Dual Output DC-DC Isolated Resonant Converter

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Abstract: The world of electrical and electronics is witnessing a daily increase in the use of DC-DC converters. The higher-frequency DC-DC converters reduce system bulk and increase power density; they are widely used in various applications. By Introducing the Resonant Converter, it reduces the switching loss and improves the system performance. The growing trend of industries relying more and more on machinery makes it necessary to conduct a thorough analysis in order to comprehend and compile information on the different isolated topologies and the most widely used resonant switching layout. This will optimize design and development of converter. It has able potential to enhance the performance and reduce the energy consumption of systems, contributing to a more sustainable and cost-effective industrial landscape. The main objective is to develop a compact and reliable converter that takes a single 230V DC input and provides two distinct output voltages: 100V DC for the spindle motor and 42V DC for powering various essential components.

Keywords: DC-DC Converter, Dual Output, LLC, ZVS.

I.   INTRODUCTION

Considering the realm of power electronics, DC-DC converters play pivotal part in transforming electrical energy from one voltage level to another efficiently and effectively. They serve as indispensable components in a wide array of applications, including renewable energy systems, telecommunications, industrial automation, and consumer electronics. The significance of DC-DC converters lies in their ability to facilitate power conversion with minimal losses, thereby enabling the efficient utilization and distribution of electrical power. Among the various types of DC-DC converters, the LLC resonant converter (LLC) stands out for its unique characteristics and advantages. The LLC resonant converter operates on the principle of resonance, leveraging the inherent properties of inductors and capacitors to achieve high efficiency and robust performance. By employing resonant switching techniques, the LLC minimizes switching losses and provides inherent soft-switching capabilities, leading to enhanced efficiency and reduced electromagnetic interference (EMI). Additionally, the isolation provided by the transformer in the LLC resonant converter enables voltage regulation and galvanic isolation, making it particularly suitable for applications requiring precise voltage control and electrical isolation.

The motivation behind choosing an LLC resonant converter stem from its distinct advantages over other types of DC-DC converters, especially in applications where efficiency, reliability, and EMI mitigation are paramount. The inherent soft-switching characteristics of the LLC resonant converter contribute to reduced stress on semiconductor devices, thereby extending their lifespan and improving overall system reliability. Furthermore, the high efficiency of the LLC translates into lower power losses and reduced cooling requirements, making it an attractive choice for power-dense applications where space constraints are a concern. This paper aims to provide a comprehensive exploration of the design, analysis, and control of DC-DC isolated LLC resonant converters. The structure of our project is discussed as follows.

II.   PROPOSED SYSTEM

In existing systems, Linear regulators are used which creates an extreme heat dissipation and may damage the device. Hence the utilization losses of linear devices were substituted by Switched mode power converters. The presented system is defined about the LLC resonant topology along with ZVS Switching. The major advantage of this setup is that it offers soft-switching characteristics, reduced switching losses, and improved efficiency across a wide load range. We have controlled the converter using a PID Controller. The voltages produced will power the motor and the auxiliary load individually and simultaneously. The idea applied which we have proposed LLC converter as it possesses enhanced output performances. The presented system steps are as follows.

A.   LLC RESONANT CONVERTER

In an LLC converter, the triple reactive elements enable two resonant frequencies, which are useful for filtering square waves and producing sinusoidal output of voltages and currents. Voltage regulation for the dual output voltages in LLC resonance and full-bridge converter is achieved through the control of switching frequency and phase angle, respectively.

Resonant inductors and transformers, despite their good tolerance for parameter inconsistencies, can lead to current imbalances. Among the existing three-element resonant converters, the LLC resonant converter has gained significant attention due to its zero-voltage switching (ZVS) and zero current switching (ZCS) capabilities for power switches and diodes. This enables high power density and efficiency. Variable frequency modulation technique is commonly used in LLC soft-switched converters to achieve voltage stability and regulation.

By adjusting the switching frequency, variable frequency control can attain the required voltage with the essential gain. Nevertheless, varying the switching frequency can affect factors such as electromagnetic interference, increased conduction losses, and reduced performance. In applications with narrow input voltage range, switching frequency with wide variation is not necessary. LLC resonant converter has two resonant frequencies, fr1 lower resonant frequency corresponds to $(L_r + L_m)$ and C_r, f_r series resonant frequency corresponds to L_r and C_r.

B.   ZERO VOLTAGE SWITCHING(ZVS)

Zero-voltage switching (ZVS) is a cornerstone technology in LLC converter design, enabling significant reductions in switching losses and boosting overall efficiency. During switching events in conventional converters, rapid voltage, and current transitions lead to energy dissipation as heat. ZVS tackles this issue by ensuring the voltage across a switch reaches zero before the current through it is interrupted. In LLC converters, this translates to zero voltage across the primary power switches when the current ceases to flow during the turn-off phase. This minimization of voltage and current transients dramatically reduces switching losses, enhancing converter efficiency.

However, achieving ZVS is not without its constraints. The optimal LLC converter operation design space is limited to a specific region within the resonant tank circuit, typically represented by the right side of resonant gain curves. Operating in this zone guarantees the conditions necessary for ZVS on the primary side. Deviating from this recommended area may compromise ZVS, leading to increased switching losses and a decline in converter efficiency. In conclusion, ZVS is critical in maximizing the efficiency of LLC converters. By carefully considering the resonant gain characteristics and restricting operation to the appropriate region within the resonant tank circuit, designers can leverage ZVS to achieve superior performance.

C.   BLOCK DIAGRAM

This Block diagram investigates the performance of a DC-DC isolated resonant LLC converter operating with a 230V DC input voltage. The converter utilizes a full-bridge inverter to drive the LLC resonant tank circuit, comprised of inductors and a capacitor. An isolated transformer provides voltage step-down functionality followed by a rectifier circuit that converts the AC waveform to a regulated DC output voltage of 100V and 42V. The PID controller continuously monitors the output voltage and adjusts the switching frequency of the converter to maintain a stable output regardless of input voltage variations or load changes. The paper delves into the operational principles of each stage, analyses the converter's efficiency, and explores potential areas for further research.
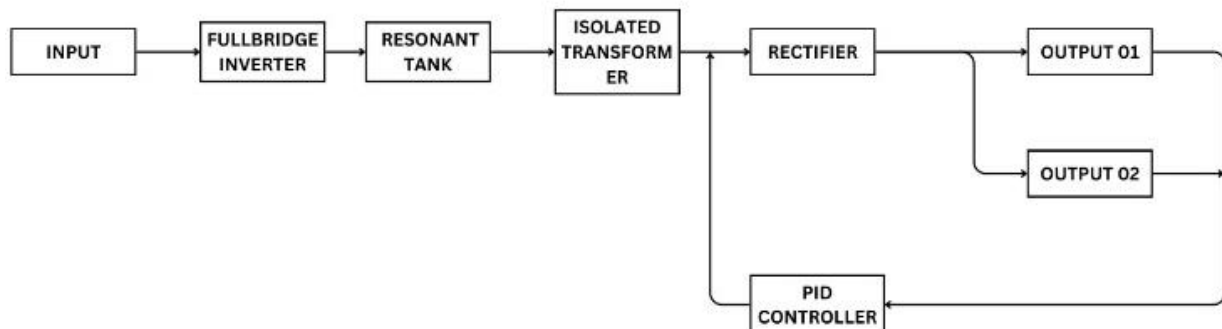

Fig. 1 Block Diagram of the Proposed System

III. DESIGN OF CONVERTER

D. CIRCUIT DESCRIPTION

The circuit of a single DC input to Dual DC output of an Isolated LLC Resonant converter is shown in Fig:2. Here the LLC resonant converter is designed to give a buck with two outputs. The first output of 100 V is for the main drive of the machines and the second output with a 42V is for supplementary access purposes. The input voltage is achieved with a 230V DC input source. Here, on the primary side of the proposed isolated converter, there is an inductor (L_m), inductor (L_r), and capacitor (C_r).

In Between this, the isolated transformer is used for isolation purposes in between the input and output. The resonant circuit provides ZVS for the resonant tank and full bridge inverter circuit. This reduces the high voltage spikes that occur during the hard switching, significantly reducing switching losses and improving the efficiency of the converter. On the secondary side, the transformer step down the voltage and processes to the Rectifier. This Rectifier is used to convert the Ac source into a Regulated DC Output for the Dual outputs with the motor load and resistive load.
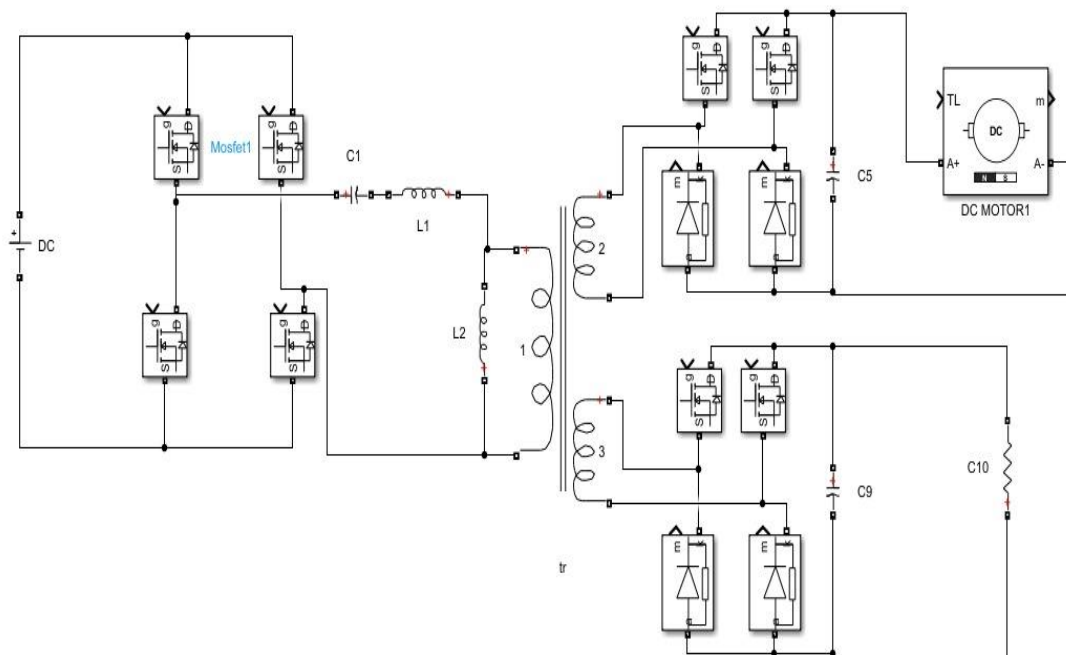

Fig. 2 LLC Resonant Converter

E. MATHEMATICAL MODELLING

TABLE I LLC RESONANT CONVERTER PARAMETERS

Converter parameter	Value
Magnetizing Inductor (L_m)	$79.1 \ X \ 10^{-6} \ H$
Resonant capacitor (C_r)	$112 \ X \ 10^{-9} \ F$
Resonant Inductor (L_r)	$22.6 \ X \ 10^{-6} \ H$
Input Voltage (V_{in})	230V
Output Voltage (V_{o1})	100V
Output Voltage (V_{o2})	42V

The mathematical modelling and calculation of the converter can be expressed as follows:

1) Turns ratio of the Transformer ($N_1 : N_2$)

Winding 1(Primary):

$$V_1 = \frac{V_{in}}{\sqrt{2}}$$

Winding 2(Secondary):

$$V_2 = \frac{V_{out}}{N_{1:N_2}}$$

Where, V_{in} and V_{out} represents the input and output Voltage of the Converter.

2) Quality factor:

$$Q = \frac{\sqrt{L_r/C_r}}{R_{ac}}$$

Here,

Q depends on the load current. Setting Q value with the load is crucial.

To attain the desired maximum voltage gain, we can avoid tuning the Q value as a design iteration; instead, we shall depend on tuning the m value, as discussed in the further step. This Q value can assist us in attaining the maximum gain, thereby widening the range of frequency modulation.

3) Selecting the m value:

As discussed previously,

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

As m is a static parameter for which we must optimize its value at the beginning of the design process, it is crucial to comprehend how the m ratio affects the functioning of the converter.

Higher boost gain and a shorter frequency modulation range are also possible with smaller values of m, which allows for greater flexibility in control and regulation—a useful characteristic for wide input voltage range applications.

However, lower values of m for the same quality factor Q and resonant frequency f_r indicates reduced magnetizing inductance L_m, thereby, increase in higher magnetizing peak-peak current ripple, thus shooting up the circulating energy and conduction losses.

To be able to get the highest m value as continues to satisfy the maximum gain need under all load situations, we must first select a viable initial value for m (6–10) followed by optimizing it through a few iterations.

4) Resonant components values:

After attaining the ideal m value, we can further calculate the resonant tank components values, Eq.2, Eq.3 and Eq.4 can be solved to find L_r and C_r, and L_m.

$$R_{ac} = \frac{8}{\pi^2} \frac{N_P^2}{N_S^2} R_o \qquad \text{Eq.1}$$

$$Q = \frac{\sqrt{L_r/C_r}}{R_{ac}} \qquad \text{Eq.2}$$

$$\omega_r = \frac{1}{2\pi\sqrt{L_r C_r}} \qquad \text{Eq.3}$$

$$m = \frac{L_r + L_m}{L_r} \qquad \text{Eq.4}$$

It should be noted that the choice of the resonant frequency ω_r was not considered in the above mentioned design procedure, because there's no impact on the maximum gain and operation region of the resonant converter, however it is chosen by taking into account of the converter power density and power losses.

F. DESIGN PROCEDURE OF LLC RESONANT CONVERTER

Step 1: Determine Operating Parameters*: Based on system specs and component restrictions, establish the operating frequency range and voltage requirements.

Step 2: Select Q and M Values*: Plotting load lines that correspond to the intended output voltage and power levels will help you calculate the suitable values. Refer to the Q-value and M-value graphs for assistance. Fig 3 shows that graph.
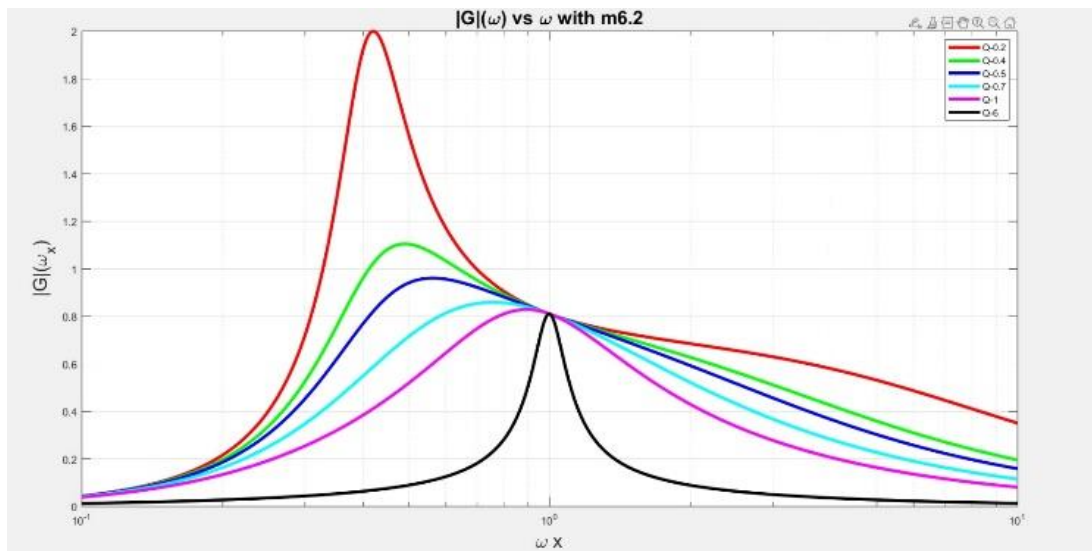

Fig. 3 'm' Graph

Step 3: Choose Resonant Tank Components*: Based on the established Q and M values, choose the values of the inductance and capacitance to make sure they function within the designated frequency range and power levels.

$$L_{r=22.6 \times 10^{-6} \ H}$$
$$C_{r=112 \times 10^{-9} \ F}$$
$$L_{m=79.1 \times 10^{-6} \ H}$$

Step 4: Design Gate Driver Circuit: Create the gate driver circuitry for the complete bridge inverter, making sure to choose parts that will enable dependable and effective power device switching.

Step 5: Design Transformer: Design the Transformer: Based on the required input and output voltages, choose the turns ratio and core material for the transformer. In order to attain the intended voltage transformation ratio and guarantee sufficient isolation between the input and output, transformer windings should be designed.

Step 6: Design Rectification and Filtering Circuit: Create a diode bridge rectification circuit to convert the transformer secondary's AC output to DC. Incorporate filtering elements (such inductors and capacitors) to lessen ripple and smooth the output voltage.

Step 7: Integrate Control and Protection Circuitry: Integrate Control and Protection Circuitry: Create and put into practice control circuitry, which should include a PID controller to stabilize and regulate output voltage. To protect the converter and linked devices, incorporate protective features including heat, overvoltage, and overcurrent protection.

Step 8: Simulation and Testing: To confirm performance and stability, simulate the LLC resonant converter design using the relevant software tools. To validate the design and guarantee that it complies with standards, conduct thorough testing under a range of operational circumstances.

IV.   SIMULATED RESULTS & DISCUSSION

The simulation of the presented LLC Resonant converter with dual output has been done in MATLAB-Simulink. These results express the performance of the proposed system under various situations. Please note, in the attached figures, the horizontal axis is time in seconds, and the vertical axes are the voltage in Volt or current in Amp respectively.

The below Fig.4. presents the most significant achievement of LLC is the activation of ZVS. The MOSFET is tuned when the drain-to-source voltage (V_{ds}) is zero. To achieve this, the MOSFET's body diode conducts the magnetizing current before the switch is turned on. A successful ZVS requires adequate inductive energy. Selected L_m should offer sufficient magnetizing current for ZVS.
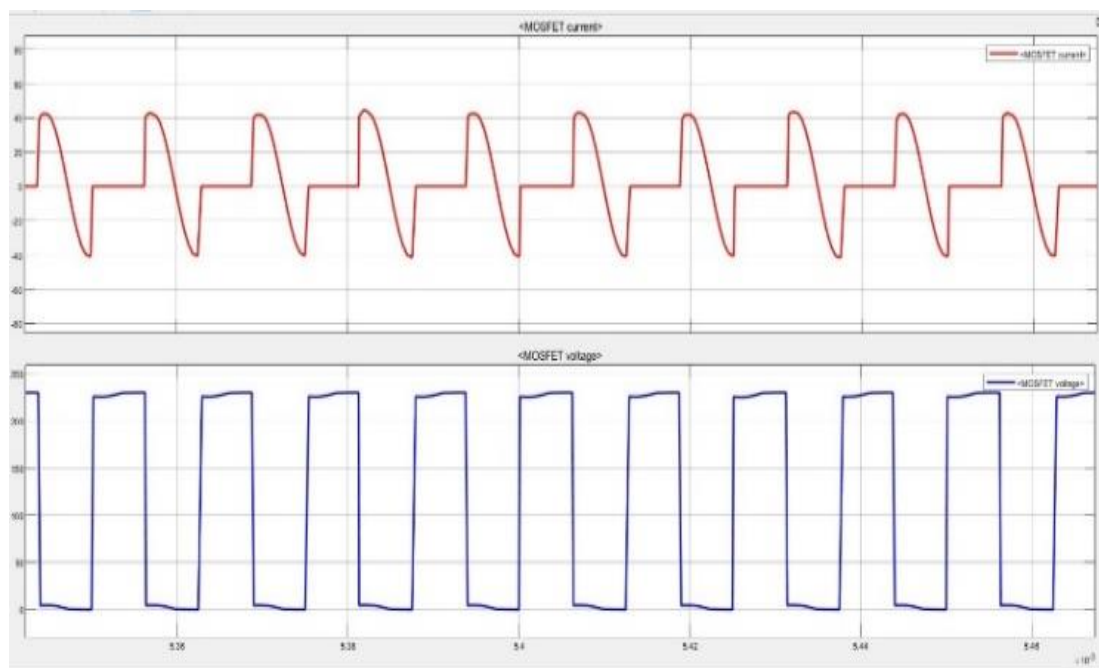

Fig. 4 ZVS Waveform

The simulation results of the main drive Voltage and Current of the output 1 are illustrated in Fig. 5.

Here the respective voltage can be achieved by using the LLC converter and by choosing the proper parameter values for the converter. Thus, it helps us to achieve the targeted output and current waveforms.
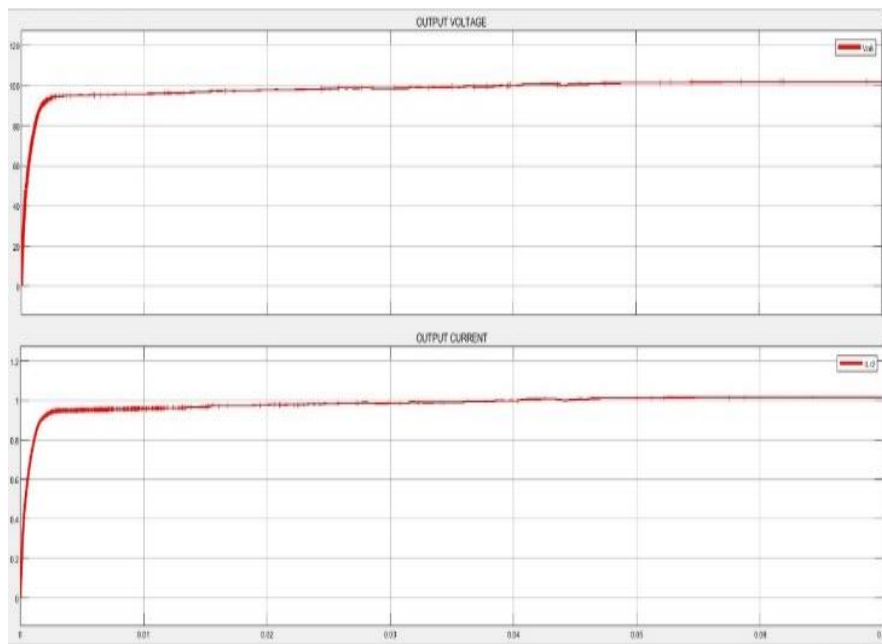
Fig. 5 Simulation result of output Voltage (V_{o1}) and current waveforms

The voltage and current waveforms of the output 2 of the proposed system illustrated in Fig.6.This image shows the clear output of the minor accessories output properly by simulating the converter.
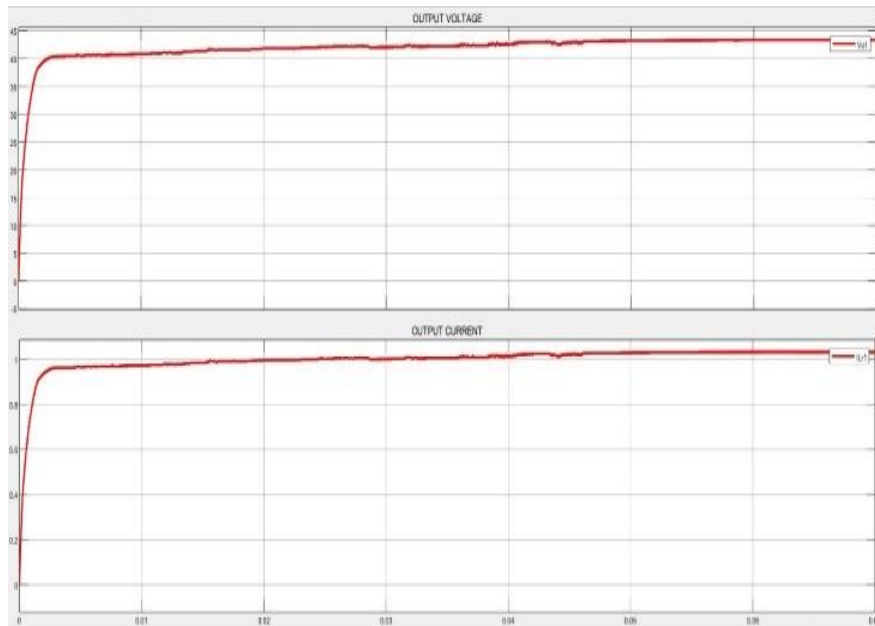

Fig. 6 Simulation result of output Voltage (V_{o2}) and current waveforms

V.   CONCLUSION

To conclude, the LLC resonant converter stands out as a versatile and efficient power conversion solution. Its ability to achieve Zero Voltage Switching (ZVS) during turn-on represents a significant advancement in converter technology, minimizing switching losses and enhancing overall efficiency. By carefully tuning the MOSFET and ensuring sufficient inductive energy, ZVS operation can be reliably achieved, leading to improved performance and reduced electromagnetic interference.

The LLC converter's capability to operate in both buck and boost modes further enhances its versatility, making it suitable for a wide range of applications. With ongoing research and development efforts focused on optimizing its design and performance, the LLC resonant converter continues to be a promising technology for high-efficiency power conversion in various industrial and consumer electronics applications.

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