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Novelty Half-Bridge LLC Resonant Converter with Magnetizing Inductance and Hybrid Rectifier

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ABSTRACT

Half-Bridge LLC Resonant converters are widely used in high-power supply applications due to their high efficiency and ability to operate at high frequencies. However, under hold-up conditions or during large fluctuations in input voltage, conventional topologies often experience reduced output stability and increased losses. Therefore, a method that can maintain efficiency and output voltage stability without excessively broadening the switching frequency range is required. To address this, this study proposes a Novelty Half-Bridge LLC Resonant Converter with Magnetizing Inductor and Hybrid Rectifier (NHB-LLCRC-MIHR), incorporating a magnetizing inductor (Lm) in the primary path and a MOSFET-based hybrid rectifier on the secondary side. The research methodology was conducted using MATLAB/Simulink simulation, focusing on five main areas, including optimal switching frequency conditions, operating thresholds, DC conversion ratio (Vo/Vs), comparison of output voltage with conventional topologies, and analysis of output voltage ripple. Simulation results demonstrate that NHB-LLCRC-MIHR can maintain a more stable output voltage, lower ripple, and increase efficiency compared to conventional converters. Thus, this topology shows significant potential for industrial applications that demand high efficiency and optimal power stability.

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1. INTRODUCTION

Balancing high frequency and high efficiency in hard-switching converters can increase switching frequency but often results in higher losses, increased heat dissipation, and reduced operational lifespan. Therefore, a soft-switching converter capable of achieving high frequencies by adding resonant elements is required. When voltage and current cross zero, the switches are controlled to turn on or off [1]. The LLC resonant converter offers advantages in smaller volume, simpler structure, and a wide output range [2]. This converter is highly valuable for various applications such as distributed power sources, power systems for computer hardware, and other industrial applications that demand efficient power conversion with precise control over voltage and current [3]. The topology of the LLC resonant converter is divided into three parts: inverter, resonant network, and rectifier, with the structure of the resonant network being relatively fixed [4]. The Half-Bridge LLC Resonant Converter is a DC-DC power converter that utilizes resonance principles in inductive and capacitive elements to convert voltage with high efficiency and low electromagnetic interference. This topology uses two MOSFET switches in a half-bridge configuration to operate the LC resonant circuit, as well as a magnetizing inductor on the transformer to achieve ZVS, allowing the switches to operate without voltage during switching transitions. This significantly reduces the switching losses that commonly occur in conventional Pulse Width Modulation (PWM)-based converters. With improved thermal performance and stable output regulation, the Half-Bridge LLC Resonant Converter is an ideal choice for high-power, high-efficiency power supply applications [5].

The LLC resonance enables a smaller transformer size and lower costs, as its operating frequency is more flexible and can be adjusted according to system requirements, whereas in conventional PWM converters, input voltage fluctuations can significantly affect output voltage stability [3]. The LLC resonant converter is considered an optimal choice due to its efficiency. However, a major challenge lies in the occurrence of large input voltage fluctuations during operation, particularly under transition or "hold-up" states. Such conditions frequently occur when the main power supply is lost, but the system must maintain a stable output voltage for a certain period. To overcome this issue, a more advanced control method is required one that can adjust voltage gain and switching frequency according to varying input conditions [6]. The LLC resonant converter is one of the most popular isolated DC/DC converters, and it has been widely used in many different applications, including on-board battery charger, distributed power system, renewable energy generation system, server power supply, light emitting diode (LED) driver, and laptop adaptor [7]. [8] Proposed a two-bridge LLC resonant converter with an auxiliary switch, which adopts fixed-frequency PWM control and changes the effective input voltage of the resonator by adjusting the duty cycle of the auxiliary switch tube to achieve the stability of the output voltage. The topology can achieve soft switching in the full-load range. However, the normalized gain of this topology can only be adjusted to between 0.5 and 1, and the gain range is still limited.

Recent research on LLC resonant converters has mainly targeted wider voltage-gain regulation, higher efficiency, and improved soft-switching under abnormal input conditions. A hybrid control strategy proposed based on an improved fruit fly optimization algorithm that combines hybrid phase-shifted and frequency-modulated control for an LLC converter in X-ray machines. MATLAB simulation and prototype verification showed improved stability and reduced conduction loss, but the method still depends on control tuning rather than structural enhancement [9]. A phase-shifting adaptive LLC converter proposed with PSM/PFM hybrid control, where ZVS was maintained over a wide voltage-gain range and turn-off loss was reduced, yet the solution again relied on control adaptation to extend the operating range [10]. Method proposed by [11] experimentally showed that, for a 22 kW, 40 kHz LLC converter, shifting the DC-link operating point so the converter spends about 75% of the grid period above resonance increased average efficiency from 97.66% to 97.70% and reduced resonant-capacitor stress, while still leaving below-resonance loss as a key limitation. Study by [12] used sampled-data analysis to derive a discrete state-space model that improves accuracy for LLC operation below resonance, whereas [13] proposed a state-trajectory-based synchronous rectification method for CLLC converters and validated it on an 800 W prototype with 97.38% rated efficiency. However, these studies mainly address modeling or secondary-side loss reduction separately. A remaining gap in the literature is the lack of an integrated topology-level solution that simultaneously improves hold-up behavior, output-voltage stability, ripple, and efficiency within one converter structure.

This study aims to evaluate the performance and advantages of the proposed converter NHB-LLCRC-MIHR, particularly in the context of operation with PWM control. The main focus of this research is to analyze the impact of implementing an auxiliary switch (Qa) on the primary side on power conversion efficiency, voltage gain, and the reduction of conduction losses caused by current in the magnetizing inductor. Additionally, this study examines the dynamic characteristics of the RLC circuit forming the resonant tank, as well as the role of PWM duty cycle in maintaining output voltage stability and efficiency under varying DC input conditions. The research is conducted through simulation using MATLAB/Simulink, with the experimental design. Each parameter is analyzed through circuit simulation results under various load and input variations, providing a comprehensive overview of the advantages and application potential of the proposed converter compared to conventional topologies.

2. METHOD

The NHB-LLCRC-MIHR topology is an advancement of the half-bridge LLC resonant converter with a *Qa* as presented [14], incorporating two key innovations: the addition of a *Lm* in the primary path and the implementation of a hybrid rectifier on the secondary side. The magnetizing inductor, which is integrated in series with the primary winding (NP), serves to extend the ZVS operating range, enhance energy transfer flexibility, and suppress RMS current, thereby reducing conduction losses and increasing efficiency [15]. On the secondary side, two diodes in the rectifier are replaced by two MOSFETs (M3 and M4) operated synchronously at the same frequency as the primary switches, allowing for current rectification with lower voltage losses and faster switching response compared to conventional diodes. The combination of the resonant tank (*Lr*-*Cr*), the use of a MOSFET-based hybrid rectifier, as well as the output filter (*Co*) and load resistor (*Ro*), results in a converter capable of maintaining output voltage stability, reducing ripple, and significantly improving power efficiency, making this topology highly ideal for high-power and maximum-efficiency applications [16].

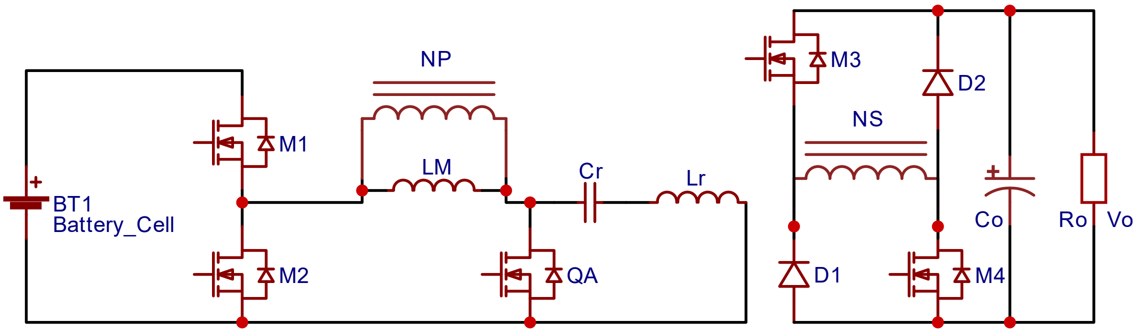

Figure 1. NHB-LLCRC-MIHR topology

2.1 Resonant Network

The operating principle of this converter focuses on the use of LLC resonance involving the inductor and capacitor in the resonant network. When the switch is first opened, the inductor current initiates a resonance cycle with the capacitor. During this resonance process, the inductor and capacitor together generate a resonant frequency sufficient to ensure the switches operate under ZVS, thereby reducing power losses commonly found in conventional switches. At the ZVS condition, the voltage across the switch approaches zero, so no high voltage is applied during switching transitions, which decreases switching losses and enhances converter efficiency [17]. In the LLC–LC resonant converter, ZVS operation is achieved for all power devices under all operation conditions without using active auxiliary circuits, which are usually used in soft switching PWM converters [18].

2.2 Half-Bridge LLC Resonant Converter in Hold-Up Mode

In hold-up mode, when a sudden drop in input voltage occurs, the *Qa* is activated with PWM control to maintain stable output voltage using the energy stored in the link capacitor. The current in the resonant inductor (*Lr*) increases as *Qa* is turned on, and this energy is then delivered to the load once *Qa* is turned off. This PWM method enables control of the output voltage gain without the need to significantly widen the switching frequency range, thus maintaining efficiency and allowing for a reduction in link capacitor size. A similar approach was also proposed in [6], emphasizing the importance of additional PWM control to maintain stability and efficiency during hold-up conditions without significantly increasing system complexity. By actively controlling the duty cycle of the secondary-side auxiliary MOSFET in a PWM-LLC resonant converter, wide voltage regulation can be achieved while maintaining fixed resonant frequency operation and Zero-Voltage Switching (ZVS) for all MOSFETs [19]. The transformer in the LLC resonant converter plays a critical role in high-voltage applications, as its parasitic capacitance and leakage inductance significantly affect soft-switching conditions, voltage gain, and overall efficiency of the converter [20].

2.3 Magnetizing Inductor

According to [17], the role of the *Lm* in the LLC resonant converter topology is crucial, as *Lm* not only functions as an energy storage element during the switching cycle but also determines the resonance characteristics and ZVS capability. The greater the value of *Lm* relative to the *Lr*, the flatter the resulting gain curve, so that frequency variations do not drastically affect the output voltage conversion ratio. The magnetizing inductor Lm participates in resonance, improving the stability and efficiency of the LLC resonant converter [21].

2.4 Hybrid Rectifier

The hybrid rectifier approach provides a new degree of control freedom on the secondary side, enabling more adaptive output voltage regulation and current sharing among parallel modules. The hybrid rectifier is also effective in suppressing switching losses and increasing efficiency, particularly during light-load operation or in multi-converter (interleaved) systems that require balanced current distribution. Experimental results show that this method can maintain converter stability and high performance, while minimizing output fluctuations under various operating conditions [22].

2.5 Zero voltage switching

ZVS is a condition where the power switch, such as the main MOSFET in a Half-Bridge LLC Resonant Converter, is activated when the drain-source voltage approaches zero volts, thus eliminating switching losses caused by the overlap of voltage and current. ZVS is achieved naturally through resonance between Cr and *Lm*, which generates sufficient current to discharge the internal parasitic capacitance of the switch during the gate-off period. When one switch turns off, the magnetizing inductor current empties the opposing switch's Coss, so that the voltage across the switch reaches zero when it is turned on again. This condition not only increases efficiency by reducing switching losses and thermal stress on the switches but also lowers electromagnetic interference (EMI). Studies such as [5] support that appropriate resonance design and magnetizing inductance are critical to ensuring ZVS, thereby achieving high efficiency and optimal performance in LLC resonant converters.

2.6 Operational Characteristics and Gain (fr/fs)

The gain characteristics of the Half-Bridge LLC Resonant Converter are highly dependent on the ratio of switching frequency (Fs) to resonant frequency (Fr). Thus, [14] proposed using PWM control on *Qa* during hold-up mode, keeping the main switching frequency close to the optimal resonant frequency while regulating gain via the PWM duty cycle. This approach maintains high efficiency without significantly widening the switching frequency range, ensuring that the transformer and resonant tank design remain optimal. This is in line with the findings of [23], which emphasize the importance of resonance design and adaptive control for high efficiency and stable output.

Figure 2 illustrates the MATLAB/Simulink implementation of the proposed NHB-LLCRC-MIHR converter, which is organized into four main functional blocks, a monitoring section, a primary switching stage, a resonant tank, and a secondary hybrid rectifier. The monitoring block records the key electrical variables used in the analysis, especially the input voltage, output voltage, and DC conversion ratio. The primary stage operates the inverter switches, while the resonant network, consisting of L_r, C_r, and L_m, shapes the energy-transfer process and supports soft-switching operation. On the secondary side, the hybrid rectifier improves rectification performance by reducing conduction and reverse-recovery losses. Table 1 summarizes the component values used in the simulation, namely the 250 V DC source, L_r = 120 uH, C_r = 22nF, L_m = 360 uH, C_o= 3 uF, and R_o = 1000 ohm. These values were selected to define the resonant behavior, output filtering, and load condition of the converter.

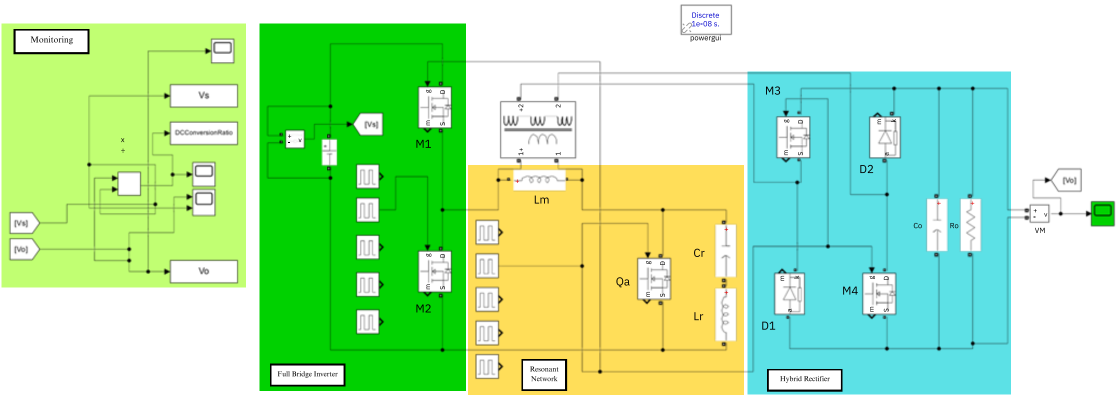

Figure 2. NHB-LLCRC-MIHR simulation with MATLAB/simulink

Tabel 1. Main parameters of proposed converter.

Component	Main Parameter Value
DC Voltage Source	250 V

MOSFET 1, 2, 3, 4	Ron = 0.1 Ω, Rd = 0.01 Ω, Rs = 1e5 Ω
Resonant Capacitor (Cr)	22 nF
Resonant Inductor (Lr)	120 µH
Diode	Ron = 0.001 Ω, Vf = 0.8 V, Rs = 500 Ω, Cs = 250 nF
Output Capacitor (Co)	3 µF
Load Resistor (Ro)	1000 Ω
Magnetizing Inductor (*Lm*)	360uH

The proposed method was evaluated through MATLAB/Simulink simulation by sweeping the switching frequency and load condition, then comparing the proposed topology with the conventional converter. In line with the reference work by In-Ho Cho et al., the nominal-state operation is expected to stay close to the resonant point for maximum efficiency, while the hold-up state uses the auxiliary switch (Q_a) with PWM control to increase the voltage gain without excessively widening the switching-frequency range. The main performance metrics used in the evaluation are resonant frequency, output voltage, DC conversion ratio, efficiency, output ripple, and settling behavior. These metrics make it possible to verify whether the proposed converter achieves higher output stability, lower loss, and faster recovery than the conventional topology.

The resonant frequency equation calculates the frequency at which the inductor and capacitor in a resonant circuit naturally oscillate, with *Lr* representing the resonant inductance and *Cr* representing the resonant capacitance.

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

Hence, the resonation inductance (L_r) is determined to be 120 µH and the resonation capacitance (C_r) is 22 nF. As we get this equations. Based on these values, the product of the inductance and capacitance, which is a key parameter in determining the resonant behavior of the circuit, can be calculated as follows:

$$LC = L_r x\, C_r \tag{2}$$

$$LC = 120\, x\, 10^{-6}\, x\, 22\, x\, 10^{-9} = 2.64\, x\, 10^{-12} \tag{3}$$

By applying equations (1), the resonant frequency is found to be 97.953 kHz, indicating the frequency at which the circuit naturally oscillates with maximum energy transfer.

The design of an NHB-LLCRC-MIHR circuit simulation uses MATLAB/Simulink software, based on the conventional topology reference [14], which was then modified by adding a *Lm* and a MOSFET-based hybrid rectifier on the secondary side. The designed circuit was tested under various switching frequencies and load conditions, with output parameters such as voltage, current, ripple, and response time to steady-state being measured. The experimental data were directly compared with the conventional topology to identify the advantages of the proposed innovations, and all results were interpreted comprehensively based on the main performance parameters as well as the phenomena observed during testing.

3. RESULT AND DISCUSSIONS

3.1 Resonant Frequency

The first test focused on characterizing the impedance of the series resonant tank, which consists of a resonant capacitor (*Cr* = 22 nF) and a resonant inductor (*Lr* = 120 µH). Using simulations in Simulink, a frequency sweep was performed in the range of 80 kHz to 120 kHz to observe the impedance and phase behavior of the circuit. The impedance magnitude graph shows a minimum point at a frequency of approximately 97.953 kHz, which corresponds to the theoretical calculation using the resonance formula.

At this resonant frequency, the circuit impedance reaches its minimum value due to the cancellation of inductive and capacitive reactance, resulting in a purely resistive circuit with only minor resistive losses remaining. Below the resonant frequency, the circuit exhibits capacitive characteristics with the current leading the voltage, while above the resonant frequency, the circuit is inductive with the current lagging behind the voltage.

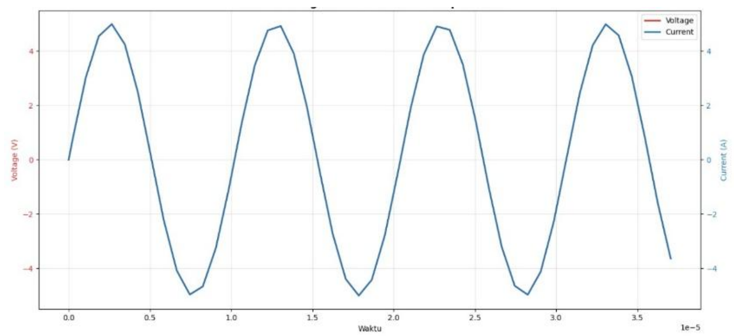

Figure 3. Current and voltage waveforms at resonance

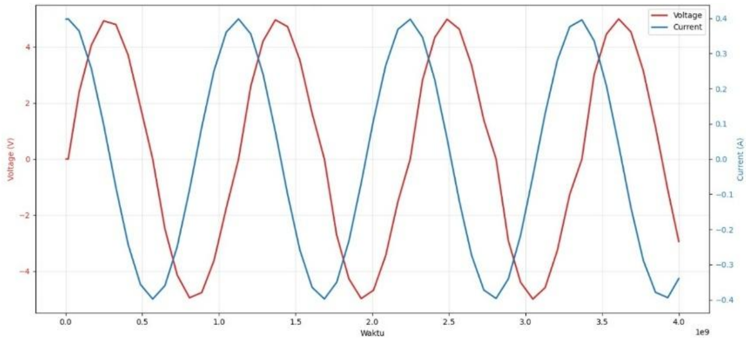

Figure 4. Current leading voltage at frequencies below resonance

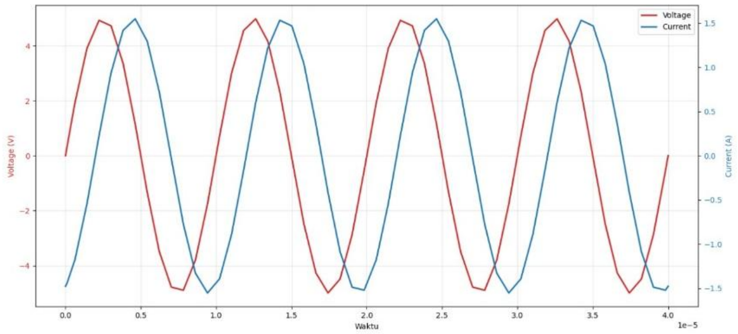

Figure 5. Current lagging voltage at frequencies above resonance

Efficiency testing of the LLC converter was carried out by operating the converter at various frequencies between 80 kHz and 120 kHz, with a constant resistive load. Maximum efficiency was achieved at the resonant frequency of approximately 97.953 kHz, reaching the highest efficiency value. At frequencies below or above resonance, efficiency decreases due to an increase in the reactive current component, which leads to higher copper and switching losses. These results highlight the importance of operating the converter at the resonant frequency to maximize power conversion efficiency.

3.2 Switching Frequency

In the test illustrated in Figure 3.4, the results show that the output voltage of the NHB-LLCR-MIHR converter remains stable and reaches steady-state at 311V when the switching frequency is within the range of 50 kHz to 1,000 kHz. This indicates that the LC tank resonance design is already functioning optimally in transferring energy from the primary to the secondary side.

The addition of the *Lm* makes energy transfer more efficient under ZVS conditions. A larger *Lm* helps to reduce RMS current on the primary side, thereby minimizing conduction losses. The use of a hybrid rectifier with MOSFETs that are frequency-synchronized with the main MOSFETs provides faster switching response, reduces switching losses, and decreases reverse recovery losses commonly found in conventional diodes. This combination ensures output voltage stability across a wide range of switching frequencies, even under dynamic loads. At frequencies below 20 kHz, the output voltage tends to oscillate and become unstable, whereas at very high frequencies (above 1000 kHz), the output voltage drops drastically to near zero. This is due to the imbalance of energy transfer in the resonant tank. A large *Lm* ensures more energy is stored during each switching cycle. At excessively low frequencies, too much energy is released, resulting in an overdamped and unstable system. At very high frequencies, very little energy is delivered to the load because the resonance time is too short, causing the output to drop. The hybrid rectifier allows the secondary MOSFETs to adaptively synchronize their timing with the primary switching, reducing the likelihood of rectifier dead time and ensuring optimal energy delivery to the load over a wider frequency range compared to standard diodes. The wide output voltage control is enabled by adjusting the switching frequency, which changes the gain characteristics of the LLC resonant tank, allowing efficient regulation of output voltage over a broad range [6].

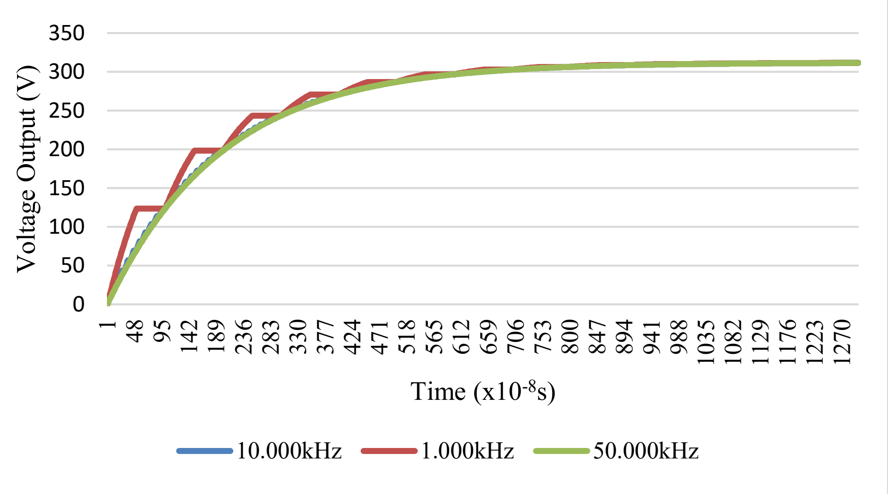

Figure 6. NHB-LLCR-MIHR at various switching frequencies

3.3 DC Conversion Ratio

Testing at the optimal frequency (50 kHz) demonstrated a high and stable DC conversion ratio, indicating very efficient power transfer from input to output. A larger magnetizing inductor enables the transformer to be designed at its optimal operating point. The hybrid rectifier minimizes losses due to forward voltage drop at the rectifier, as MOSFETs exhibit lower resistance compared to diodes. This leads to higher efficiency in the DC conversion ratio, especially at higher currents. The LLC Resonant Converter can regulate the output voltage by increasing switching frequency in case that the output voltage rises according to input or load change... the junction capacitance of rectifier diode is the main element of the additional resonant frequency, and selecting different rectifier can reduce the effect of junction capacitance [24].

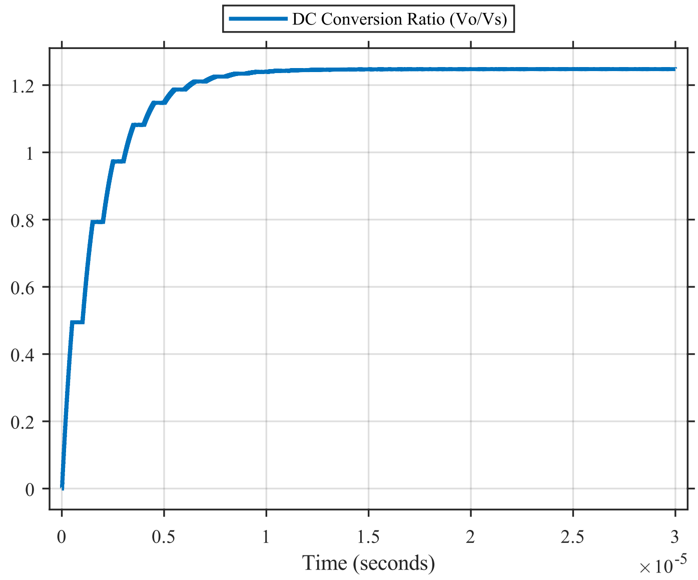

Figure 7. DC conversion ratio (Vo/Vs)

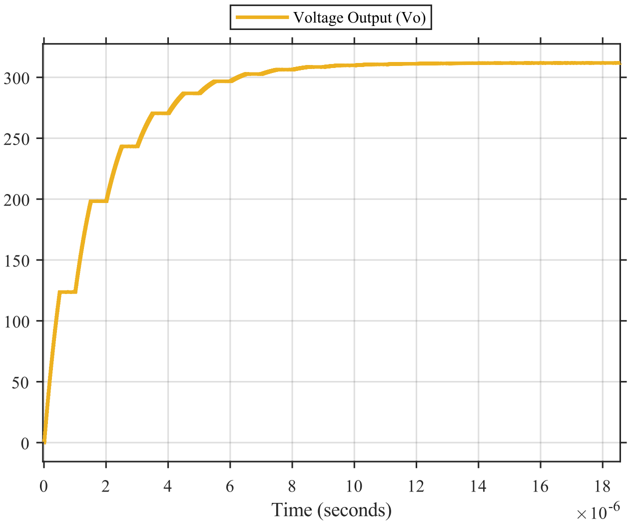

Figure 8. Voltage output (Vo)

3.4 Comparison with Conventional Converter

The results show that the proposed converter (with a large *Lm* and hybrid rectifier) delivers a slightly higher output (311V) compared to the converter in [14] (309V) at the same optimal frequency. This improvement in output voltage is attributed to two main factors: a large *Lm* reduces conduction losses because the magnetizing current in the transformer is lower, allowing more power to be delivered to the output; and the hybrid rectifier eliminates reverse recovery on the secondary side, which in diodes typically causes transient current spikes and switching losses, especially under dynamic loads and high switching rates. As a result, the output becomes higher and more stable without the need to increase the switching frequency, which would otherwise increase switching losses.

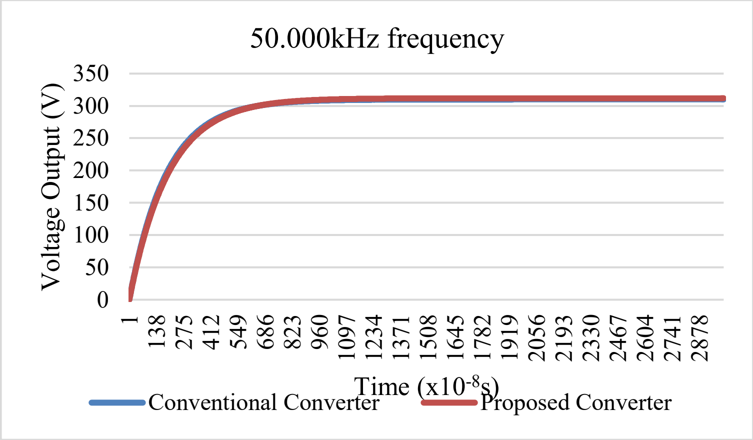

Figure 9. Comparison between the conventional and proposed converter

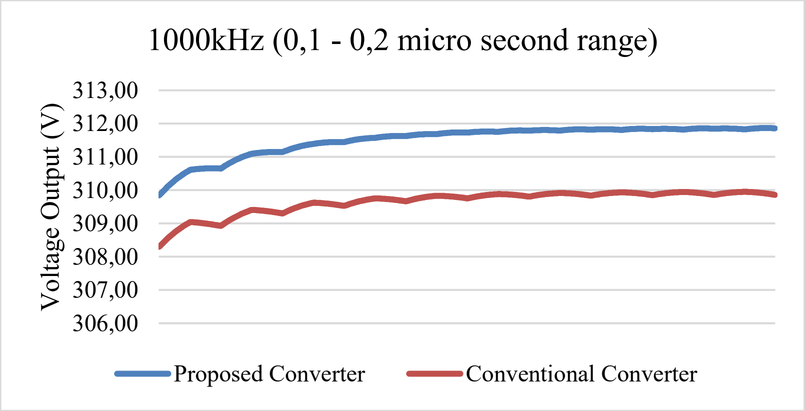

Figure 10. Comparison of output voltage ripple

The proposed converter has a lower output ripple and a shorter time to reach steady-state compared to the conventional converter. A large *Lm* in the transformer acts as a natural filter, helping to suppress current spikes and minimize output ripple. The MOSFETs in the hybrid rectifier also provide rectification with extremely low delay, enabling the output voltage to reach steady-state more quickly. This not only improves efficiency but also extends the lifespan of load components, as the load receives a more stable voltage with minimal noise. This advantage of low ripple makes the proposed converter highly suitable for sensitive power applications, such as precision electronic devices and modern power distribution systems. The proposed LLC resonant converter with a large magnetizing inductance effectively reduces the primary circulating current, thereby decreasing conduction and switching losses and achieving higher output voltage and efficiency compared to the conventional topology [25].

4. CONCLUSION

Simulation results and analysis confirm that the Novelty Half-Bridge LLC Resonant Converter with Magnetizing Inductor and Hybrid Rectifier (NHB-LLCRC-MIHR) achieves significant improvements in efficiency, output voltage stability, and reductions in both switching and conduction losses compared to conventional converters. Operation at the resonant frequency (around 97.9 kHz) produces minimum impedance and maximum efficiency, reflecting the essential characteristics of LLC converters. The addition of *Lm* and a hybrid rectifier keeps the output voltage stable across a wide switching frequency range (50 kHz to 1 MHz). The resonant tank design and synchronous secondary MOSFET control support optimal energy transfer and minimize dead time during rectification. High DC conversion ratio efficiency persists due to low voltage drop in the hybrid rectifier and an optimized Lm, especially at high current levels. The proposed converter produces higher output voltage, lower voltage ripple, and a faster time to reach steady-state compared to the conventional converter. A larger Lm serves as a natural filter. Secondary MOSFETs deliver rapid and efficient rectification. The NHB-LLCRC-MIHR topology offers promising potential for precision power supplies, electric vehicle systems, and renewable energy sources requiring high efficiency and power stability. Recommended future work includes adaptive digital control for the hybrid rectifier and further transformer optimization to reduce physical size without sacrificing efficiency. Higher power testing and analysis of disturbance resilience in industrial environments remain essential. Experimental validation using a physical prototype and investigation of dynamic load effects on long-term performance remain important aspects for improvement.

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