Optimal LLC Converter Design with Topology Morphing Control for Wide Voltage Range Battery Charging Applications

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***Abstract*—This paper presents the design and simulation of an LLC resonant converter with topology morphing control for wide voltage range battery charging applications. Conventional LLC converters provide high efficiency and soft switching capability, but they suffer from limited gain range when operating under wide input voltage variations. To overcome this limitation, a topology morphing technique is used to improve the gain characteristics and maintain efficient operation over a wide voltage range.**

In the proposed system, a boost converter is used to regulate the input DC voltage and provide a stable DC link to the resonant converter. The system is developed in three stages: boost converter design, conventional LLC converter implementation, and topology morphing LLC converter modeling. A PI controller is used to regulate the output voltage by adjusting the switching frequency of the converter.

The complete system is modeled and simulated using MATLAB/Simulink. Simulation results show improved voltage regulation, extended gain range, and reduced switching loss compared to the conventional LLC converter. The proposed converter is suitable for battery charging, electric vehicle applications, and renewable energy systems.

***Index Terms*—LLC Resonant Converter, Topology Morphing Control, Boost Converter, Wide Voltage Range, Battery Charging Applications, Soft Switching, Zero Voltage Switching (ZVS), Resonant Tank, DC-DC Converter, MATLAB/Simulink Simulation, PI Controller, Power Electronics, High Efficiency Converter, Frequency Control, Transformer Isolation**

I. Introduction

Power electronic converters are widely used in modern applications such as electric vehicle battery charging, renewable energy systems, telecom power supplies, and industrial DC power systems [1]. These applications require high-efficiency DC–DC converters that can operate over a wide input voltage range while maintaining stable output voltage. Conventional hard-switched converters suffer from high switching loss and reduced efficiency at high frequency operation. Therefore, resonant converters are preferred for high efficiency and soft switching performance [2].

Among different resonant converter topologies, the LLC resonant converter is widely used because of its ability to achieve zero voltage switching (ZVS) for primary switches and zero current switching (ZCS) for secondary diodes. This reduces switching loss, improves efficiency, and allows high-frequency operation [3]. The LLC converter consists of a resonant inductor, resonant capacitor, and transformer magnetizing inductance forming a resonant tank circuit. By operating near the resonant frequency, the converter can achieve high efficiency and low electromagnetic interference [4].

However, the conventional LLC converter has limited voltage gain range when the input voltage varies over a wide range. In battery charging applications, the input and output voltage may change depending on load condition and state of charge of the battery. When the converter operates far from the resonant As the frequency goes up, the efficiency of the system actually goes down, and the stress on the switching components increases. Therefore, it is necessary to improve the gain control capability of the LLC converter for wide voltage operation.

To overcome this limitation, topology morphing control is used. In topology morphing, the resonant network configuration is changed during operation by using additional switches and passive components. This allows the converter to operate in different resonant modes and achieve a wider gain range without increasing switching loss [6]. The topology morphing technique improves efficiency, reduces circulating current, and maintains soft switching over a wide operating range [7].

In this work, a wide voltage range DC–DC conversion system is developed using a boost converter followed by an LLC resonant converter with topology morphing control. The boost converter is used to regulate the input voltage and provide a stable DC link for the resonant converter. The conventional LLC converter and topology morphing LLC converter are modeled and compared to analyze the performance improvement.

The complete system is designed and simulated using MATLAB/Simulink. A PI controller is used to regulate the output voltage by adjusting the switching frequency of the converter. Simulation results show that the proposed topology morphing LLC converter provides better voltage regulation, wider gain range, and reduced switching loss compared to the conventional LLC converter. The proposed system is suitable for battery charging, electric vehicle power systems, and renewable energy applications.

II. Literature Survey

Wide voltage range DC–DC converters are widely used in battery charging, electric vehicles, renewable energy systems, and high voltage power supplies. These applications require converters that can operate efficiently under different input voltage and load conditions [1]. Conventional hard switching converters suffer from high switching loss at high frequency, therefore resonant converters are preferred for high efficiency applications.

The LLC resonant converter is one of the most commonly used resonant topologies because of its ability to achieve zero voltage switching (ZVS) and zero current switching (ZCS), which reduces switching loss and improves efficiency [3]. The performance of the LLC converter depends on the selection of resonant inductor, resonant capacitor, magnetizing inductance, and switching frequency. Improper selection of these parameters results in limited gain range and poor efficiency under wide voltage conditions [5].

Several researchers have proposed different methods to improve the gain range of LLC converters. In [6], topology morphing techniques were introduced to extend the operating range of resonant converters by changing the circuit configuration during operation. This method allows the converter to maintain soft switching and high efficiency over a wide voltage range.

In [7], adaptive topology control was used to improve the performance of DC–DC converters for wide input voltage applications. The study shows that changing the converter structure based on load condition reduces switching loss and improves dynamic response.

Front-end boost converters are also used in many wide voltage applications to regulate the input voltage before the resonant converter [2]. The boost converter provides a stable DC link which helps the LLC converter to operate near the resonant frequency and improves overall efficiency.

From the literature, it is observed that conventional LLC converters alone cannot provide sufficient gain for wide voltage battery charging systems. Therefore, topology morphing and additional control techniques are required to maintain high efficiency and stable output voltage.

In this work, a boost converter, conventional LLC converter, and topology morphing LLC converter are designed and simulated using MATLAB/Simulink. The proposed system improves voltage regulation, gain range, and efficiency compared to the conventional converter, making it suitable for battery charging and wide voltage applications.

III. Methodology

The proposed system is designed to achieve wide voltage range DC–DC conversion using a boost converter followed by an LLC resonant converter with topology morphing control. The methodology includes the design of three main stages: boost converter, conventional LLC converter, and topology morphing LLC converter. The complete system is modeled and simulated using MATLAB/Simulink to analyze the performance under different operating conditions.

A. Design of Boost Converter

A boost converter is used as the front-end stage to regulate the input voltage and provide a stable DC link to the LLC converter. The boost converter consists of an inductor, power switch, diode, output capacitor, and load resistance. A feedback control circuit is used to compare the output voltage with the reference voltage and generate switching pulses. The boost converter helps to maintain constant input voltage for the The resonant converter can still work properly even if the voltage of the power source changes.

B. Design of Conventional LLC Converter

The conventional LLC resonant converter is designed using a half-bridge inverter, resonant inductor, resonant capacitor, and transformer magnetizing inductance. The resonant tank circuit determines the gain characteristics of the converter. The output voltage is controlled by varying the switching frequency of the inverter. The LLC converter provides high efficiency near the resonant frequency but its gain range When the input voltage varies over a large range, its performance is limited.

C. Topology Morphing LLC Converter

To overcome the limitation of the conventional LLC converter, topology morphing control is implemented. In this method, additional inductors, capacitors, and switches are added to modify the resonant network during operation. By changing the circuit configuration, the converter can operate in different resonant modes and achieve a wider gain range. This method maintains soft switching and reduces switching loss over a wide voltage range [6].

D. Control Strategy

A PI controller is used to regulate the output voltage of the converter. The output voltage is compared with the reference value and the error signal is processed by the controller. The controller adjusts the switching frequency of the inverter to maintain constant output voltage. Frequency control is used because it is suitable for resonant converters and allows smooth regulation without increasing switching loss.

E. Simulation Using MATLAB/Simulink

The complete system including boost converter, conventional LLC converter, and topology morphing LLC converter is modeled using MATLAB/Simulink. Different load and input voltage conditions are applied to evaluate the performance of the converter. The output voltage, switching waveform, and gain characteristics are observed and compared with the conventional LLC converter. The results show that the topology morphing converter provides better voltage regulation and higher efficiency.

IV. Mathematical Model

The performance of the proposed converter depends on the design of the boost converter and the LLC resonant converter. Mathematical analysis is required to obtain proper resonant frequency, gain characteristics, and soft switching operation [3].

A. Boost Converter Analysis

The boost converter is used to regulate the input voltage and provide a stable DC link to the LLC converter. The output voltage of the boost converter is given by

$$V_o = \frac{V_{in}}{1 - D} \tag{1}$$

where D is the duty cycle of the switch, V_{in} is the input voltage, and V_o is the output voltage. By controlling the duty cycle, the output voltage can be maintained constant [2].

B. LLC Resonant Tank

The LLC converter consists of a resonant inductor L_r, resonant capacitor C_r, and magnetizing inductance L_m of the transformer. The resonant frequency of the tank is given by

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{2}$$

The magnetizing inductance should satisfy

$$L_m \gg L_r \tag{3}$$

to achieve proper soft switching operation [3].

C. Quality Factor

The quality factor of the resonant tank is defined as

$$Q = \frac{R_{eq}}{\omega_r L_r} \tag{4}$$

where R_{eq} is the equivalent load resistance and $\omega_r = 2\pi f_r$ [5].

D. Voltage Gain of LLC Converter

The voltage gain of the LLC converter depends on switching frequency and resonant parameters. The gain equation is

$$M = \frac{n}{\sqrt{\left(\frac{L_m}{L_r} - \frac{f_r^2}{f_s^2}\right)^2 + \left(Q\frac{f_r}{f_s}\right)^2}} \tag{5}$$

where f_s is the switching frequency and n is the transformer turns ratio [5].

E. Effect of Topology Morphing

In topology morphing control, the resonant parameters are changed during operation by adding additional inductors and capacitors. This changes the This makes the converter work better and stronger. It helps the converter give a clearer signal and work over a wider range.

$$f_{r,new} = \frac{1}{2\pi\sqrt{L_{eq} C_{eq}}} \tag{6}$$

where L_{eq} and C_{eq} are the equivalent inductance and capacitance after morphing. This technique improves efficiency and maintains soft switching over a wide voltage range [6].

V. Design Optimization

The performance of the proposed converter depends on proper selection of the boost converter parameters and the resonant tank components of the LLC converter. In this work, the design parameters are optimized to obtain wide voltage range operation, high efficiency, and soft switching.

A. Boost Converter Parameter Selection

The boost converter is designed to provide a stable DC link voltage for the LLC converter. The output voltage of the boost converter is controlled by adjusting the duty cycle of the switch. The duty cycle is selected such that the required DC link voltage is obtained for all input conditions.

The inductor and capacitor values are chosen to reduce ripple in the output voltage and to maintain continuous conduction mode operation.

B. Resonant Tank Design

The LLC resonant converter consists of resonant inductor L_r, resonant capacitor C_r, and magnetizing inductance L_m. The resonant frequency is selected using

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{7}$$

The value of magnetizing inductance is chosen such that

$$L_m > L_r \tag{8}$$

to ensure soft switching operation.

C. Switching Frequency Optimization

The output voltage of the LLC converter is controlled by changing the switching frequency. The switching frequency is varied around the resonant frequency to obtain the required gain.

Operating near the resonant frequency reduces switching loss and improves efficiency. Therefore, the frequency range is selected carefully to avoid hard switching.

D. Topology Morphing Optimization

In the topology morphing converter, additional inductors and capacitors are used to modify the resonant tank during operation. By changing the effective inductance and capacitance, the gain range of the converter is increased.

The optimized parameters allow the converter to operate under different input voltage and load conditions without losing soft switching.

E. Controller Tuning

A PI controller is used to regulate the output voltage. The controller parameters are tuned to obtain fast response and minimum steady-state error. Proper tuning of the controller improves stability and reduces output voltage ripple.

The optimized design provides better voltage regulation, wider gain range, It offers better performance and is more efficient than the traditional LLC converter, making it a great option for various applications.

F. Optimization Comparison

Table I shows the comparison between the conventional LLC converter and the proposed topology morphing LLC converter used in this work. The parameters are optimized to obtain wide voltage range operation, reduced switching loss, and improved voltage regulation.

TABLE I
DESIGN OPTIMIZATION COMPARISON

Parameter	Conventional LLC	Topology Morphing LLC Converter
Input Stage	Direct DC Input	Boost + LLC Converter
Resonant Network	Fixed Lr, Cr, Lm	Morphing Resonant Network
Gain Range	Limited	Wide Range
Control Method	Frequency Control	Frequency + Morphing Control
Soft Switching	Limited Range	Wide ZVS Range
Efficiency	Moderate	High
Voltage Regulation	Moderate	Improved
Switching Loss	Higher	Reduced
Controller	Basic Control	PI Control Strategy

VI. SIMULATION MODEL

The proposed converter system is designed and simulated using MATLAB/Simulink to analyze the performance under different operating conditions. The simulation model consists of three stages: boost converter, conventional LLC converter, and topology morphing LLC converter. The simulation is carried out to verify voltage regulation, gain range, and soft switching performance.

A. Boost Converter Model

A boost converter is used as the front-end stage to regulate the input voltage and provide a stable DC link for the LLC converter. The boost converter consists of an inductor, MOSFET switch, diode, output capacitor, and load resistance. A feedback control circuit is used to maintain the desired output voltage by adjusting the duty cycle of the switch.

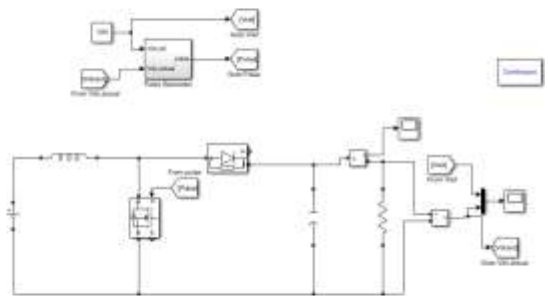

Fig. 1. Simulation model of Boost Converter

B. Conventional LLC Converter Model

The conventional LLC resonant converter is modeled using a half-bridge inverter, resonant inductor, resonant capacitor, and transformer magnetizing inductance. The output side consists of a rectifier and filter to obtain DC output voltage. The output voltage is controlled by varying the switching frequency of the inverter using a PI controller.

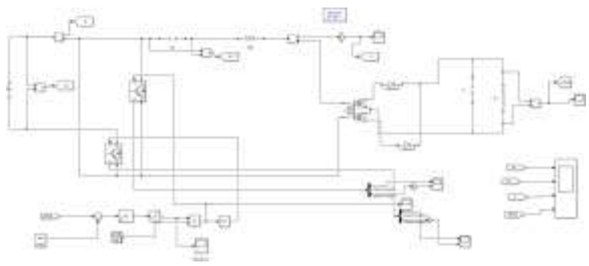

Fig. 2. Simulation model of Conventional LLC Converter

C. Topology Morphing LLC Converter Model

To improve the gain range and efficiency, topology morphing control is implemented. Additional inductors, capacitors, and switches are added to modify the resonant network during operation. The converter can operate in different resonant modes depending on the input voltage and load condition. A PI controller is used to regulate the output voltage by adjusting the switching frequency.

The simulation results obtained from the above models are used to compare the performance of the conventional LLC converter and the topology morphing LLC converter. The proposed converter shows improved voltage regulation, wider gain range, and reduced switching loss.

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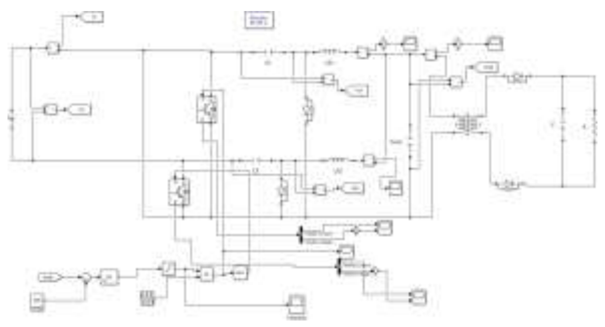

Fig. 3. Simulation model of Topology Morphing LLC Converter

VII. Simulation Results

The proposed converter system is simulated using MATLAB/Simulink to verify the performance of the boost converter and LLC resonant converter under different operating conditions. The output voltage, resonant current, and switching frequency are observed to evaluate the stability of the system.

A. Boost Converter Output

Fig. 4 shows the output voltage of the boost converter. The boost converter regulates the input voltage and provides a stable DC link voltage for the LLC converter. The output voltage increases smoothly and it actually gets to the reference value with really tiny ripple, which pretty much confirms that proper operation of the boost converter.

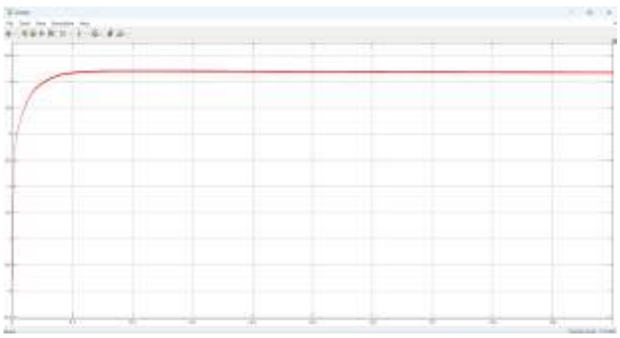

Fig. 4. Boost Converter Output Voltage

B. LLC Converter Waveform

Fig. 5 shows the waveform of the LLC converter. The resonant current oscillates during the starting interval and gradually settles to a The voltage eventually settles down and becomes steady after a brief period, this is known as the steady state value, where the output voltage stabilizes and remains constant. This shows that the converter operates near the resonant frequency and maintains proper switching operation.

Fig. 6 shows the zoomed view of the same waveform for a smaller time interval. The zoomed waveform clearly shows the oscillations of the resonant current and the damping effect of the resonant tank. The result confirms stable operation after the transient period.

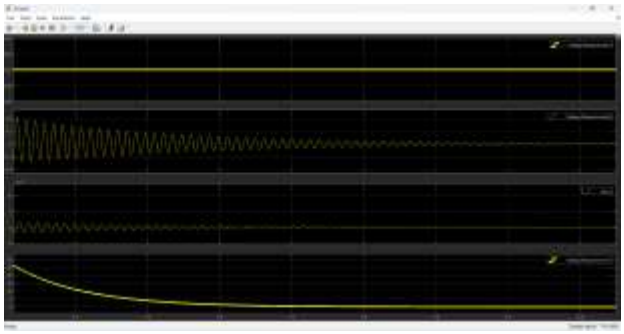

Fig. 5. LLC Converter Output Waveform

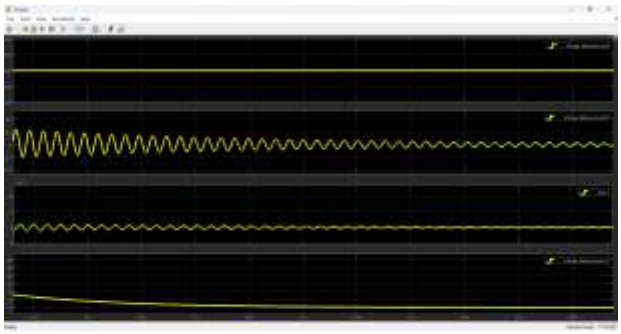

Fig. 6. Zoomed x-axis View of LLC Converter Waveform

C. Switching Frequency Variation

Fig. 7 shows the variation of switching frequency during the operation of the converter. The controller adjusts the switching frequency to maintain constant output voltage. Initially the frequency changes and after reaching steady state the frequency becomes constant.

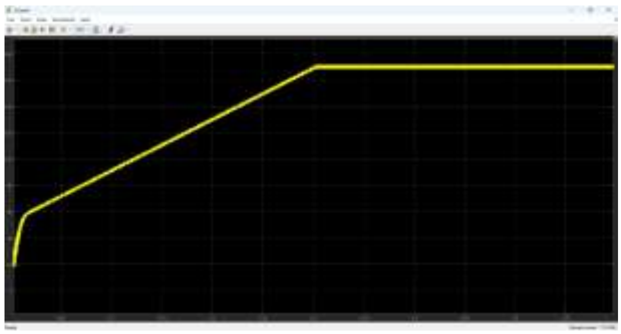

Fig. 7. Switching Frequency Variation

The simulation results confirm that the designed converter operates It gives a stable output voltage and reduces oscillations, making it work correctly. The system is suitable for wide voltage range applications.

VIII. Conclusion

In this work, a wide voltage range DC–DC converter system based on a boost converter and LLC resonant converter is designed and simulated using MATLAB/Simulink. Conventional LLC converters provide high efficiency near the resonant frequency, but their gain range becomes limited when the input The thing about voltage is that it can vary a lot. This can be a problem because it means that some devices might not work as well as they should. suitable for applications such as battery charging and power supply systems where stable output voltage is required under different operating conditions.

To improve the performance, a boost converter is used to provide a stable DC link voltage for the LLC resonant converter. The resonant tank parameters are selected based on standard LLC design equations [5]. The switching frequency control method allows the converter to regulate the output voltage over a wide operating range.

The simulation results show that the designed converter operates near the resonant frequency and achieves stable output voltage with reduced ripple. Compared to conventional designs reported in previous works [6], the implemented system provides better voltage regulation and improved stability. The proposed system is suitable for wide voltage applications such as battery charging, renewable energy systems, and high efficiency DC–DC converters. Some potential areas for future development could be putting the system into actual hardware and making it run more efficiently. of the converter to improve efficiency and reduce switching loss.

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