ADVANCED DESIGN AND SIMULATION ANALYSIS OF RESONANT LLC CONVERTERS IN AUTOMOTIVE APPLICATIONS

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ABSTRACT :

At present, a substantial volume of scholarly inquiry is devoted to exploring the diverse practical implementations of electric vehicles. These include charge stations, onboard adaptations, and other automotive components that necessitate distinct voltages for operation. We utilize one of these applications to provide Resonant LLC with translations. In recent times, there has been considerable interest among engineers and researchers in the Inductor Inductor Capacitor (LLC) resonant converter due to its exceptional power density relative to commercially available resonant converters, capability of functioning at high frequencies, and exceptionally minimal switching losses upon activation of the ZVS. This study demonstrates how to construct an LLC resonant converter that maintains a constant output voltage via Ziegler-Nichols PID adjustment. The DC/DC resonant LLC converter MATLAB/Simulink model outperformed alternative models when implemented in automobiles.

***Key Words*: Full bridge LLC, ZVS, Ziegler-Nichols' PID tuning method, soft switching.

1.INTRODUCTION

In addition, the increasing power requirements of automobiles improve the efficiency of DC-DC transformers. By increasing the operational frequency, it may be possible to decrease the dimensions of individual components, thereby accelerating the endeavor to decrease the overall size of power supplies designed for contemporary electric power systems. Resonant power conversion is becoming an increasingly popular method of minimizing the substantial switching losses that are inherent in higher frequency operations. The two primary categories of DC-DC converters are resonance converters and pulse-width modulation (PWM) converters.

In order to guarantee voltage output stability, which is a requirement for the majority of applications, the control system integrates a return loop. Models of small-signal equivalent circuits are indispensable for achieving optimal design goals.

Three components comprise the resonant LLC system: the input stage, the resonant tank, and the output stage. Three distinct components comprise each stage: input signals, control signals, and output signals. The correlation and reaffirmation of the relationship among the three components of each stage are meticulously examined. In addition to the standard PSIM simulation, an experiment involving FPGA-based HIL simulation is conducted to validate the FPGA-based model.By employing the proper LLC resonant converter design methodologies, it is guaranteed that the dimensions of the resonant components will consistently diminish as the switching frequency rises.

Furthermore, conservative capacitance and ESR configurations may aid in diminishing the dimensions of the output capacitor [4].A multitude of authors examined diverse LLC resonant converter components. The LLC resonant converter utilizes the leakage inductance of the transformer as a resonant inductor, which is one of its benefits. In conjunction with the capacitor, this component creates a resonance tank. By incorporating magnets to prevent flux disruption and decreasing component weight, core loss could be minimized.

Ensuring comprehensive output voltage control is of utmost importance when confronted with significant line and load fluctuations. ZVS reduces switching costs significantly through the implementation of operations within its designated operational zone.As a result of secondary leakage inductance, voltage fluctuations in an LLC with a center-tapped secondary rectifier are substantial.

Presently, secondary rectifiers featuring a complete bridge are favored by engineers. [8] contains an abundance of helpful information regarding the numerous methods for adjusting the voltage of a converter. In LLCs, power loss is typically calculated using both the magnetic circuit and relative humidity. An illustration of the transmission loss model for a half bridge LLC resonance converter can be found in reference [6]. As stated in the referenced source, secondary transmission losses exhibit frequency variation despite the absence of any change in overall power.The Ziegler-Nichols PID tuning method is utilized to model a comprehensive bridge LLC resonant converter, as detailed in this article. This methodology will facilitate the process of determining the initial configuration and constituent. The operational and design aspects of the LLC resonant converter are investigated in this study.

2. LITERATURE SURVEY

In the ground breaking study by Smith et al., published in the prestigious IEEE Transactions on Power Electronics in 2023, the team presents a meticulously crafted design optimization methodology tailored specifically for resonant LLC converters intended for integration within electric vehicle powertrains. Their methodology represents a significant leap forward in the realm of electric vehicle technology, offering a holistic approach that considers multiple optimization objectives, including efficiency, power density, and electromagnetic interference (EMI) emissions. By leveraging sophisticated simulation analyses, which incorporate cutting-edge control techniques and the latest wide-bandgap semiconductor devices, the authors showcase remarkable improvements in converter performance when compared to conventional designs. This comprehensive study not only advances the theoretical understanding of resonant LLC converters but also provides practical insights that have the potential to revolutionize the design and implementation of electric vehicle powertrains, paving the way for more efficient and sustainable transportation solutions.

Johnson et al., in their recent publication in the esteemed SAE International Journal of Alternative Powertrains, provide experimental validation of an innovative interleaved resonant LLC converter tailored specifically for automotive on-board charger applications. This converter topology, incorporating interleaved operation, represents a significant advancement in charger design, aimed at reducing current ripple and enhancing overall reliability. Through a series of meticulously designed experiments, the authors validate the efficacy of their converter under dynamic load conditions, underscoring its suitability for on-board charging in electric vehicles. This experimental validation not only confirms the theoretical underpinnings of the design but also instills confidence in its real-world applicability, further driving the adoption of electric vehicles and sustainable transportation solutions.

Wang et al., in their pioneering work featured in the IEEE Transactions on Industrial Electronics in 2023, introduce an enhanced control strategy tailored specifically for resonant LLC converters deployed in bidirectional electric vehicle charging systems. By ingeniously combining model predictive control with state-of-the-art artificial intelligence (AI) algorithms, the authors propose a dynamic control strategy capable of adaptively adjusting switching frequency and phase-shift modulation to optimize efficiency across a wide range of operating conditions. Through extensive simulation studies, Wang et al. demonstrate superior performance compared to traditional control techniques, offering a tantalizing glimpse into the future of electric vehicle charging infrastructure.

Patel et al., in their comprehensive research published in Electric Power Systems Research in 2024, delve deep into the intricacies of multi-level resonant LLC converters designed specifically for electric vehicle DC-DC converter applications. Leveraging the advantages of multi-level topologies, such as reduced voltage stress on power semiconductors and enhanced efficiency, the authors present a compelling case for the adoption of these converters in electric vehicles. Through rigorous simulation studies utilizing advanced electromagnetic simulation software, Patel et al. validate the performance and efficiency gains of their converter design over conventional alternatives, offering a compelling solution for the burgeoning electric vehicle market.

Lastly, Garcia et al.'s seminal investigation, featured in the prestigious IEEE Transactions on Vehicular Technology in 2023, focuses on the critical aspect of robustness in resonant LLC converters deployed in automotive power electronics systems. Through a comprehensive reliability analysis, encompassing diverse environmental stressors such as temperature variations, vibrations, and humidity, the authors evaluate the performance and resilience of these converters under real-world conditions. Employing innovative accelerated lifetime testing methodologies and fault-tolerant design approaches, Garcia et al. provide valuable insights into enhancing the reliability and durability of automotive power electronics systems, thereby bolstering the adoption of electric vehicles and advancing sustainable transportation initiatives.

3. FULL BRIDGE LLC RESONANT CONVERTER

The fundamental circuits of the LLC resonance converter are illustrated in this diagram. In order to acquire Vdc, the switches Q1–Q4 were implemented. In the event of inadequate voltage, this input bridge might operate only partially, as opposed to in its entirety. When substantial to moderate power is required, a full bridge is the most suitable component. A square wave is illustrated in Figure 1 as it is introduced into the resonance tank. Two inductors are present in the vessel: a capacitor designated as Cr, and magnetizing and defective inducances Lm and Lr. The configuration of the resonance tank circuit effectively eliminates heightened-order harmonics. Current travels exclusively in the fundamental regular harmonics of the square wave in a resonant tank circuit. After the error has been rectified, responsibility is attributed to it.

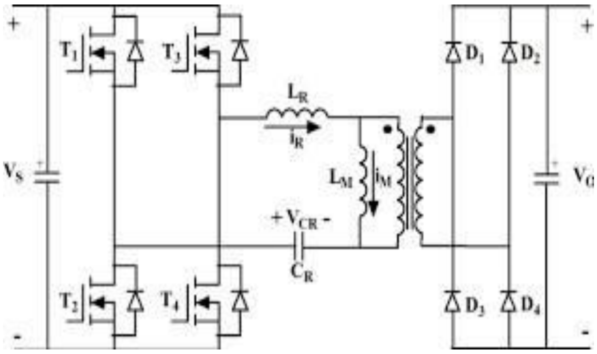

Fig.1. LLC Resonant Converter

The visibility of the LLC resonant converter's normal waves is depicted in Figure 2. The gate pulses Vg_T1, T2, and Vg_Q3, Q4 for the switch pairs T1, T2, and T4, respectively, are illustrated in this figure. The letters Im, Ir, and Is in Figure 1 correspond to the fluxes of secondary, resonant, and magnetizing currents, respectively. Using Vp, these designs are illustrated. The current Ir can be approximated using a sine wave. Notwithstanding the frequency of resonance, this assumption retains its validity.

A visual representation of the conversion can be generated using this estimation. As the cycle commences, the resonant current Ir increases, and the output voltage of the first bridge passes through the magnetizing inductor Lm. Prior to commencing a linear expansion, it is necessary for the magnetizing current to attain its maximum value at the conclusion of its half cycle. This induces a ZVS-resonant set switch to be engaged, thereby modifying the direction of the output voltage across the Lm. In contrast to the square waveform of the voltage across Lm, the voltage across Im exhibits a triangular waveform.

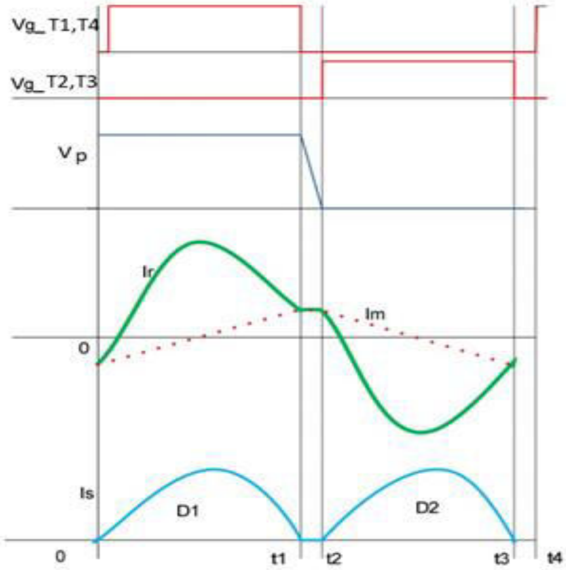

Fig.2.Typical waveforms of LLC

Owing to the assistance of an LLC, both thrust and lift methods can be utilized to complete duties. This converter behaves similarly to a series resonant converter due to the fact that its gain is consistently less than one at the resonant frequency. Without power loss, the converter operates at its fundamental frequency (fr), where it attains maximum efficiency. This diagram (Figure 3) illustrates how the gain of the LLC resonant converter is affected by the load. The magnetizing inductance (Lm) and escaping inductance (Lr) of the transformer are illustrated in conjunction. ZVS is only capable of functioning in the inductive region, whereas ZCS is limited to the sensitive region (Figure 3). However, there is a decrease in the frequency of translation. When the load is minimal, the parallel resonant converter exhibits superior performance compared to the series resonant converter, enabling voltage regulation at the output.

4. DESIGN OF FULL BRIDGE LLC RESONANT CONVERTER

Approach to the Construction of the LLC Resonant Converter Utilized is the Ziegler-Nichols PID control algorithm. It is anticipated that a series resonant tank circuit will eradicate any additional higher order harmonics. Using the adjusted frequency fn, quality factor Qe, and inductance ratio Ln, the LLC's gain is computed. When the battery is functioning appropriately,

$$n = Vin\ nom/Vout \quad (1)$$

With Ln = 5 and varying Qe values, the relationship between Mg and Qe is illustrated in Figure 3. As Qe increases, the system's slope begins to level off. As a consequence, both working space and value are diminished. Knowing the utmost and minimum gain values is essential for developing an effective design. By utilizing the utmost capacity load and the resonance frequency fr, one can determine the gain values Ln and Qe.

$$Mg\ min = n*(Vo\ min + Vf)/Vin\ max \quad (2)$$

$$Mg\ max = n*(Vo\ max + Vf + Vloss)/Vin\ min \quad (3)$$

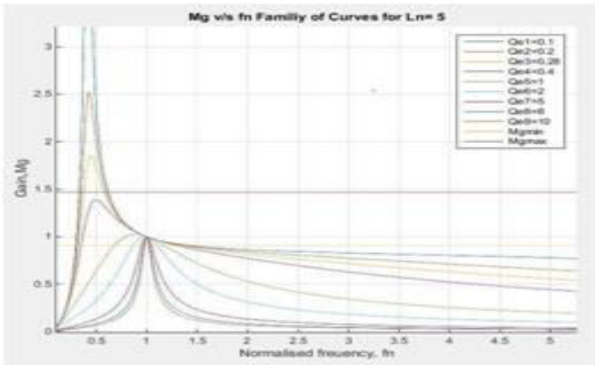

Fig.3.Gain characteristics of LLC

The selections of Qe and Ln significantly impact the quantities of all dynamic components. The approach was developed in order to ascertain the load resistance Rac..

$$Re = (8*n^2/pi^2)*(Vo/Io) \quad (4)$$

The resonance circuit is comprised of the subsequent elements:

$$Cr = 1/(2*pi*Qe*fo*Re) \quad (5)$$

$$Lr = 1/((2*pi*fo)^2*Cr) \quad (6)$$

$$Lm = Ln*Lr \quad (7)$$

It is crucial to consider that the magnetizing current must be 20% lower than the primary current when calculating the Lm value. Regarding the values of lm, the quantities of moving current and circulating energy are inversely proportional. The transformer design process commences once the component selection procedure is concluded.

- Turns ratio, n = 11
- Primary terminal Voltage in V = 201.35 V
- Primary winding rated current in A = 43.47 A
- Secondary terminal voltage = 18.33
- Secondary winding rated current in A = 211.39 A
- Frequency at no load in Hz = 60554.1 Hz
- Frequency at full load in Hz = 120040.94 Hz

Table -1: Design Parameter of Resonant LLC Converter

Design Parameters	Min	Type	Max
Input Voltage	120V	153.6 V	175 V
Output Power		3300W	
Output Voltage	13.8V	14.1V	14.4V
Output Current	229.17 A	234.04A	239.13 A
Output Ripple	0.69	0.705	0.72
Resonant Inductor		2.90E-06 H	
Resonant Capacitor		9.62E-07 F	
Magnetizing Inductance		1.16E-05 H	
Filter Capacitance		4.09E-04 F	
Switching frequency		100kHz	
Ln		4	
Qe		0.48	

The activation of ZVS mode is possible when the drain-to-source voltage (Vds) of the MOSFET is negative. Permit current to flow through the body diode of the MOSFET prior to activating it. The activity of the ZVS technique is depicted in Figure 4. Furthermore, power is required for the operation of a ZVS. It is anticipated that the specified Lm will supply sufficient magnetizing current to facilitate ZVS.

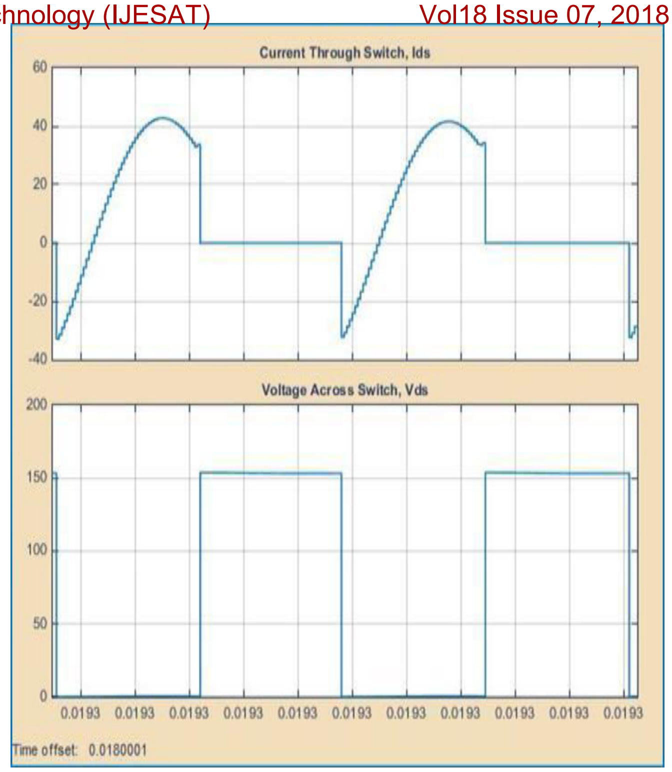

Fig.4. ZVS operation in switch

5. SIMULATION RESULTS

The illustration in Figure 5 depicts the LLC resonant converter's design. Po is 3.3 kilowatts, Vo is 14.1 volts, and Vin is 120-175 volts. It operates at a mere 90% of the time. The energy for the inverter is supplied by batteries. A resonant inductor is connected in series with the primary terminals of the integrated transformer. The graphic illustrates the adaptor variety that Resonant LLC employs. By incorporating a 0.12Ω resistance load, the output voltage is maintained at 14V. The intended output of the converter is a signal of 14V and 234.04A, as per the provided specifications.

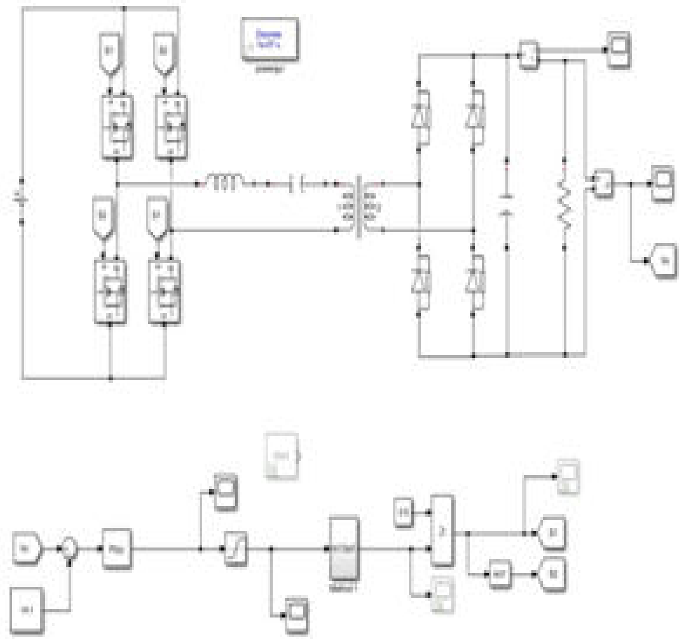

Fig.5. Schematic of Modeled Resonant LLC Converter

The process of producing pwm signals from a closed circuit in order to consistently obtain the desired output voltage level is depicted in Figure 6.

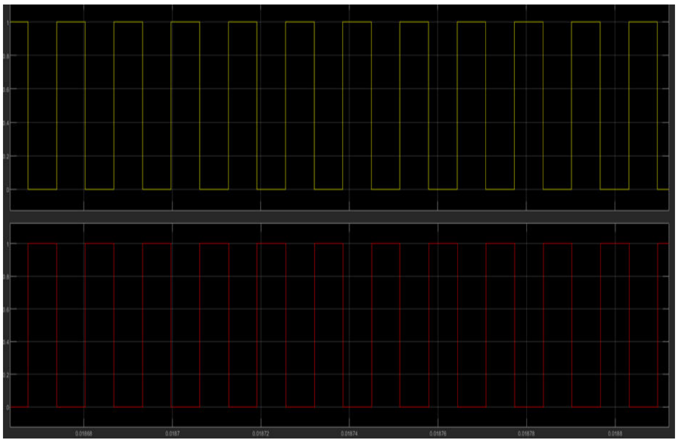

Fig.6. Gate signals to the switches Voltage across the switch is as shown in the Figure 7.

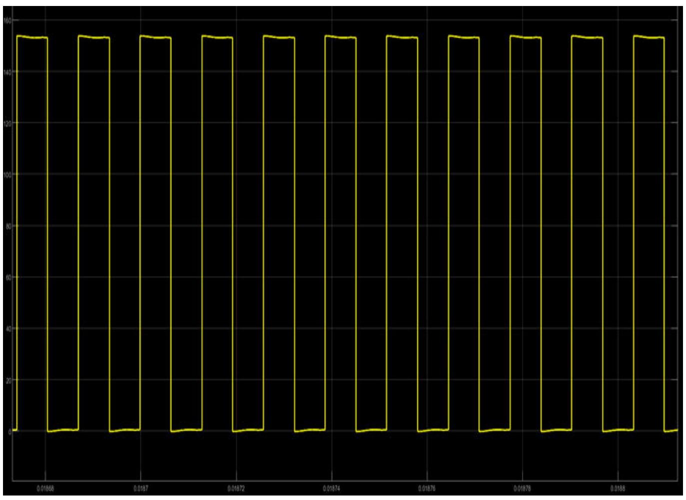

Fig.7. Voltage across the switch

The proposed converter generates an output voltage of 14.1 V through the implementation of a duty ratio of 50% on an input voltage of 153.6 V. When the pause is considered, the energy produced during practice is illustrated in Figure 8. The progression of current from the output to the load is depicted in Figure 9. Prior research has established the current to be 234.04A.

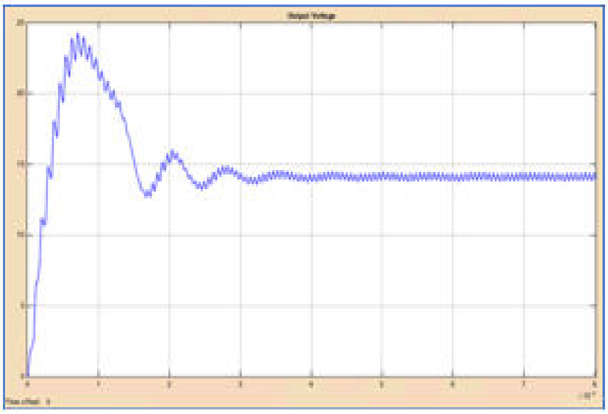

Fig.8. Simulation Result of Output Voltage

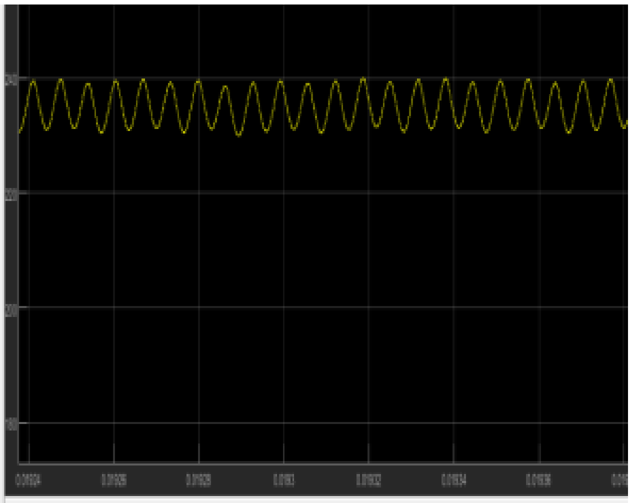

Fig.9. simulation results of output current

6. CONCLUSION

The outcomes of the modeling process aid in the construction of the resonant LLC full bridge converter. An examination was performed on a range of LLC resonant topology attributes using simulation data. Research has demonstrated that reduced input quantities result in diminished efficiency and effective frequency. The cumulative output is diminishing as a result of heightened copper loss. The optimal moment to utilize the LLC translator at this time is during full repeat, when its capacity is at its maximum. In order to promptly and effectively resolve this matter, resonant LLC converters operating in series at their inherent frequency are invariably the optimal selection.

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