

Article

A Detailed Analysis and Gain Derivation of Reconfigurable Voltage Rectifier-Based LLC Converter

Fahad Alaql ^{1,*}, Walied Alfraidi ¹, Abdullah Alhatlani ¹, Abdullrahman A. Al-Shamma'a ¹, Hassan M. Hussein Farh ¹, and Ahmed Allehyani ²

¹ Electrical Engineering Department, College of Engineering, Imam Mohammad Ibn Saud Islamic University (IMSIU), Riyadh 11564, Saudi Arabia

² Electrical and Electronic Engineering Department, College of Engineering, University of Jeddah, Jeddah 21589, Saudi Arabia

* Correspondence: faaql@imamu.edu.sa

Abstract: In this paper, a complete analysis of an LLC resonant converter with a customized rectifier structure is presented. The converter is intended for wide, low-input, high-output voltage DC bus applications. The performance of the converter is assessed using comprehensive time-domain and fundamental harmonic approximation (FHA), which demonstrates its capacity to operate across an ample range of voltages by precisely adjusting the rectifier structure. The converter's capability is illustrated by deriving and discussing detailed mode operation, steady-state analysis, and DC gain equations. In order to verify the theoretical analysis, a prototype with a power output of 250 watts is constructed and subjected to testing. The results of the testing demonstrate that the converter is both feasible and effective. The experimental findings illustrate its capacity to manage vast voltage ranges while upholding high efficiency. In addition, the converter utilizes a frequency switching modulation (FSM) to connect with a photovoltaic (PV) panel and control the high output voltage. This demonstrates its adaptability in renewable energy applications. The validation is in accordance with theoretical predictions, demonstrating the converter's high-efficiency performance and versatility.



Citation: Alaql, F.; Alfraidi, W.; Alhatlani, A.; Al-Shamma'a, A.A.; Hussein Farh, H.M.; Allehyani, A. A Detailed Analysis and Gain Derivation of Reconfigurable Voltage Rectifier-Based LLC Converter.

Electronics **2024**, *13*, 3788. <https://doi.org/10.3390/electronics13193788>

Academic Editor: Francisco Javier Ruiz-Rodríguez

Received: 27 July 2024

Revised: 24 August 2024

Accepted: 1 September 2024

Published: 24 September 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: LLC converter; resonant; wide voltage; gain; rectifier

1. Introduction

With the ongoing increase in global energy consumption, primarily due to industrial expansion and higher load needs, the drawbacks of traditional grid systems that rely on fossil fuels have become more evident. Around three billion people worldwide have limited access to energy, and more than one billion have no access to electricity [1]. Given that more than 80% of the world's energy is now obtained from finite and polluting fossil fuels, the demand for sustainable alternatives is exceptionally urgent [2]. The primary objective of the International Renewable Energy Agency (IRENA) is to achieve a significant increase in renewable energy generation, specifically from solar and wind power, to reach 85% by the year 2050 [3]. This transition is additionally reinforced by the increasing embrace of hybrid renewable energy systems (HRES), which integrate photovoltaic (PV) panels, wind turbines, and fuel cells. These systems mitigate the environmental issues linked to fossil fuels and provide a dependable and cost-efficient solution for supplying electricity to isolated and rural regions where expanding the traditional power grid is difficult. Incorporating these sustainable sources is crucial for fulfilling the increasing energy requirements while reducing environmental harm [4–6].

To address electricity access issues, photovoltaic (PV) energy systems optimize energy storage, control systems, and DC–DC converters for microinverters to maximize energy collection and consumption. PV watttrouters need to track voltage and current

waveforms to prevent surplus electricity from returning to the grid to manage residential power flow [7–10]. Furthermore, the PV tilt and azimuth angles have a significant impact on the amount of solar radiation that reaches the PV modules, thus directly affecting energy output [11]. PV systems can be categorized as grid-tied, grid-interactive, or off-grid systems, with more than 90% of them being connected to the electrical grid [12]. Microinverters have several advantages over other types of inverters. They can operate effectively even when there is partial shade, give flexibility, and provide better safety. Nevertheless, the sporadic characteristics of PV systems need the use of energy storage devices [13,14]. The integration of PV panels involves the utilization of DC–DC converters such as the Dual Active Bridge (DAB) converter. This converter is employed to transform the low and fluctuating voltage generated by PV panels into a high and stable voltage. Although DAB converters offer advantages, they encounter efficiency obstacles in large voltage range applications because of limited soft-switching ranges and substantial turn-off losses [15–17]. The LLC resonant converter, renowned for its Zero-Voltage Switching (ZVS) and Zero-Current Switching (ZCS) characteristics, provides a straightforward, high-amplification, and high-power-density solution for a broad range of voltage applications in PV systems and high-voltage batteries [18–20].

The effectiveness and dependability of DC–DC converters in power electronic transformers (PETs) are significantly impacted by the design and performance of the preceding multilevel converter. An efficiently designed multilevel converter improves the quality of the input voltage, decreases harmonic distortion, and enables better control of voltage and current. These factors collectively enhance the dynamic response and stability of the system, even when the load conditions change. The multilevel converter increases efficiency and improves operational effectiveness and power transfer capacity by decreasing stress on components and enabling soft switching. This makes it an essential component in high-power applications and contributes to the overall performance of PET systems [21–23].

Numerous LLC resonant topologies have been described in [19,24–30] to improve efficiency and overcome the constraints of traditional LLC converters in applications with a wide range of voltages. Ren et al. have introduced a Sigma DC/DC converter that integrates a conventional LLC converter as a DC transformer with two multi-resonant converters for voltage regulation. This architectural design effortlessly switches between DCX and D2D modes based on input voltage range, optimizing efficiency and adaptability [24]. In [19], the authors examine an LLC converter circuit specifically designed to achieve ZVS. This circuit includes a voltage doubler rectifier and a variable transformer turn-ratio, which allows for three configurations depending on the input voltage levels. The topology proposed by Elezab et al. in [25] uses a split resonant capacitor and adjustable secondary component, allowing for parallel mode for low output voltages and series mode for high output voltages. This design keeps operation near to the resonance frequency, reducing strain on the components and improving efficiency. In [26], the author presents a modified two-channel LLC resonant converter with two primary power switches, resonant inductors, and capacitors. This design maintains high voltage gain and performance regardless of input circumstances. This circuit's layout provides low input impedance at low voltages for high gain and high input impedance at high volts for low gain. The author in [27] introduces a bidirectional three-level T-type LLC resonant isolated DC–DC converter that utilizes a new three-degrees-of-freedom (3DOF) modulation technique. The converter employs phase-shift control, variable frequency modulation, and pulse width modulation to perform soft switching over a broad voltage ratio range and under low loads, thereby greatly improving efficiency compared to conventional converters. The paper in [28] presents a new multi-mode rectifier-based LLC resonant converter that includes a new rectifier construction capable of operating in three different modes. The rectifier architecture enables a substantial increase in voltage amplification while simultaneously restricting the range of switching frequencies, resulting in enhanced efficiency. The converter described in [29] has two HB

switching networks on the primary side. On the secondary side, there is a rectification stage that uses two secondary-side windings of transformers connected in series. The converter accomplishes ZVS and ZCS by employing fixed-frequency operation with phase-shift control, thereby eliminating losses. In [30], a dual-bridge LLC resonant converter incorporates a buck-boost converter in the front stage to accommodate higher input voltage. This, in turn, enhances the transformer turns ratio and decreases primary conduction losses. In addition, the converter employs full-bridge and half-bridge structures to efficiently function with different input voltages. The auxiliary switches are employed to regulate the functioning of the converter, facilitating the transfer from full-bridge to half-bridge modes.

The paper in [31] presents a novel LLC converter that incorporates a reconfigurable rectifier. The converter is specifically built to cater to applications that require wide input voltage ranges and high output voltage. The converter effectively addresses the efficiency challenges of conventional wide-range converters by incorporating three distinct rectifier structures: voltage-doubler (VDR), voltage-tripler (VTR), and voltage fifth-folder (VFR). These structures adapt based on input voltage levels, narrowing the switching frequency range. The design incorporates advanced features such as zero-voltage switching (ZVS) in power MOSFETs and zero-current switching (ZCS) in power diodes. These features effectively minimize voltage stress on rectifier components and promote overall efficiency.

This paper extends the work presented in [31] and introduces several key contributions. The time-domain approach is utilized to provide a comprehensive examination of voltage gain. In addition, it illustrates the waveforms during mode transitions. Furthermore, it examines the voltage amplification of the reconfigurable voltage rectifier-based LLC converter using time-domain analysis and compares it with frequency harmonic analysis (FHA) approaches. Theoretical method validation is achieved by the presentation of experimental results, which showcase the time-domain modes and the two operational stages. Furthermore, the transition mode is demonstrated capable of maintaining a constant output voltage during the presence of fluctuations in the input voltage. The paper additionally provides a comprehensive analysis of converter efficiency across various input voltages, emphasizing the benefits of adjusting between modes.

The paper is organized in the following manner: Section 2 introduces the time-domain analysis and explores the potential signal shapes for the converter. Section 3 provides a detailed analysis of each stage, including a mathematical model for each. Next, in Section 4, the DC gain equations and characteristic curves of the LLC Converter based on a reconfigurable voltage rectifier are derived. The experimental results are presented in Section 5, while the conclusions are provided in Section 6.

2. Time-Domain Analysis

The proposed converter, shown in Figure 1, is an LLC converter that is equipped with a reconfigurable rectifier. It is specifically designed to work effectively across a wide variety of input and output voltages, while also retaining a limited spectrum of switching frequencies [31]. The system incorporates three types of rectifiers: a voltage-doubler rectifier (VDR), a voltage-tripler rectifier (VTR), and a voltage fifth-folder rectifier (VFR). These rectifiers can be switched automatically depending on the input voltage, resulting in a significant increase in voltage and a reduction in voltage stress on the components [31].

With the intention of simplifying the study of the reconfigurable voltage rectifier-based LLC Converter shown in Figure 1, we will assume that the four primary switches are ideal and will disregard the dead time instead. Moreover, the symbol T denotes the specific number that characterizes the rectifier circuit. The VDR configuration corresponds to a rectifier of type 2, the VTR configuration corresponds to a rectifier of type 3, and the VFR configuration corresponds to a rectifier of type 5. Figures 2–4 present an analysis of the waveforms of the converter when it is operating in a steady state. The converter that is

being presented can function in five different modes, which are depicted in Figures 2–4 and are described in more depth below:

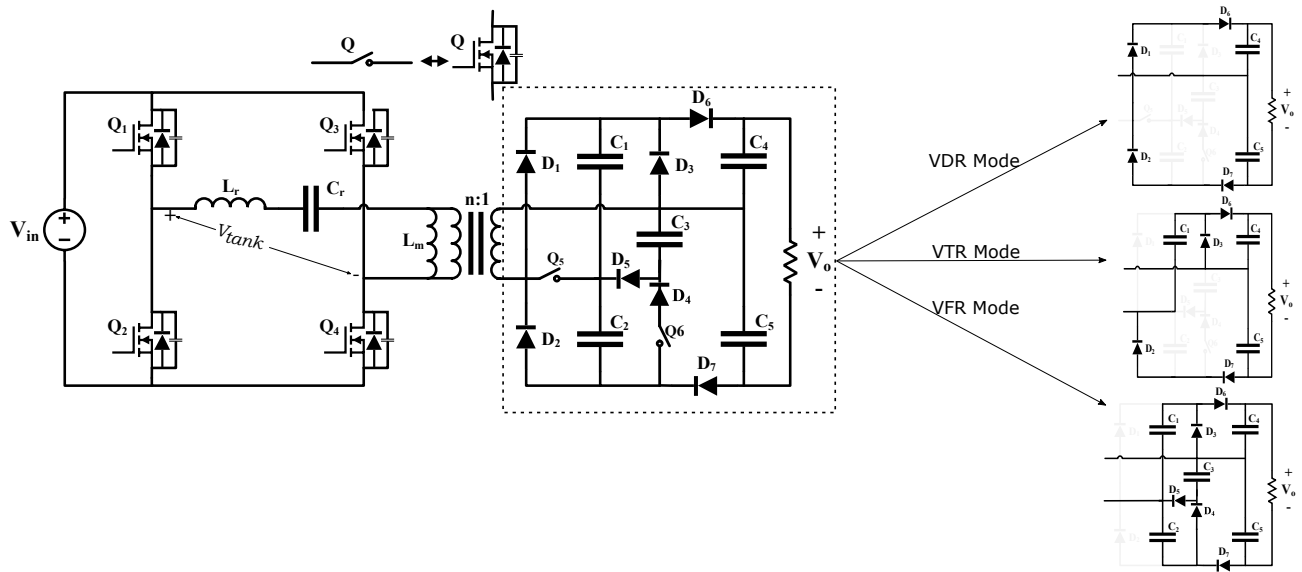


Figure 1. Proposed LLC resonant converter based on reconfigurable voltage rectifier and its rectifier configurations, VDR, VTR, and VFR [31].

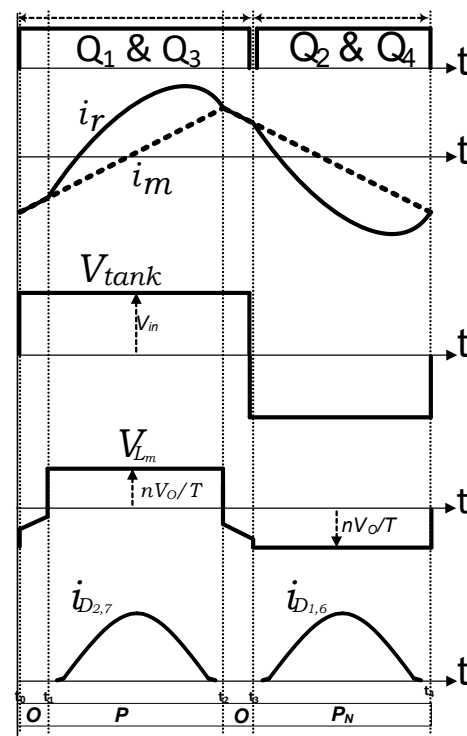


Figure 2. The waveforms of the resonant tank components during the entire switching cycle in VDR mode.

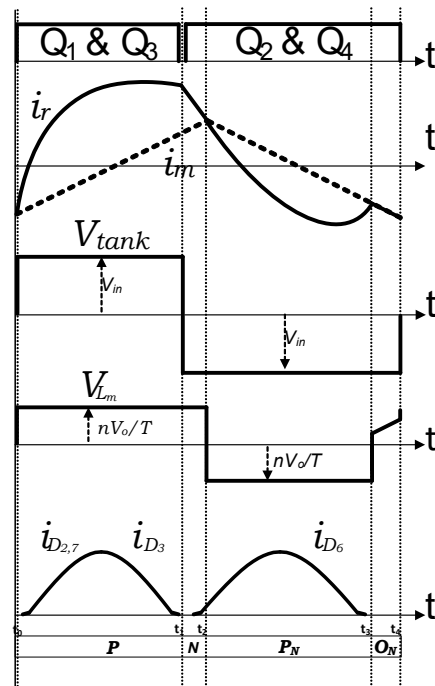


Figure 3. The waveforms of the resonant tank components during the entire switching cycle in VTR mode.

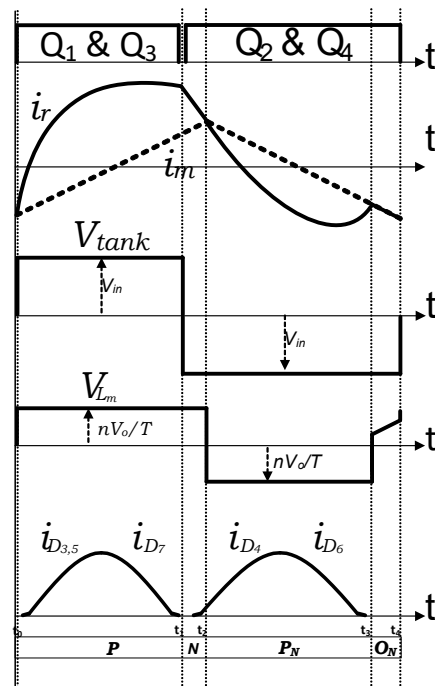


Figure 4. The waveforms of the resonant tank components during the entire switching cycle in VFR mode.

In *P*-mode, the tank voltage is equal to the input voltage, and the voltage across the magnetizing inductance is positively clamped to the output voltage. This is determined by the turns ratio and rectifier type, as shown in Figure 5. As a consequence, a sinusoidal resonant current with a positive value is produced.

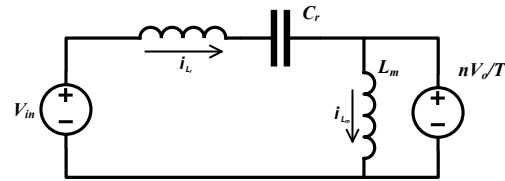


Figure 5. The P mode circuit.

P_N -mode occurs when the tank voltage becomes negative and the voltage across the magnetizing inductance is clamped to the output voltage in a negative manner. This is determined by factors such as the turns ratio and rectifier type. In P_N -mode, the resonant current takes the shape of a negative sine wave, as depicted in Figure 6.

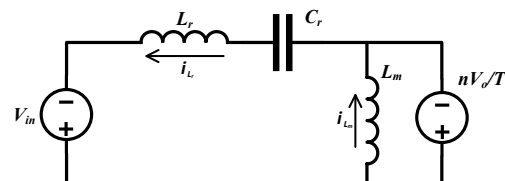


Figure 6. The P_N mode circuit.

In N -mode, shown in Figure 7, there is a resonant tank that is similar to P -mode. However, in N -mode, the voltage of the magnetizing inductance is clamped negatively to the output voltage. This is influenced by the turns ratio and the type of rectifier used.

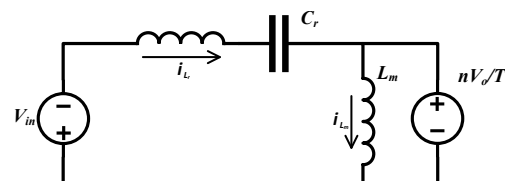


Figure 7. The N mode circuit.

O -mode refers to the operational state of the converter when the output power becomes zero, resulting in the elimination of the impact of the output voltage on the magnetizing inductance, as depicted in Figure 8. In addition, the voltage of the tank is clamped to the input voltage in a positive manner.

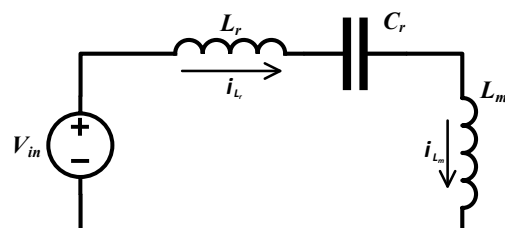


Figure 8. The O mode circuit.

O_N -mode occurs when the input voltage of the resonant tank in O -mode becomes negative, causing a negative voltage across the input, as shown in Figure 9.

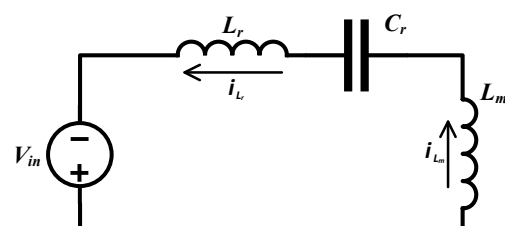


Figure 9. The O_N mode circuit.

The steady-state waveforms, shown in Figures 2–4, of the reconfigurable converter can be classified into two shapes: $OPOP_N$ and PNP_NO_N based on the switching frequency of Q_1 and Q_2 . The following is a description of these waveform shapes:

- The waveform shape $OPOP_N$ happens when the switching frequency matches the resonant frequency. This shape is represented in Figure 2.
- The waveform shape PNP_NO_N is depicted in Figure 3 for VTR and Figure 4 for VFR, showing the steady-state waveforms. The steady-state waveforms of converter exhibit the PNP_NO_N shape when the switching frequency exceeds the resonant.

3. Stage by Stage Analysis

To determine the gain occurring in the converter, a step-by-step examination is necessary. The study presupposes that the principal switches are in their optimal state and disregards any delay in the system. Each waveform, namely $OPOP_N$ and PNP_NO_N , consists of four primary stages (I–IV) during a whole cycle, as depicted in Figures 2–4. The subsequent paragraph provides a concise description of the four stages that occur during a switching cycle when the converter runs at a resonant frequency ($OPOP_N$). Furthermore, each stage description includes the equations for the resonant inductor current (i_{L_r}), resonant capacitor voltage (v_c), and magnetizing inductor current (i_{L_m}).

Stage I: $[t_0, t_1)$. The switching cycle initiates with the O-mode due to the fact that the magnetizing voltage does not first attain the value of nV_o/t . At this stage, the resonant frequency is equal to the value of the magnetizing current. The resonant tank is subjected to a positive voltage. In addition, the secondary side is disconnected, resulting in all rectifier diode currents being zero.

$$v_c(t) = i_{L_r}(t_0)Z_m \sin[\omega_m(t - t_0)] + (V_c(0) - V_{in})\cos[\omega_m(t - t_0)] + V_{in} \quad (1)$$

$$i_{L_r}(t) = i_m(t) = i_{L_r}(t_0)\cos[\omega_m(t - t_0)] - \frac{V_c(0) - V_{in}}{Z_m} \sin[\omega_m(t - t_0)] \quad (2)$$

where $i_{L_r}(t_0)$, $V_c(t_0)$, and $i_m(t_0)$ are the initial inductor current, capacitor voltage, and magnetizing current, respectively, $\omega_m = 1/\sqrt{(L_r + L_m)C_r}$ and $Z_m = \sqrt{(L_r + L_m)/C_r}$.

Stage II: $[t_1, t_2)$. Once the magnetizing voltage reaches its maximum, the converter is capable of working in P mode, causing the resonant current signal to transform to a sinusoidal waveform. The resonant tank maintains a positive voltage while the magnetizing current remains below the resonant current. During this stage, the secondary side of the circuit is connected, resulting in the conduction of the rectifier diodes. In addition, the currents reach their maximum value as they pass through D_2 and D_7 .

$$v_c(t) = i_{L_r}(t_1)Z_r \sin[\omega_r(t - t_1)] + \left(\frac{nV_o}{T} + V_c(t_1) - V_{in}\right)\cos[\omega_r(t - t_1)] + V_{in} - \frac{nV_o}{T} \quad (3)$$

$$i_{L_r}(t) = i_{L_r}(t_1)\cos[\omega_r(t - t_1)] - \frac{\frac{nV_o}{T} + V_c(t_1) - V_{in}}{Z_r} \sin[\omega_r(t - t_1)] \quad (4)$$

$$i_m(t) = \int \frac{V_m}{L_m} dt = \frac{nV_o}{TL_m}(t - t_1) + i_m(t_1) \quad (5)$$

Stage III: $[t_2, t_3)$. Due to the insufficient reversal of the magnetizing voltage, the converter must operate in O mode once more. As a result, when the rectifier diodes are turned off, the secondary circuit is disconnected from the primary circuit.

$$v_c(t) = i_{L_r}(t_2)Z_m \sin[\omega_m(t - t_2)] + (V_c(t_2) - V_{in})\cos[\omega_m(t - t_2)] + V_{in} \quad (6)$$

$$i_{L_r}(t) = i_m(t) = i_{L_r}(t_2)\cos[\omega_m(t - t_2)] - \frac{V_c(t_2) - V_{in}}{Z_m} \sin[\omega_m(t - t_2)] \quad (7)$$

Stage IV: $[t_3, t_4)$. During the second half of the switching cycle, the converter mainly functions in P_n mode due to the ability of the magnetizing voltage to sustain its negative

value, $-nV_o/t$. At this stage, the voltage of the resonant tank is adjusted to match the negative input voltage. On the secondary side, D_1 and D_6 begin to conduct current and reach their maximum value in the middle of this stage until they turn off at the end of the P mode.

$$v_c(t) = i_{L_r}(t_3)Z_r \sin[\omega_r(t - t_3)] + \left(\frac{-nV_o}{T} + V_c(t_3) + V_{in} \right) \cos[\omega_r(t - t_3)] - V_{in} + \frac{nV_o}{T} \quad (8)$$

$$i_{L_r}(t) = i_{L_r}(t_3) \cos[\omega_r(t - t_3)] - \frac{\frac{-nV_o}{T} + V_c(t_3) + V_{in}}{Z_r} \sin[\omega_r(t - t_3)] \quad (9)$$

$$i_m(t) = \int \frac{V_m}{L_m} dt = \frac{-nV_o}{TL_m}(t - t_3) + i_m(t_3) \quad (10)$$

The following paragraph presents the equations for the current in the resonant inductor (i_{L_r}), the voltage across the resonant capacitor (v_c), and the current in the magnetizing inductor (i_{L_m}) for every stage in PNP_NON . Furthermore, a detailed explanation of the behavior of the primary voltages and current during this switching cycle.

Stage I: $[t_0, t_1)$. The start of this stage occurs when switches Q_1 and Q_4 are activated using soft switching. The amplitude of the resonant current exceeds that of the magnetizing current, resulting in the formation of a sinusoidal waveform. The resonant tank's input voltage reaches its maximum, which is equivalent to the input voltage, while the voltage across the magnetizing inductor is equal to the total output voltage on the primary side. During VTR mode, the currents pass through diodes D_2 , D_3 , and D_7 on the secondary side. In VFR mode, the currents pass through diodes D_3 , D_5 , and D_7 on the secondary side. The cycle concludes when the tank voltage switches to a negative input voltage, resulting in the deactivation of D_2 , D_3 , D_5 , and D_7 .

$$v_c(t) = i_{L_r}(t_0)Z_r \sin[\omega_r(t - t_0)] + \left(\frac{nV_o}{T} + V_c(0) - V_{in} \right) \cos[\omega_r(t - t_0)] + V_{in} - \frac{nV_o}{T} \quad (11)$$

$$i_{L_r}(t) = i_{L_r}(t_0) \cos[\omega_r(t - t_0)] - \frac{\frac{nV_o}{T} + V_c(0) - V_{in}}{Z_r} \sin[\omega_r(t - t_0)] \quad (12)$$

$$i_m(t) = \int \frac{V_m}{L_m} dt = \frac{nV_o}{TL_m}(t - t_0) + i_m(t_0) \quad (13)$$

Stage II: $[t_1, t_2)$. Due to the fact that the duration of switches Q_1 and Q_4 are less than half of the resonant time, Stage I is not fully completed, resulting in the resonant current being unequal to the magnetizing current at t_1 . Resonant current begins to diminish at Stage II. The input voltage of the resonant tank is negative, while the magnetizing voltage remains constant. The currents that are flowing through D_6 for VTR mode and D_4 and D_6 for VFR mode are gradually intensifying.

$$v_c(t) = i_{L_r}(t_1)Z_r \sin[\omega_r(t - t_1)] + \left(\frac{nV_o}{T} + V_c(t_1) + V_{in} \right) \cos[\omega_r(t - t_1)] - V_{in} - \frac{nV_o}{T} \quad (14)$$

$$i_{L_r}(t) = i_{L_r}(t_1) \cos[\omega_r(t - t_1)] - \frac{\frac{nV_o}{T} + V_c(t_1) + V_{in}}{Z_r} \sin[\omega_r(t - t_1)] \quad (15)$$

$$i_m(t) = \int \frac{V_m}{L_m} dt = \frac{nV_o}{TL_m}(t - t_1) + i_m(t_1) \quad (16)$$

Stage III: $[t_2, t_3)$. This stage is analogous to Stage I, with the distinction that the resonant current reaches its entire cycle and becomes equal to the magnetizing current by the end of this stage. Furthermore, the input voltage that resonates remains negative, but the voltage across the magnetizing inductor undergoes an opposite change. The currents flowing through D_6 for VTR mode and D_4 and D_6 for VFR mode reach their peak values at the midpoint of the stage.

$$v_c(t) = i_{L_r}(t_2)Z_r \sin[\omega_r(t - t_2)] + \left(\frac{-nV_o}{T} + V_c(t_2) + V_{in} \right) \cos[\omega_r(t - t_2)] - V_{in} + \frac{nV_o}{T} \quad (17)$$

$$i_{L_r}(t) = i_{L_r}(t_2)\cos[\omega_r(t-t_2)] - \frac{\frac{-nV_o}{T} + V_c(t_2) + V_{in}}{Z_r}\sin[\omega_r(t-t_2)] \quad (18)$$

$$i_m(t) = \int \frac{V_m}{L_m} dt = \frac{-nV_o}{TL_m}(t-t_2) + i_m(t_2) \quad (19)$$

Stage IV: $[t_3, t_4)$. At this stage, the rectifier diodes are deactivated since the resonant current is equivalent to the magnetizing current. The converter switches to a mode that limits the output current from flowing through the primary side.

$$v_c(t) = i_{L_r}(t_3)Z_m\sin[\omega_m(t-t_3)] + (V_c(t_3) + V_{in})\cos[\omega_m(t-t_3)] - V_{in} \quad (20)$$

$$i_{L_r}(t) = i_m(t) = i_{L_r}(t_3)\cos[\omega_m(t-t_3)] - \frac{V_c(t_3) + V_{in}}{Z_m}\sin[\omega_m(t-t_3)] \quad (21)$$

4. Voltage Gain Analysis

Various techniques can be used to calculate the voltage gain (G), and each technique has its own advantages and disadvantages. Fundamental harmonic approximation (FHA) and time-domain analysis are commonly employed techniques to manage the gain of the LLC converter. The FHA approach, as described and examined in article [31], eliminates the higher harmonics of the input tank voltage ($v_{i_{ac}}$) and the output tank voltage ($v_{o_{ac}}$) in order to generate a pure sine wave. This paper will examine and discuss the process of determining the gain by time-domain analysis and thereafter compare it to the FHA technique.

The most precise approach for determining the voltage gains of the converter is through time-domain analysis. This approach is renowned for its accuracy since it examines the resonant inductor current, resonant capacitor voltage, and magnetizing inductor current in every mode of operation. Three assumptions are taken into account when studying the voltage gains in time-domain analysis: The dead time between switches Q_1 and Q_2 and Q_3 and Q_4 is disregarded; the output capacitors in VDR, VTR and VFR structures are excessively big to uphold a consistent output voltage; the passive and active components are assumed to be excellent. The output rectifier current can be obtained by using the following method.

$$I_o = \frac{n}{t_4 - t_0} \int_{t_0}^{t_4} (i_{L_r}(t) - i_{L_m}(t))dt = \frac{TV_o}{R_o} \quad (22)$$

The Equation (22) mentioned above is applicable only to the P , P_N , and N stages. This is because the resonant current is equal to the magnetizing current in the O and O_N stages.

The time intervals in the steady-state waveforms of the converter in VDR, VTR, and VFR can be computed based on the notion of P , P_N , N , O and O_N stages. The P stage begins at time t_1 and finishes at time t_2 for VDR mode, while it begins at time t_0 and ends at time t_1 for VTR and VFR modes. The P_N stage exists during the last time interval from t_3 to t_4 in VDR mode, and from t_2 to t_3 in VTR and VFR modes. Alternatively, the O stage occurs throughout the time intervals t_0 to t_1 and t_2 to t_3 in VDR mode. In VTR and VFR mode, the O_N stage is present from t_3 to t_4 . The converter transitions to stage N in both VTR and VFR mode between time t_1 and t_2 . The time interval following t_4 in all modes exhibits symmetrical characteristics to the time interval between t_0 and t_4 . This property yields the following conditions:

$$\begin{cases} i_{L_m}(t_4) = i_{L_m}(t_0) \\ i_{L_r}(t_2) = i_{L_m}(t_2) \\ v_{C_r}(t_4) = -v_{C_r}(t_0) \\ i_{L_r}(t_4) = i_{L_m}(t_0) \end{cases} \quad (23)$$

Analyses are used to determine the initial values of the resonant inductor current, resonant capacitor voltage, and magnetizing inductor by exploiting the continuity between

the modes of operation. The initial currents $i_{L_r}(t_0)$ and $i_{L_m}(t_0)$ can be computed using the following equations.

$$i_{L_r}(t_0) = i_{L_m}(t_0) = -\frac{nt_r V_o}{4L_m T} \quad (24)$$

The initial voltage of the capacitor, $v_{C_r}(t_0)$, can be calculated by substituting the formulae for the resonant current and magnetizing current into the equation for the output current, Equation (22).

$$v_{C_r}(t_0) = -\frac{\frac{t_r(nV_o - TV_{in})}{T} + \frac{Z_r t_s \pi TV_o}{2nR_o}}{t_r} \quad (25)$$

To get the voltage gain of the converter (G), one can substitute the beginning values of $i_{L_r}(t_0)$, $i_{L_m}(t_0)$, and $v_{C_r}(t_0)$ into the operating stage equations of P , P_N , N , O and O_N stages as follows:

$$G = \frac{2}{\cos \left[w_m \left(\frac{t_r}{2} - \frac{t_s}{2} \right) \right] \left(\frac{2n}{T} - \frac{Z_r \pi \left(\frac{Tt_s}{2nR_o} + \frac{nt_r}{TZ_r \pi} \right)}{t_r} \right) + \frac{Z_r \pi \left(\frac{Tt_s}{2nR_o} + \frac{nt_r}{TZ_r \pi} \right)}{t_r} + \frac{nt_r Z_r \sin \left[w_m \left(\frac{t_r}{2} - \frac{t_s}{2} \right) \right] \sqrt{m+1}}{4L_m T}} \quad (26)$$

The voltage gain of the converter (G) with different rectifier structures can be illustrated in Figure 10 by utilizing Equation (26).

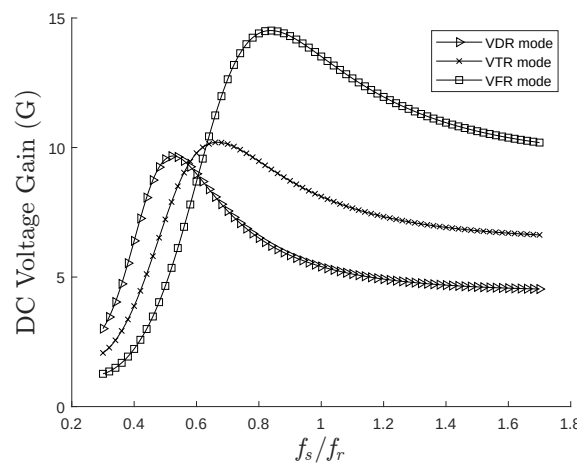


Figure 10. The voltage gain of the reconfigurable voltage rectifier-based LLC converter (G) is plotted with respect to the normalized switching frequency.

In the analysis of FHA, the quality factor (Q) indicates the extent to which the voltage gain is increased or decreased. The AC equivalent resistance R_{acT} , which has an inverse relationship with Q , fluctuates depending on the rectifier construction. Therefore, the Q values for the three rectifier designs can be computed in the following manner:

$$Q = \frac{2\pi L_r f_r}{R_{acT}} = \begin{cases} \frac{\pi^3 L_r f_r}{n^2 R_o} & \text{(VDR mode)} \\ \frac{3\pi^3 L_r f_r}{2n^2 R_o} & \text{(VTR mode)} \\ \frac{5\pi^3 L_r f_r}{2n^2 R_o} & \text{(VFR mode)} \end{cases} \quad (27)$$

For a comparison between the time-domain method and FHA method, the voltage gain of the converter is depicted in Figure 11 using both approaches. The time-domain technique can provide precise gain when the converter runs within the frequency range of f_r and f_m . Nevertheless, the accuracy of the time-domain technique declines as the converter operates beyond resonance and enters the capacitive zone. Conversely, the FHA method is a method that provides an estimation of the voltage gain of the LLC resonant converter. Thus, the accuracy of the FHA technique is much inferior to that of the time-domain method.

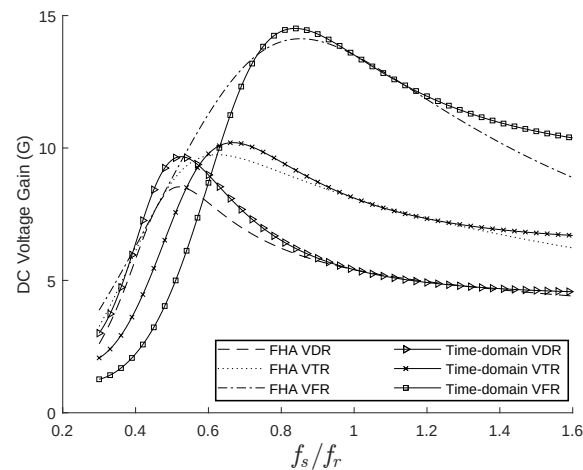


Figure 11. Comparing the voltage gain of the reconfigurable voltage rectifier-based LLC converter using the time-domain technique and the FHA method.

5. Experimental Results

An experimental prototype with a power output of 250 W has been created to verify the functioning and efficiency of the reconfigurable rectifier LLC converter for PV microinverters designed for high DC bus applications. Table 1 provides a concise overview of the primary specifications and design parameters. The four main switches are regulated by FSM signals with a duty cycle of 50% and a dead time of 100 nanoseconds. The prototype employs the *STM32F334K8T6* microprocessor to regulate the PWM signals for Q_1 – Q_4 and the gate signals for Q_5 and Q_6 . Figure 12 depicts the laboratory prototype.

Table 1. Specifications of the executed prototype.

Parameter	Value/Description
Input voltage	$V_{in} = 25$ – 100 V
Output Voltage	$V_o = 500$ V
Rated Power	$P_o = 250$ W
Resonant frequency	$f_r = 100$ kHz
Switching frequency	$f_s = 69$ – 113 kHz
Resonant inductor	$L_r = 18$ μ H
Resonant capacitor	$c_r = 144$ nF
Magnetizing inductor	$L_m = 60$ μ H
Output capacitor	100 nF
Transformer	$n = 37 : 100$
Primary MOSFET	IPB320N20N3
Secondary MOSFET	FCB070N65
Rectifier Diode	VS8ETH03

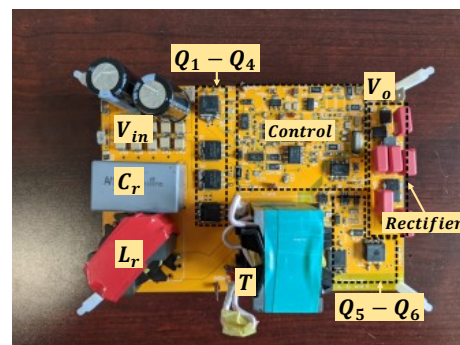


Figure 12. Laboratory prototype of the reconfigurable voltage rectifier-based LLC converter.

Figures 13–15 display the measurement waveforms of the output voltage (v_o), resonant current (i_{Lr}), gate-source voltage (v_{gs}), and drain-source voltage (v_{ds}) for Q_1 and Q_2 under various situations. As seen in Section 2, switches Q_1 and Q_4 have the same switching cycle and are complementary to switches Q_2 and Q_3 .

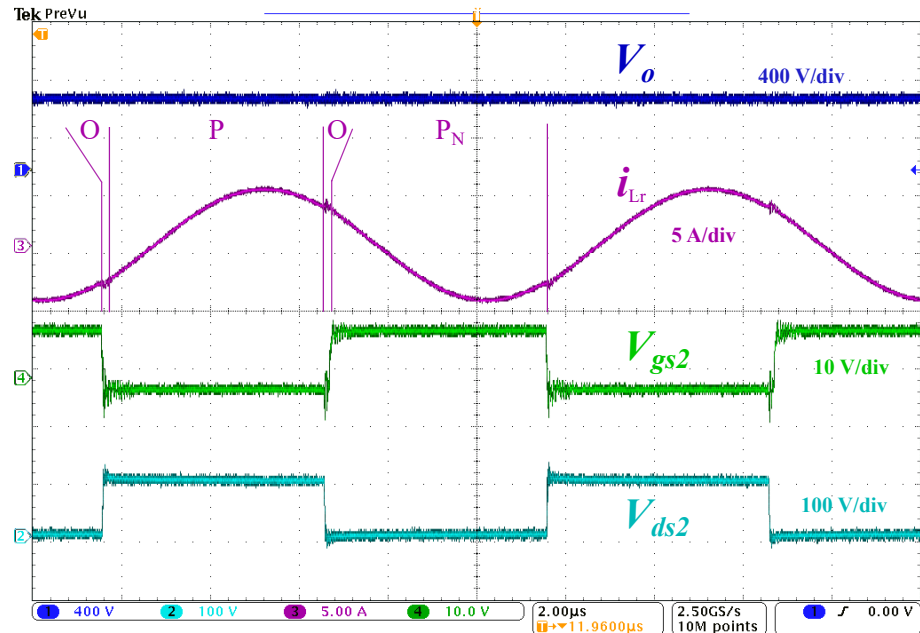


Figure 13. Experimental waveforms when the converter operates in VDR mode, generating a $OPOP_N$ waveform.

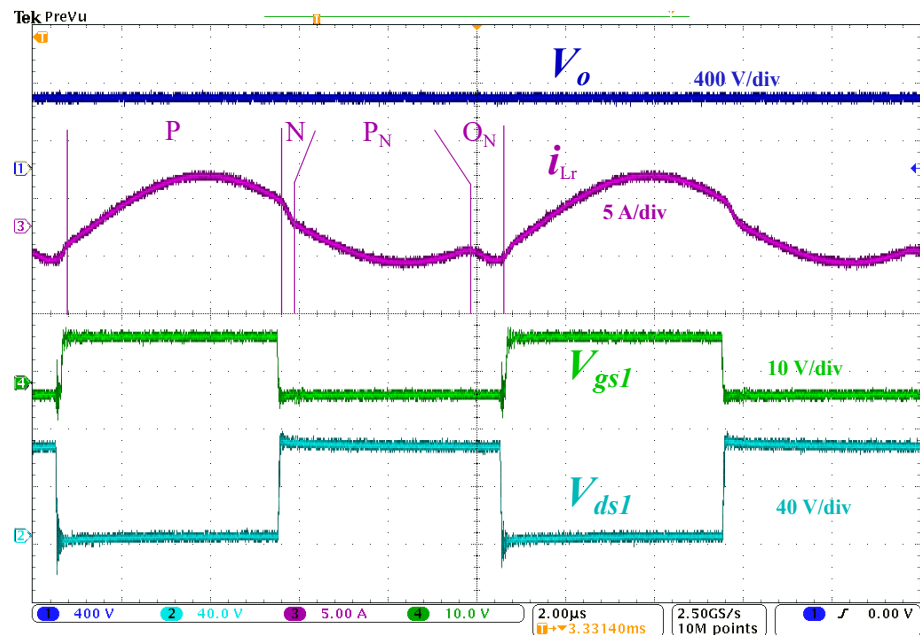


Figure 14. Experimental waveforms when the converter operates in VTR mode, generating a PNP_NO_N waveform.

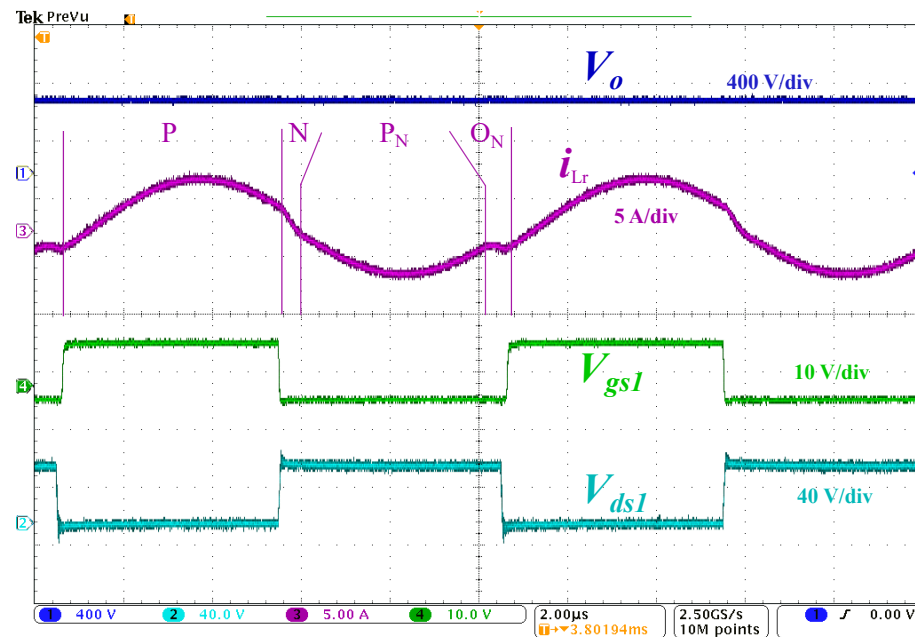


Figure 15. Experimental waveforms when the converter operates in VFR mode, generating a PNP_NO_N waveform.

Figure 13 illustrates the tank's performance when it works in close proximity to resonance under typical load circumstances. In this case, the converter functions in VDR mode, where the output voltage on the rectifier side can be doubled. The resonant current exhibits a waveform shape known as an $OPOP_N$. When Q_1 is activated, the O mode initiates and becomes visible prior to the P -mode if the magnetizing voltage is insufficiently clamped to the load at the start of the half cycle. Following that, the P mode commences with a duration that is shorter than half of the switching frequency. Subsequently, the O mode reappears due to the absence of the voltage required to achieve completion of the P mode. During the second half of the cycle, the resonant tank can only operate in P_N mode since the magnetizing voltage is sufficient to maintain the required voltage for completing the P_N mode.

When the converter switches to VTR mode, the main parameters are displayed in Figure 14. Here, the resonant current initiates in the P mode when Q_1 and Q_4 are activated, and the magnetizing voltage is constrained to its highest voltage level. Subsequently, the N mode commences as the P mode cannot be accomplished due to the deactivation of V_{gs} . Furthermore, the P_N mode begins anew, this time with a negative input voltage. The waveform concludes in the O_N mode due to the inability of the magnetizing voltage to sustain its negative voltage.

Figure 15 shows that the switching time is generally shorter than the resonant time in VFR mode. As a result, the P mode cannot complete its stage and the resonant current does not match the magnetizing current when the V_{gs} is deactivated. The second halves of all waveforms are being generated while the tank voltage is negative as a result of V_{gs2} and V_{gs3} being activated. The P_N mode is capable of completing its cycle since it has enough time available. At the conclusion of the cycle, the O_N mode occurs, while the magnetizing voltage cannot be clamped to a completely positive voltage.

The experimental results are used to draw the gain characteristics curve, which serves to verify the gain equations derived in Equation (26). Figure 16 displays the gain curves for three modes, namely VDR, VTR, and VFR modes, both experimentally and theoretically, at two different power levels: 100 W and 250 W. The figure demonstrates that the experimental findings closely align with the gain equations across a broad range, both below and above resonance. It is important to acknowledge that the precision of the gain equation decreases slightly toward the second resonant frequency, f_m . Overall, the resulting gain equations

provide an effective indicator of the tank behavior for the reconfigurable rectifier-based LLC converter.

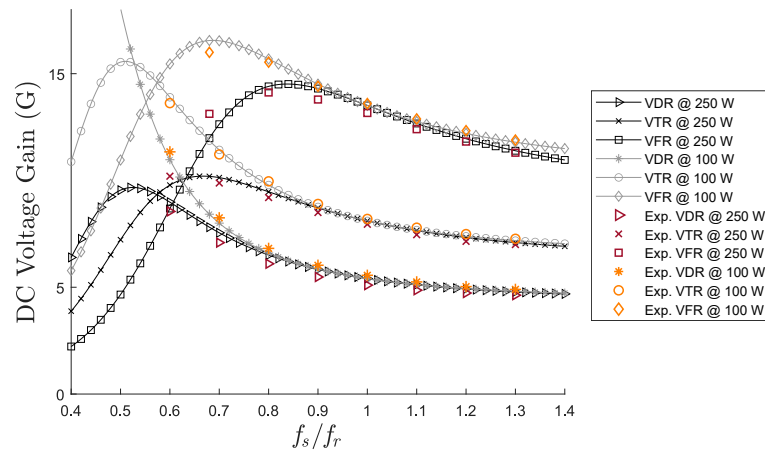


Figure 16. The gain curves of the reconfigurable voltage rectifier-based LLC converter derived from both gain equations and experimental results.

Figure 17 illustrates the gate signals of transistors Q_5 and Q_6 , as well as the output voltage (V_o) and input voltage (V_{in}). The reconfigurable rectifier-based LLC converter adjusts the rectifier structure by selectively activating and deactivating Q_5 and Q_6 in response to variations in the input, with the goal of maintaining a stable output voltage of 500 V.

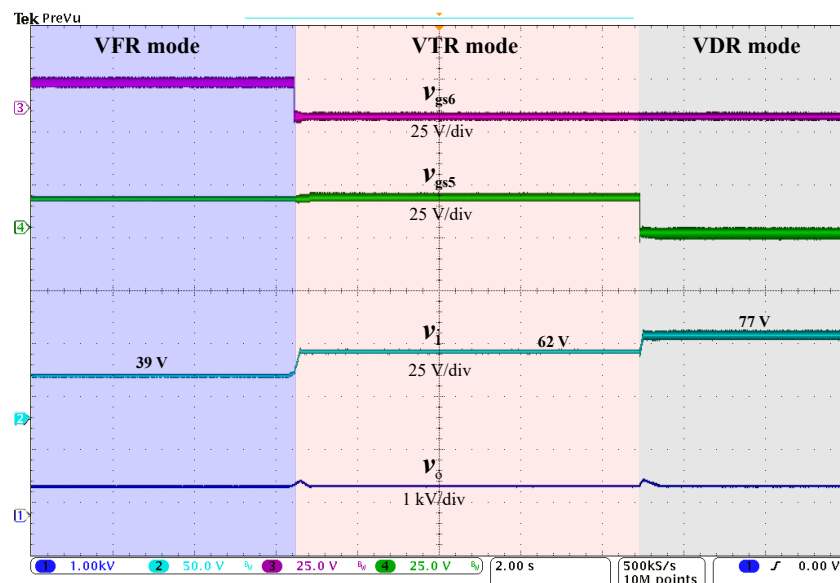


Figure 17. Experimental waveforms displaying mode transition at various input voltage levels.

The efficiency curve for various input voltages is shown in Figures 18–20. At an input voltage of 80 V, the converter functions in VDR mode. Figure 18 illustrates the effectiveness when the input voltage is set at 80. Figure 19 depicts an input voltage of 62 V and the converter is functioning in VTR mode. Nevertheless, the graph illustrates how the efficiency might be diminished when the converter runs in VDR mode at that specific input voltage. When the input voltage is 40, the efficiency decreases in VDR and VTR modes compared to VFR mode, as illustrated in Figure 20. Efficiency curves demonstrate the advantages of the converter by transitioning to a different mode as the input voltage begins to decline, resulting in excellent efficiency throughout a broad range of input voltages.

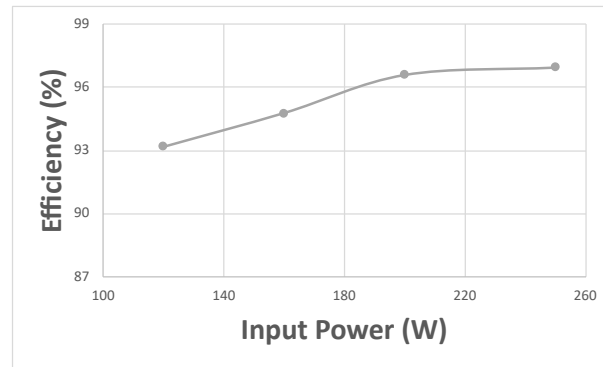


Figure 18. Measured efficiency at an input voltage of 80 V, considering different levels of input power.

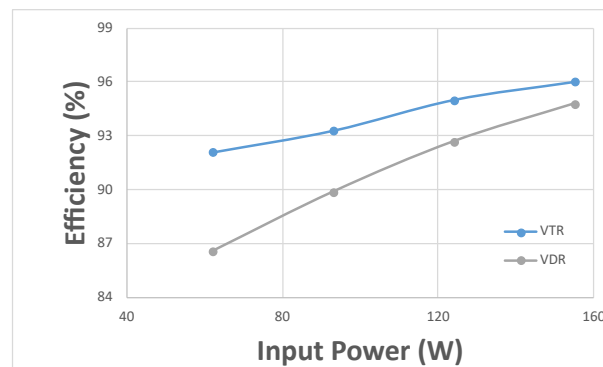


Figure 19. Measured efficiency at an input voltage of 62 V, considering different levels of input power.

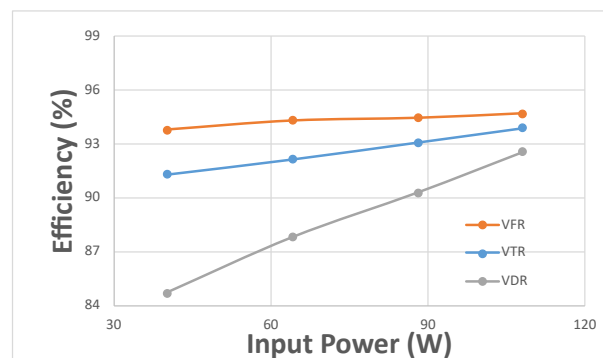


Figure 20. Measured efficiency at an input voltage of 40 V, considering different levels of input power.

6. Conclusions

This study presents a thorough investigation of the steady-state behavior of the Re-configurable Voltage Rectifier-Based LLC Converter when connected to a PV panel for applications requiring high DC voltage. The primary objective of the paper is to analyze the influence of switching frequency and rectifier structure on the converter. At first, there are five modes of functioning that are explained, providing specific information about the situations in which they occur. Next, a comprehensive step-by-step analysis is provided for the scenarios in which switches Q_1 and Q_4 are activated, as well as when switches Q_2 and Q_3 are activated. In addition, the gain equation for the converter is constructed, encompassing all essential equations, such as the initial voltage and current equations, output current, and symmetrical conditions. This paper presents a discussion on the accuracy differences between two gain derivation methods, aiming to provide a clear comparison between them. Moreover, the gain curve is examined across different parameters to comprehend the impact of each parameter on the converter's gain. In order to verify the theoretical calculations, a prototype of the converter with a power rating of 250 watts is constructed. The experimental waveforms exhibit a high degree of similarity to the analysis offered, and

the experimental gain curves correspond closely to the gain equations generated. Therefore, the developed gain equations can precisely forecast the gain characteristics of the converter. The gain characteristics and their variable dependence will provide significant insights for future studies when choosing design parameters.

Author Contributions: Conceptualization, F.A.; methodology, F.A. and A.A. (Abdullah Alhatlani); software, W.A. and A.A.A.-S.; validation, F.A., H.M.H.F.; formal analysis, W.A. and A.A. (Abdullah Alhatlani); investigation, F.A.; resources, A.A.A.-S., A.A. (Ahmed Allehyani) and H.M.H.F.; data curation, F.A.; writing—original draft preparation, F.A. and A.A. (Abdullah Alhatlani); writing—review and editing, W.A., A.A.A.-S., A.A. (Ahmed Allehyani) and H.M.H.F.; visualization, F.A. and W.A.; supervision, F.A.; project administration, A.A. (Abdullah Alhatlani); funding acquisition, A.A.A.-S. and H.M.H.F. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported and funded by the Deanship of Scientific Research at Imam Mohammad Ibn Saud Islamic University (IMSIU) (grant number IMSIU-RPP2023072).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Empower A Billion Lives. Available online: <https://empowerabillionlives.org> (accessed on 10 July 2024).
2. Khattak, S.; Yousif, M.; Hassan, S.U.; Hassan, M.; Alghamdi, T.A.H. Techno-economic and environmental analysis of renewable energy integration in irrigation systems: A comparative study of standalone and grid-connected PV/diesel generator systems in Khyber Pakhtunkhwa. *Heliyon* **2024**, *10*, e31025. [CrossRef] [PubMed]
3. IRENA. *Global Energy Transformation: A Roadmap to 2050*, 2019th ed.; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2019.
4. Wang, Y.; He, X.; Liu, Q.; Razmjoo, S. Economic and Technical Analysis of an HRES (Hybrid Renewable Energy System) Comprising Wind, PV, and Fuel Cells Using an Improved Subtraction-Average-Based Optimizer. *Heliyon* **2024**, *10*, e32712. [CrossRef] [PubMed]
5. Hussain, S.; Alammari, R.; Jafarullah, M.; Iqbal, A.; Sanjeevikumar, P. Optimization of Hybrid Renewable Energy System Using Iterative Filter Selection Approach. *IET Renew. Power Gen.* **2017**, *11*, 1440–1445. [CrossRef]
6. Adefarati, T.; Bansal, R.C.; Justo, J.J. Techno-economic analysis of a PV–wind–battery–diesel standalone power system in a remote area. *J. Eng.* **2017**, *2017*, 740–744. [CrossRef]
7. Gullu, S.; Djaho, A.-C.; Mensah, A.; Batarseh, I. Demonstration Project: 1.86 MWH Battery Energy Storage System and 540 KVA Inverter Integration. *Electronics* **2024**, *13*, 2596. [CrossRef]
8. Ye, D.; Martinez, S. A Three-Port DC–DC Converter with Partial Power Regulation for a Photovoltaic Generator Integrated with Energy Storage. *Electronics* **2024**, *13*, 2304. [CrossRef]
9. Ghosh, S.; Alhatlani, A.; Rezaii, R.; Batarseh, I. Control of Gridtied Dual-PV LLC Converter using Adaptive Neuro Fuzzy Interface System (ANFIS). In Proceedings of the IECON 2021–47th Annual Conference of the IEEE Industrial Electronics Society, Toronto, ON, Canada, 13–16 October 2021; pp. 1–6. [CrossRef]
10. Havlík, M.; Libra, M.; Poulek, V.; Kouřim, P. Analysis of Output Signal Distortion of Galvanic Isolation Circuits for Monitoring the Mains Voltage Waveform. *Sensors* **2022**, *22*, 7769. [CrossRef]
11. Božiková, M.; Bilčík, M.; Madola, V.; Szabóová, T.; Kubík, L.; Lendelová, J.; Cviklovič, V. The Effect of Azimuth and Tilt Angle Changes on the Energy Balance of Photovoltaic System Installed in the Southern Slovakia Region. *Appl. Sci.* **2021**, *11*, 8998. [CrossRef]
12. Kouro, S.; Leon, J.I.; Vinnikov, D.; Franquelo, L.G. Grid-Connected Photovoltaic Systems: An Overview of Recent Research and Emerging PV Converter Technology. *IEEE Ind. Electron. Mag.* **2015**, *9*, 47–61. [CrossRef]
13. Harb, S.; Kedia, M.; Zhang, H.; Balog, R.S. Microinverter and string inverter grid-connected photovoltaic system—A comprehensive study. In Proceedings of the 2013 IEEE 39th Photovoltaic Specialists Conference (PVSC), Tampa, FL, USA, 16–21 June 2013; pp. 2885–2890. [CrossRef]
14. Shahidehpour, F.; Schwarts, M. Don't let the sun go down on PV. *IEEE Power Energy Mag.* **2004**, *2*, 40–48. [CrossRef]
15. Cárcamo, A.; Fernandez-Hernandez, A.; Gonzalez-Hernando, F.; Vázquez, A.; Rodríguez, A. Variable Switching Frequency for ZVS over Wide Voltage Range in Dual Active Bridge. *Electronics* **2024**, *13*, 1800. [CrossRef]
16. Li, X.; Fang, X. Passive Backstepping Control of Dual Active Bridge Converter in Modular Three-Port DC Converter. *Electronics* **2023**, *12*, 1074. [CrossRef]
17. Alaql, F.; Batarseh, I. Review and Comparison of Resonant DC–DC Converters for Wide-Output Voltage Range Applications. In Proceedings of the 2020 IEEE Energy Conversion Congress and Exposition (ECCE), Detroit, MI, USA, 11–15 October 2020; pp. 1197–1203.

18. Zhou, K.; Liu, Y.; Wu, X. Research on Wide Input Voltage LLC Resonant Converter and Compound Control Strategy. *Electronics* **2022**, *11*, 3379. [[CrossRef](#)]
19. Lin, B.-R.; Liu, Y.-C. Implementation of a Wide Input Voltage Resonant Converter with Voltage Doubler Rectifier Topology. *Electronics* **2020**, *9*, 1931. [[CrossRef](#)]
20. Alaql, F.; Rezaii, R.; Alhatlani, A.; Gullu, S.; Safayatullah, M.; Batarseh, I. Multi-Mode Rectifier-Based Dual-Input LLC Converter for Wide Voltage PV Applications. In Proceedings of the 2022 IEEE Energy Conversion Congress and Exposition (ECCE), Detroit, MI, USA, 9–13 October 2022; pp. 1–5. [[CrossRef](#)]
21. Xie, D.; Lin, C.; Deng, Q.; Lin, H.; Cai, C.; Basler, T.; Ge, X. Simple Vector Calculation and Constraint-Based Fault-Tolerant Control for a Single-Phase CHBMC. *IEEE Trans. Power Electron.* **2024**. [[CrossRef](#)]
22. Liu, X.; Li, H.; Wang, Z. A Start-Up Scheme for a Three-Stage Solid-State Transformer With Minimized Transformer Current Response. *IEEE Trans. Power Electron.* **2012**, *27*, 4832–4836. [[CrossRef](#)]
23. Zhang, J.; Wang, Z.; Shao, S. A Three-Phase Modular Multilevel DC–DC Converter for Power Electronic Transformer Applications. *IEEE J. Emerg. Sel. Top. Power Electron.* **2017**, *5*, 140–150. [[CrossRef](#)]
24. Ren, C.; He, Y.; Qin, Y.; Hui, Y.; Li, X.; Han, X.; He, X. A Novel Modular Sigma DC/DC Converter with a Wide Input Voltage Range. *Electronics* **2024**, *13*, 995. [[CrossRef](#)]
25. Elezab, A.; Zayed, O.; Abuelnaga, A.; Narimani, M. High Efficiency LLC Resonant Converter With Wide Output Range of 200–1000 V for DC-Connected EVs Ultra-Fast Charging Stations. *IEEE Access* **2023**, *11*, 33037–33048. [[CrossRef](#)]
26. Pi, L. Modified Two-Channel LLC Resonant Converter with Optimal Efficiency for Wide Input Voltage Applications. *IEEE Access* **2023**, *11*, 38957–38969. [[CrossRef](#)]
27. Kalayci, K.; Demirel, O.; Arifoglu, U.; Hizarci, H. Analysis of Three-Level T-Type LLC Resonant Isolated Bidirectional DC–DC Converter Under Three-Degrees-of-Freedom Modulation. *IEEE Access* **2023**, *11*, 60605–60625. [[CrossRef](#)]
28. Alaql, F.; Alhatlani, A.; Batarseh, I. Multi-Mode Rectifier-Based LLC Resonant Converter for Wide Input Voltage Range Applications. In Proceedings of the 2021 IEEE Applied Power Electronics Conference and Exposition (APEC), Phoenix, AZ, USA, 14–17 June 2021; pp. 349–354. [[CrossRef](#)]
29. Cao, Q.; Li, Z.; Xue, B.; Wang, H. Fixed Frequency Phase Shift Modulated LLC Resonant Converter Adapted to Ultra Wide Output Voltage Range. In Proceedings of the 2019 IEEE Applied Power Electronics Conference and Exposition (APEC), Anaheim, CA, USA, 17–21 March 2019; pp. 817–822. [[CrossRef](#)]
30. Hua, C.-C.; Deng, Y.-L. A Novel Dual-Bridge LLC Resonant Converter with Wide Range of Low Input Voltage. *Energy Procedia* **2019**, *156*, 361–365. [[CrossRef](#)]
31. Alaql, F.; Batarseh, I. LLC Resonant Converter with Reconfigurable Voltage Rectifier for Wide Input Voltage Applications. In Proceedings of the 2020 IEEE Energy Conversion Congress and Exposition (ECCE), Detroit, MI, USA, 11–15 October 2020; pp. 1191–1196. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.