors (Lr and Lm) and a capacitor (Cr).

The use of multi-tank resonant designs [3], demonstrates the potential for soft-switching and high power density. These components work together to establish the resonant frequency essential for the converter's operation. [2] When operating at its resonant frequency, the tank circuit facilitates soft-switching, minimizing switching losses and enabling efficient energy transfer. The transformer with a 6:1 turns ratio helps transfer energy between the input and output, ensuring optimal voltage regulation.

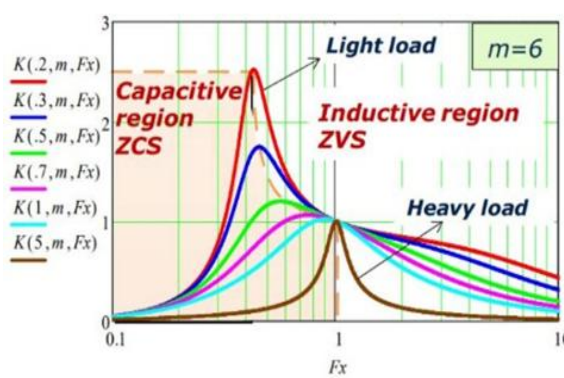


Fig. 3. LLC Converter Gain vs. Load Regions

$$Q = \frac{\sqrt{L_x/C_x}}{R_{ac}}, \quad Q \text{ - quality factor}$$

$$R_{ac} = \frac{8 \cdot N_p^2 \cdot R_o}{\pi^2 \cdot N_s^2}, \quad R_{ac} \text{ - reflected load resistance}$$

$$F_x = \frac{f_s}{f_r}, \quad F_x \text{ - normalized switching frequency}$$

$$f_r = \frac{1}{2\pi\sqrt{L_x \cdot C_x}}, \quad f_r \text{ - resonant frequency}$$

$$m = \frac{L_r + L_m}{L_r},$$

m - ratio of primary inductance to resonant inductance

2) *Calculation of Rac:*

Input Voltage : 300 V − 400 V dc,

Output Voltage : 50 V,

$$P_{out} : 1.2\,\text{kW},$$

$$N_p : N_s : 3 : 1,$$

$$Q : 0.4,$$

$$m : 6,$$

$$f_r : 100\,\text{kHz}.$$

$$R_{ac,\min} = \frac{8 \cdot N_p^2 \cdot R_o}{\pi^2 \cdot N_s^2},$$

$$R_o = \frac{V_o^2}{P_{\max}},$$

$$R_o = \frac{50^2}{1200},$$

$$R_o = 2500,$$

$$R_{ac,\min} = \frac{8 \cdot 9 \cdot 2500}{\pi^2 \cdot 1200},$$

$$R_{ac,\min} = 15.21.$$

3) *Calculation of Lr, Cr and Lm:*

$$Q_{\max} = \frac{\sqrt{L_x/C_x}}{R_{ac}} \implies 0.4 = \frac{\sqrt{L_x/C_x}}{15.21},$$

$$f_x = \frac{1}{2\pi\sqrt{L_x C_x}} \implies 100 \times 10^3 = \frac{1}{2\pi\sqrt{L_x C_x}},$$

$$\sqrt{L_x/C_x} = 6.084, \quad \sqrt{L_x C_x} = 1.6 \times 10^{-6}.$$

Solving the above equations, we get:

$$L_x = 37.01\,\mu\text{H},$$

$$L_x = 9.6\,\mu\text{H},$$

$$C_x = 0.26\,\mu\text{F}.$$

Solving for Lm using the formula, we get:

Lm = 48 µH.

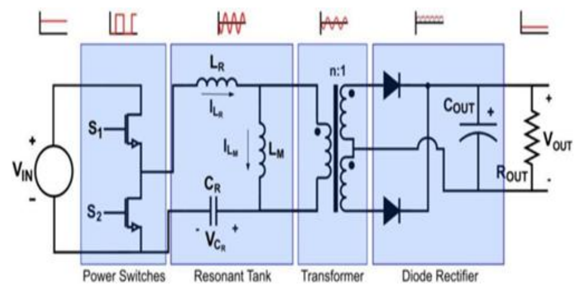


Fig. 4. LLC Resonant Tank Circuit

B. Control Strategy

The system uses a Proportional-Integral (PI) controller to regulate output voltage and current dynamically. Such strate- gies [12], enable precise voltage regulation through advanced compensation techniques. In Constant Voltage (CV) mode, the controller ensures the output voltage remains stable at 54 V, for heavy load condition where the load is above 60% adjusting the switching frequency to optimize energy conversion.In Constant Current (CC) mode, the controller limits the output current to 25 A to protect the system from over-current conditions. This limit applies under medium load conditions, where the load ranges from 30% to 60%, and light load conditions, where the load is below 30%. To ensure efficient operation, a harmonic oscillator and a phase-shift controller are used to generate precise control signals for the MOSFETs. These signals help balance power transfer and minimize losses, particularly at a 50% duty cycle [4]. In Figure 5, V ref represents the reference voltage, which is used to regulate the system to maintain a constant voltage at the specified value. V actual denotes the actual voltage reading, which is processed by the PI controller. Similarly, battery ref is the reference value set for the battery, ensuring regulation at the desired level, while battery actual indicates the actual battery measurement. The reference and actual voltages (V ref and V actual) are compared and the difference is sent to the mode selection block which then forwards it to the PI controller. The PI controller output is then passed through a saturator to maintain the output within a defined range. This output is directed to a mode selection block, which operates in either constant voltage (CV) or constant current (CC) mode. In the event of a power outage, the system transitions to battery operation. The signal is subsequently routed to a frequency scaling block, which adjusts the frequency signal sent to the switches for regulation.

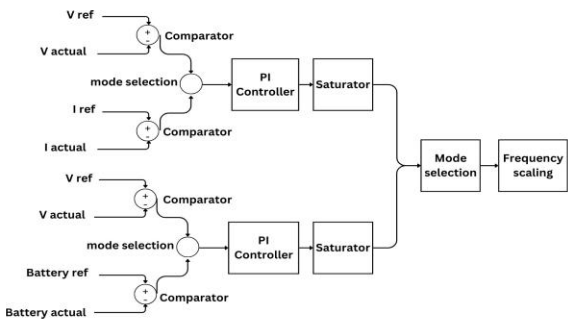


Fig. 5. Block Diagram of Mode Selection

C. Dynamic Load Handling

The converter seamlessly transitions between CV and CC modes based on load conditions [5]. [4] This dynamic load handling ensures stable operation regardless of changes in load conditions. The frequency scaling function adjusts the switching frequency according to the PI controller's output, optimizing the operation of the resonant tank and transformer under varying load conditions. Additionally, the multi-source operation ensures that current is shared proportionally among sources, preventing overloading and ensuring balanced opera- tion.

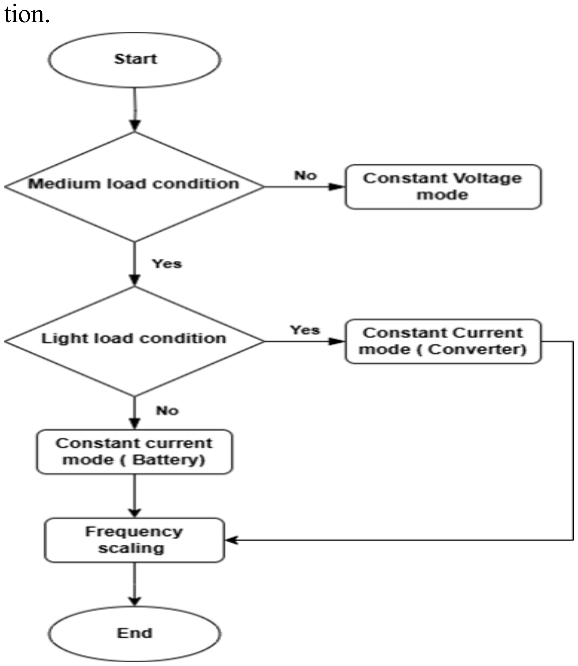


Fig. 6. Dynamic Load Handling process

VI. SIMULATION

MATLAB Simulink was used to simulate the Half-Bridge LLC Resonant Converter. The simulation model captured essential parameters influencing system efficiency, stability, and reliability.

A. Simulation Setup

1) Resonant Tank Parameters: The resonant tank parame- ters, including inductors and capacitors, are chosen to achieve the optimal resonant frequency for efficient operation. The values of Lr, Lm, Cr are set to ensure ZVS (Zero Voltage Switching) across varying loads, minimizing switching losses and improving overall efficiency.[1][3] In Figure 7, Lf repre- sents the resonant inductor, Cf denotes the resonant capacitor, and RL corresponds to the resistive load.

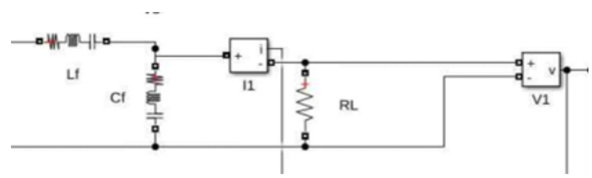


Fig. 7. LLC resonant tank

2) Transformer Design: The transformer is designed with a 3:1 turns ratio to step down the voltage from the primary to the secondary side of the circuit. This ratio ensures proper voltage transformation, providing the correct output voltage for the load while maintaining energy transfer efficiency.

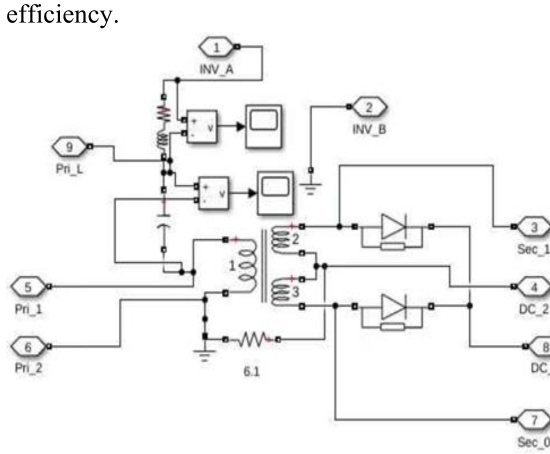


Fig. 8. Transformer Design

3). Control System: The PI controller is configured to manage both voltage and current regulation. For CV mode, the controller maintains a stable output voltage by adjusting the switching frequency. In CC mode, it limits the output current to prevent overloading. The harmonic oscillator and phase-shift controller work together to generate the necessary control signals for the MOSFET switches, ensuring efficient energy transfer. For the calculations, f max is defined as the maximum frequency within the specified range, while f min represents the minimum frequency of the same range. The frequency is scaled between 0.1 and 0.9. The system maps the minimum and maximum voltage levels to the corresponding minimum and maximum frequency values and generates the required frequency signal to regulate the output effectively.

Calculation for Frequency Scaling:

$$N = (0.9, 90)$$

$$y = (0.1, 160)$$

$$f_{max} = 160\,\text{kHz}$$

$$f_{min} = 90\,\text{kHz}$$

$$V_{min} = 2\pi f_{min}\Delta T$$

$$V_{min} = 2\pi \times 90 \times 10^{3} \times 0.1 \times 10^{-6}$$

$$V_{min} = 0.05652$$

$$V_{max} = 2\pi f_{max}\Delta T$$

$$V_{max} = 2\pi \times 160 \times 10^{3} \times 0.1 \times 10^{-6}$$

$$V_{max} = 0.1$$

The linear equation:

$$y = mx + c$$

The slope m is calculated as:

$$m = \frac{y_2 - y_1}{x_2 - x_1}$$

$$m = \frac{160 - 90}{0.1 - 0.9}$$

$$m = -0.55625$$

The intercept c is:

$$c = 0.1056$$

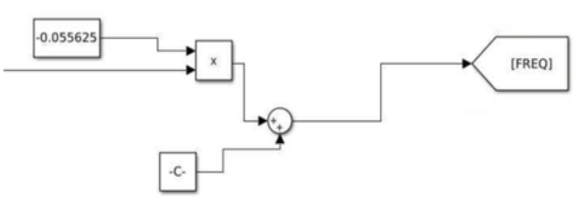


Fig. 9. Frequency scaling block

3) Load Conditions: The system is tested under varying load conditions, where the load resistance is adjusted to simulate different operational scenarios. During heavy load condition, the system operates in CV mode. Below this thresh- old, the system switches to CC mode to limit the current and protect the system.

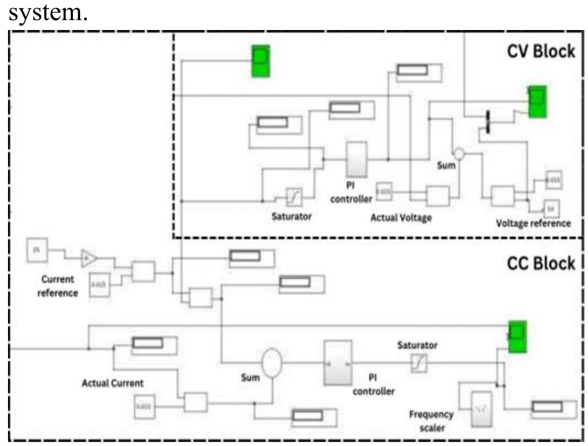


Fig. 10. MATLAB Mode selection block

B. Simulation Results

1) Voltage and Current Regulation at dynamic load con- dition: The simulation results demonstrate that the system effectively maintains a stable output voltage of 54 V in Constant Voltage (CV) mode. Under medium and light load conditions, the system transitions to Constant Current (CC) mode, limiting the output current to 25 A. The PI controller dynamically adjusts the switching frequency to ensure precise regulation of both voltage and current, achieving efficient performance across varying operating conditions. In heavy load conditions, the control loop operates exclusively in CV mode, resulting in lower current values for both the converter and the battery. During medium load conditions, the system transitions to battery mode, where the converter current is significantly reduced, and the battery current stabilizes at 25 A. In light load conditions, the system shifts to converter mode, with the converter actively regulating current and voltage while the battery retains its stored charge, which discharges gradually over time. Figures 11, 12, and 13 provide a detailed representation of the simulation outputs for these varying load scenarios.

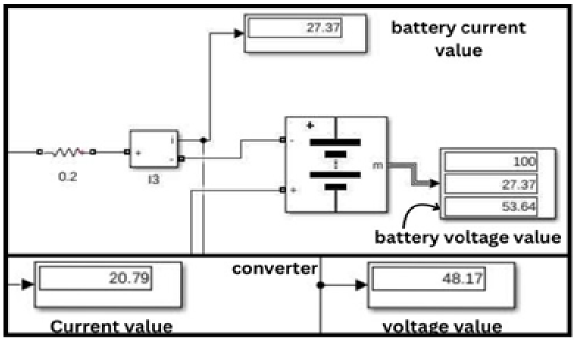


Fig. 11. Light Load condition

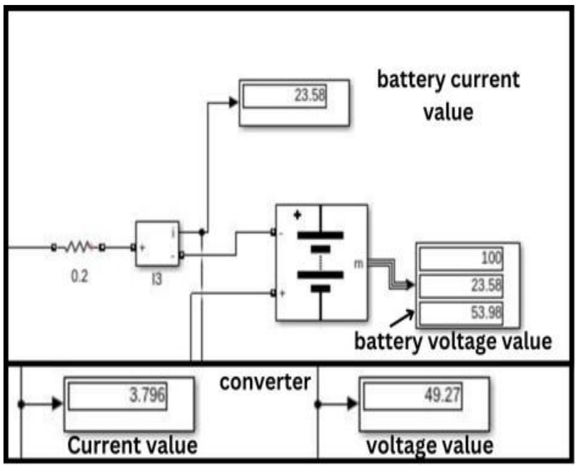


Fig. 12. Medium Load condition

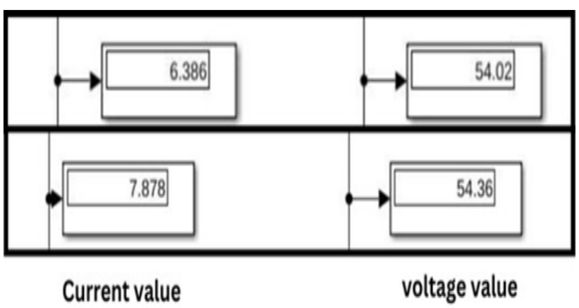


Fig. 13. Heavy Load condition

2) *Efficient Switching:* The transition between CV and CC modes is seamless, with no disruption in output stability. The system successfully adapts to changes in load resistance, switching modes when necessary, and adjusting the switching frequency to optimize energy delivery. The frequency scaling function adjusts the output by controlling the signals, ensuring that the resonant tank and transformer work efficiently. This helps maintain optimal performance, especially during transi- tions between different operating modes.

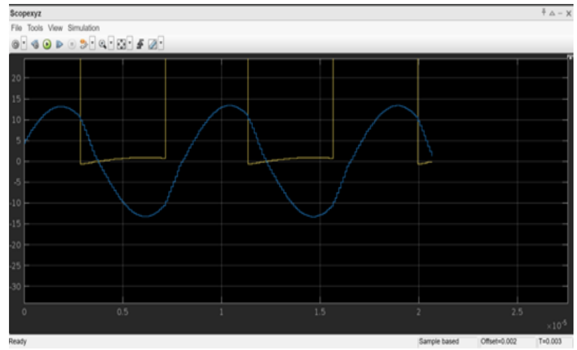


Fig. 14. Control signal and PWM

VII. CHALLENGES FACED AND SOLUTIONS

A. Resonant Tank Design

- Challenge: Determining the optimal values Lr, Cr, Lm to ensure ZVS across the entire load range. [1]
- Solution: Extensive MATLAB simulations were con- ducted to fine-tune the resonant tank parameters, ensuring minimal circulating currents and efficient power transfer.

B. Control System Tuning

- Challenge: Ensuring stable and responsive transitions between CV and CC modes.
- Solution: The PI controller was optimized through trial- and-error simulations, achieving precise frequency adjust- ments without overshoot or instability.

C. Component Selection

- Challenge: Selecting components that balance cost, per- formance, and efficiency, such as OR-ing diodes and MOSFETs.
- Solution: Research and comparison of ORing diodes and MOSFETs revealed that n-channel MOSFETs provided higher efficiency and lower conduction losses compared to traditional diodes, making them ideal for synchronous rectification.

VIII. FUTURE WORK

Future advancements in the 1.2kW Half-Bridge LLC Res- onant Converter can focus on several key areas to enhance its performance and scalability. Implementing the design in hardware is essential to validate its real-world performance while addressing challenges such as thermal management and parasitic effects to ensure reliable operation [21,22]. The integration of AI-driven control systems can enable real-time load optimization, allowing the converter to adapt dynamically to varying conditions and significantly improve operational ef- ficiency. Additionally, exploring multi-source integration, par- ticularly with renewable energy, can broaden its applicability and facilitate seamless energy distribution for hybrid systems. Scaling the converter to support higher power levels will make it suitable for a wider range of industrial applications, while investigating advanced resonant topologies can optimize energy conversion, reduce losses, and improve adaptability. Furthermore, adopting wide bandgap semiconductors such as Silicon Carbide (SiC) and Gallium Nitride (GaN) can enhance switching efficiency, reduce thermal losses, and support high- frequency operation. These developments will contribute to a more efficient, reliable, and versatile power conversion system, meeting the growing demands of modern industrial applications.

IX. CONCLUSION

The simulation and analysis of the 1.2kW Half-Bridge LLC Resonant Converter demonstrate its significant potential in achieving high-efficiency power conversion for dynamic load conditions. The research successfully addresses challenges re- lated to resonant tank optimization, seamless mode transitions, and control system tuning using advanced algorithms and iterative MATLAB simulations. By integrating components such as MOSFETs and employing a PI-based control strategy, the design achieves low switching losses, robust dynamic performance, and stable operation across varying loads. The results validate the converter's ability to maintain efficient and reliable operation, with seamless transitions between constant voltage (CV) and constant current (CC) modes. The use of frequency scaling and dynamic load handling further enhances system adaptability and performance. The study lays a strong foundation for practical hardware implementations and sets the stage for future advancements in high-efficiency power conversion systems. With its scalable design, compact size, and capability to address real-world operational challenges, this project contributes to the growing demand for energy- efficient and reliable power conversion technologies.

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