Design and Development of LLC Resonant Converter for EV Charging

MTP Stage 0 report

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Abstract

With the rapid growth of electric vehicles (EVs), the need for efficient, compact, and reliable power conversion systems in EV chargers has become critical. Resonant converters, known for their soft-switching capabilities and high efficiency, are particularly well-suited for such applications. This project focuses on the comparative study and design of resonant converter topologies—specifically the Series Resonant Converter (SRC) and Parallel Resonant Converter (PRC)—as a foundational step toward the eventual development of an LLC resonant converter for EV charging. Key parameters such as resonant tank design, determining the voltage gain using First Harmonic Approximation (FHA) technique, voltage gain characteristics, and zero-voltage switching (ZVS) conditions are analyzed. Simulation models are also developed to validate the behavior of SRC and PRC under varying load conditions and switching frquencies. The insights gained from this study will inform the optimized design of an LLC converter in the next phase. This work lays the groundwork for implementing efficient resonant-based EV chargers aligned with modern performance and reliability standards.

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Nomenclature

Abbreviations

AC	Alternating current
BEV	Battery electric vehicle
CCS	Combined charging system
CHAdeMO	Charge de Move
DC	DC current
EPA	Environmental protection agency
EV	Electric vehicle
EVCS	Electric vehicle charging station
EVSE	Electric vehicle supply equipment
FAME	Faster adoption and manufacturing of hybrid and electric vehicles scheme
FCEV	Fuel cell electric vehicle
GVWR	Grosss vehicle weight ratio
HDEV	Heavy duty electric vehicle
HEV	Hybrid electric vehicle
ICCB	In-cable control box
IEC	International electrotechnical commission
ISO	International organization for standardization
LCFS	Low carbon fuel standard
LDV	Light duty vehicle
MDV	Medium duty vehicle
OEM	Original equipment manufacturers
PFC	Power factor correction
PHEV	Plug-in hybrid electric vehicle
SAE	Society of automobile engineers
TOU	Time of use

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Chapter 1

Introduction

1.1 Overview

The global push toward sustainable transportation has significantly increased the adoption of electric vehicles (EVs), necessitating the development of efficient and compact EV charging infrastructure. At the heart of this infrastructure lies the power electronic converter, which ensures the regulated and safe transfer of power from the grid to the EV battery. Among the various converter topologies, resonant converters—such as the Series Resonant Converter (SRC), Parallel Resonant Converter (PRC), and the more advanced LLC Resonant Converter—have gained prominence due to their ability to achieve high efficiency, soft-switching (ZVS or ZCS), and reduced electromagnetic interference (EMI).

Resonant converters operate by forming a resonant tank using inductive and capacitive components, allowing energy transfer to occur at a specific frequency where switching losses are minimized. In particular, the LLC resonant converter offers superior performance in terms of efficiency and wide load regulation compared to SRC and PRC, making it a suitable candidate for high-performance EV chargers. However, understanding the behavior of SRC and PRC forms an essential foundation before progressing to the more complex LLC topology.

This stage of the MTP focuses on the modeling, simulation, and performance evaluation of SRC and PRC converters with the long-term goal of transitioning toward the design and implementation of an LLC resonant converter suitable for EV battery charging applications. The work aims to understand the fundamental behavior, design considerations, and control challenges associated with resonant converters in the context of EV charging..

1.2 Problem Statement

The problem statement of the project is to design a fully functional unidirectional single-phase battery charger for an EV charging application. Resonant Converter will be used to build the battery charger. In stage zero of the project, the overview and performance of series and parallel resonant converter based on sinusoidal approximation technique performed.

As EV adoption grows, there is a pressing need for compact, efficient, and reliable power converters in EV charging systems. Conventional hard-switched converters suffer from high switching losses and limited efficiency at high frequencies, which limits their ability to meet modern charger requirements, especially in fast-charging scenarios. Resonant converters offer a promising alternative by enabling soft-switching operation, but each topology comes with its own trade-offs in terms of design complexity, efficiency, and regulation performance.

While the LLC resonant converter is widely recognized for its high efficiency and suitability for EV charging, it is more complex in terms of analysis and design. Hence, a stepwise approach is necessary—beginning with the simpler SRC and PRC topologies—to build a deep understanding of resonant behavior, tank design, and control strategies.

The primary problem addressed in this project is to analyze, model, and simulate SRC and PRC topologies to understand their characteristics, limitations, and suitability for EV charging. This forms the basis for transitioning toward the final objective: designing a high-efficiency LLC resonant converter optimized for EV charging applications.

Chapter 2

Literature Review

Resonant Converter

Among various DC-DC converter topologies, resonant converters are preferred for EV charging applications due to their ability to achieve ZVS and ZCS operation. These soft-switching characteristics significantly reduce switching losses and allow the converter to operate at much higher switching frequencies than conventional PWM converters. Furthermore, the use of ZVS also helps suppress certain sources of electromagnetic interference typically generated by power electronic converters.

Resonant converters utilize reactive elements — a combination of inductors and capacitors — to form a resonant circuit. This circuit enables soft-switching, which minimizes both switching losses and noise. As a result, resonant converters are highly suitable for high-power applications, including EV charging.

The general structure of a resonant converter consists of three key blocks:

Figure 2.1: Conventional resonant converter structure

Switch Network: It acts as a DC-AC converter that generates a pulsating voltage or current from a DC input, operating at a specified switching frequency.

Resonant Tank: It is a two-port network of inductors and capacitors that modulates gain based on switching frequency. It facilitates soft-switching of power devices. In isolated topologies, transformer magnetizing and leakage inductances can be utilized as part of the resonant elements, helping to lower cost and component count.

Rectifier Network: It converts the high-frequency AC output from the resonant tank back into DC to supply the load.

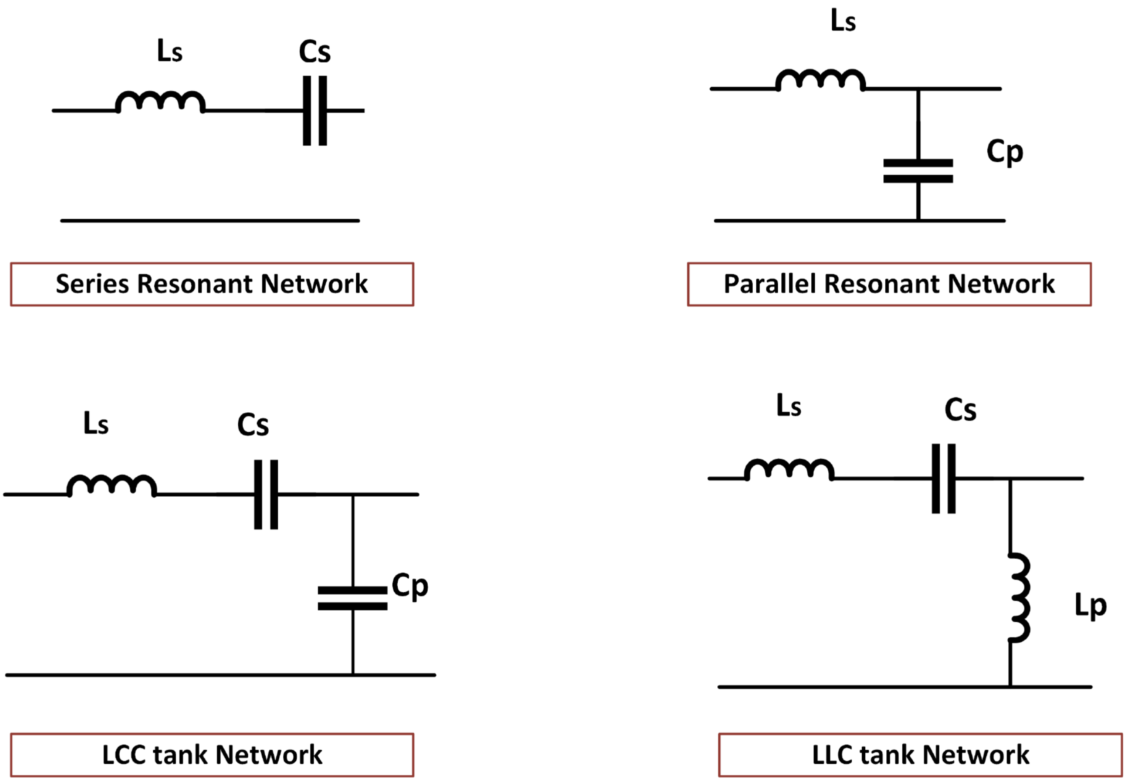

Figure 2.2: Types of resonant tanks

2.1 DC-DC Series Resonant Converter

A Series Resonant DC-DC Converter employs a series LC resonant tank network. It works on the principle of resonance, where the reactive components (inductor L_r and capacitor C_r) are connected in series with the load.

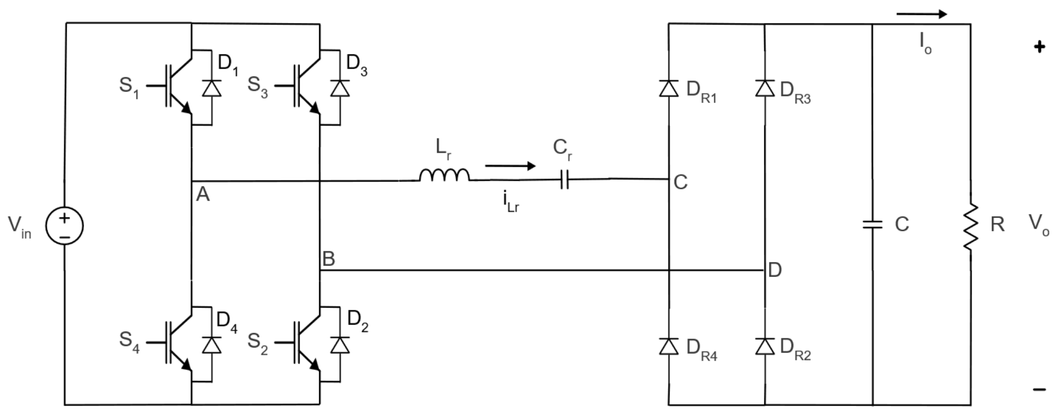

Figure 2.3: Circuit diagram of SRC

The output characteristics of the converter are regulated by varying the switching frequency. When the switching frequency is (close to the resonant frequency) varied, the tank current and, hence, the output DC current can be controlled. As the frequency shifts away from resonance, the impedance of the resonant tank increases, reducing the current and output power accordingly. This enables frequency control of the output without the need for complex PWM strategies.

The **Fundamental Harmonic Approximation (FHA)** method is commonly used for modeling and analysis. This method assumes that the resonant tank waveforms are purely sinusoidal and ignores the higher-order harmonics of the switching frequency. It provides accurate results for continuous conduction mode (CCM) operation with a high-quality factor (Q). However, this approximation becomes less accurate in low-Q scenarios or when the converter operates in discontinuous conduction mode (DCM).

Typically, the controlled switch network generates a square wave voltage near the resonant frequency of the tank circuit. This excites the LC tank, which then produces a near-sinusoidal current waveform due to its selective frequency response. Since the resonant tank filters out high-frequency harmonics, the dominant frequency component closely matches the switching frequency.

2.1.1 Modeling of series resonant converter

Switch network:

Since the switching network typically generates a square wave voltage, it is common practice to approximate this waveform using its fundamental harmonic component. This approach is justified by the frequency-selective nature of the resonant tank: when the switching frequency ($\mathrm{f_s}$) is close to the resonant frequency ($\mathrm{f_r}$) of the LC tank, the circuit primarily responds to the fundamental frequency and effectively attenuates higher-order harmonics.

This frequency-selective behavior allows the square wave input to be analyzed using only its dominant frequency component, simplifying analysis and enabling the use of the sinusoidal approximation method. Mathematically, the square wave can be represented using its Fourier Series as follows:

$$v_{AB}(t) = v_s(t) = \frac{4V_g}{\pi} \sum_{n=1,3,5,\ldots} \frac{1}{n} \sin(n\omega_s t) \tag{2.1}$$

Therefore, the switching network can be represented as a sinusoidal voltage source with frequency f_s and amplitude $\frac{4V_g}{\pi}$. The average DC input current can be obtained by averaging the current $i_g(t)$ over half of the switching period.

$$\langle i_{DC}(t) \rangle = \frac{2}{T_s} \int_0^{\frac{T_s}{2}} i_g(\tau)\, d\tau \tag{2.2}$$

$$\langle i_{DC}(t) \rangle = \frac{2}{T_s} \int_0^{\frac{T_s}{2}} I_s \sin(\omega_s \tau - \phi_s)\, d\tau \tag{2.3}$$

$$\langle i_{DC}(t) \rangle = \frac{2}{\pi} I_s \cos(\phi_s) \tag{2.4}$$

Here $i_g(t)$ is the same as $i_s(t)$ for the first half of the time period and $-i_s(t)$ for the rest half of the time period. ϕ_s is the phase difference between $v_s(t)$ and $i_s(t)$ and w_s is the switching frequency.

Tank circuit and rectifier network:

The current through the inductor in an SRC is approximately sinusoidal, and the same current passes through the rectifier stage. A large filter capacitor C_f offers a low impedance path to the AC component of the current, allowing only the DC component to pass through the load resistor. This DC output current can be determined by averaging $|i_x(t)|$ over half of the switching period, as the bridge rectifier converts the input current to unidirectional form. Here, $i_x(t)$ is equivalent to the inductor current $i_s(t)$.

$$I = \frac{2}{T_s} \int_0^{\frac{T_s}{2}} |i_x(\tau)| \, d\tau \tag{2.5}$$

$$I = \frac{2}{T_s} \int_0^{\frac{T_s}{2}} i_x |\sin(\omega_s \tau - \phi_s)| \, d\tau \tag{2.6}$$

$$I = \frac{2 i_x}{\pi} \tag{2.7}$$

Since the output voltage remains nearly constant due to the large filter capacitor, the voltage at the input of the rectifier network $v_r(t)$ appears as a square wave of amplitude V, and it remains in phase with the inductor current. This square waveform can be approximated by its fundamental harmonic using the same logic applied earlier. Using Fourier series, it is expressed as:

$$V_{CD}(t) = v_r(t) = \frac{4V}{\pi} \sum_{n=1,3,5,\ldots} \frac{1}{n} \sin(n\omega_s t - \phi_x) \tag{2.8}$$

Hence, the rectifier network can be modeled as a sinusoidal voltage source with amplitude $\frac{4V}{\pi}$, in phase with the inductor current. This rectifier stage can then be simplified by modeling it as an equivalent resistance:

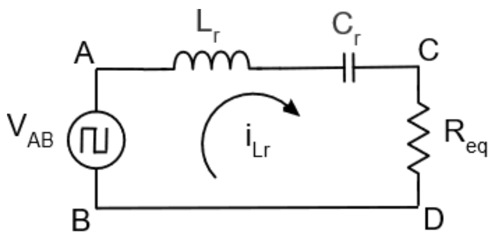

Figure 2.4: Equivalent circuit of SRC

$$R_{\text{eq}} = \frac{v_r(t)}{i_x(t)} \tag{2.9}$$

$$R_{\text{eq}} = \frac{4V}{\pi i_x} \tag{2.10}$$

Given $i_x = \frac{\pi I}{2}$ and $V = IR$, we obtain:

$$R_{\text{eq}} = \frac{8}{\pi^2} R \tag{2.11}$$

From the above analysis, the voltage transfer function is

$$H(s) = \frac{R_e}{Zi(s)} = \frac{R_e}{R_e + sL + \frac{1}{sC}} \tag{2.12}$$

$$\omega_r = \frac{1}{\sqrt{LC}} = 2\pi f_r, \quad Q_e = \frac{\omega_r L}{R_e} = \frac{1}{\omega_r R_e C} \tag{2.13}$$

The voltage gain magnitude can be written as

$$M = \frac{V_o}{V_{in}} = \frac{\frac{\omega_s}{Q_e \omega_r}}{\sqrt{1 - \left(\frac{\omega_s}{\omega_r}\right)^2 + \left(\frac{\omega_s}{Q_e \omega_r}\right)^2}} \tag{2.14}$$

$$\boxed{\frac{V_o}{V_{in}} = \frac{1}{\sqrt{1 + Q_e^2 \left(\frac{\omega_s}{\omega_r} - \frac{\omega_r}{\omega_s}\right)^2}}} \tag{2.15}$$

2.1.2 DC voltage gain characteristics

The variation in voltage gain vs different switching frequencies for different values of R, Q can be seen by figure 2.5. To obtain these results, we have chosen $V_{in} = 20V, L_{\mathrm{r}} = 84.142\mu H, C_{\mathrm{r}} = 481.67nF, R = 10ohms$.

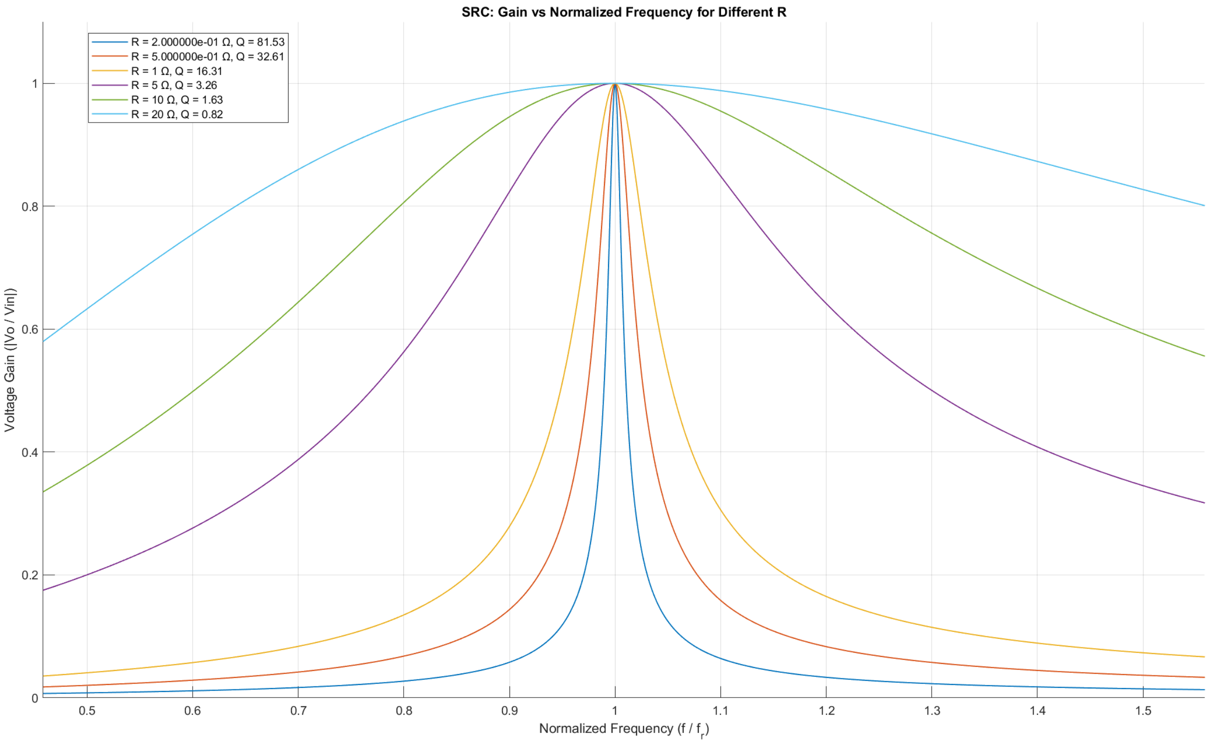

Figure 2.5: SRC Gain at different R

The resonant frequency is 25 kHz. From the figure 2.5 we can notice that moving away from the resonant frequency in either direction results in decrement in the voltage gain. The gain is maximum when the switching frequency is equal to resonant frequency ($\mathrm{f_s} = \mathrm{f_r}$). Since the conversion ratio is always less than or equal to 1, we can say that the series resonant converter acts as a buck converter. Hence the magnitude of output voltage is always less than the input dc voltage.

At $f_s > f_r$: Series resonant impedance (Z_r) is dominated by inductor

At $f_s < f_r$: Z_r is dominated by capacitor

At $f_s = f_r$: $Z_r = R_e$

2.1.3 Limitations of series resonant converter

- The main disadvantge of SRC is that for light loading conditions, large swtiching frequency variations are required for even small voltage regulation.
- When the switching frequency is much lower than the resonant frequency, the sinusoidal approximation becomes invalid.
- For low values of Q, the sinusoidal approximation loses accuracy, and discontinuous conduction mode may occur due to that current waveforms are highly distorted.

2.2 DC-DC Parallel Resonant Converter

The schematic of parallel resonant converter (PRC) is shown in the figure 2.6. The circuit diagram is almost similar to that of SRC but with the resonant capacitor in parallel with the load. The filter stage is also appropriately modified. Similar to series resonant converter, the output voltage can be regulated by changing the switching frequency. At resonant frequency, the impedance of resonant tank of equal to load resistance which is maximum, but as the switching frequency shift away from resonant frequency, the resonant tank impedance decrease which results into reduction of output power accordingly.

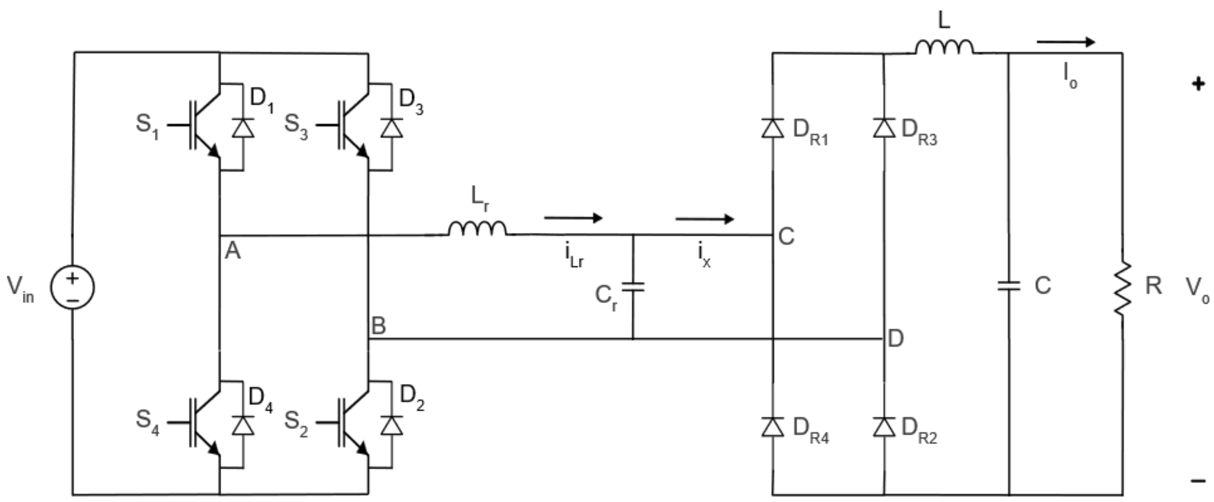

Figure 2.6: Circuit diagram of PRC

Similar to SRC, for the modeling and analysis, fundamental harmonic approximation (FHA), also known as Sinusoidal approximation, is used ignoring the higher order harmonics. The converter is fed by a square-wave voltage via switch network at a particular switching frequency. Power transfer occurs via resonant behaviour of the LC tank. When excited by the square wave, the LC tank resonates and allows selective power transfer at its resonant frequency.

2.2.1 Modeling of parallel resonant converter

Switch network:

Modeling of switch network stage in PRC is same as that of SRC.

Tank circuit and rectifier network:

Since the rectifier network is directly connected across the tank capacitor, it experiences an approximately sinusoidal voltage. The filter inductor helps maintain an almost constant current through the load resistor. As a result, the current drawn by the rectifier, $i_x(t)$, becomes a square wave of amplitude I_o, which is in phase with the resonant capacitor voltage. This rectifier input current can be expressed using a Fourier series as:

$$i_x(t) = \frac{4I_o}{\pi} \sum_{n=1,3,5,...} \frac{1}{n} \sin(n\omega_s t - \phi_x) \tag{2.16}$$

The rectifier current $i_x(t)$ is approximated as a sinusoidal waveform with an amplitude of $\frac{4I}{\pi}$, remaining in phase with the capacitor voltage. The voltage across the load resistor represents the filtered DC component of the resonant capacitor voltage and is obtained by averaging the capacitor voltage over half of the switching period.

$$V = \frac{2}{T_s} \int_0^{\frac{T_s}{2}} V_r \left|\sin(\omega_s \tau - \phi_x)\right| d\tau \tag{21}$$

$$V = \frac{2V_r}{\pi} \tag{22}$$

The rectifier network and load can again be represented with an equivalent resistance.

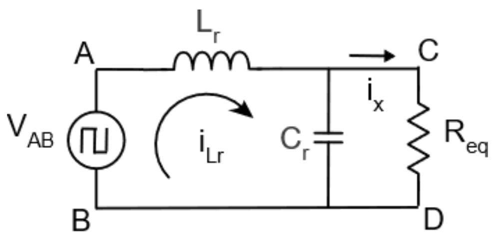

Figure 2.7: Equivalent circuit of PRC

$$R_{eq} = \frac{v_r(t)}{i_x(t)} \tag{23}$$

$$R_{eq} = \frac{\pi V}{2i_x} \tag{24}$$

Given that $i_x = \frac{4I_o}{\pi}$ and $V = I_o R$, we get

$$R_{eq} = \frac{\pi^2}{8} R \tag{25}$$

The tank circuit consists of an inductor and capacitor, the output is taken across the capacitor. From the above analysis, the voltage transfer function is

$$H(s) = \frac{R_e || \frac{1}{sC}}{R_e || \frac{1}{sC} + sL} \tag{2.17}$$

$$\omega_r = \frac{1}{\sqrt{LC}} = 2\pi f_r, \quad Q_e = \frac{R_e}{\omega_r L} = \frac{R_e}{\omega_r C} \tag{2.18}$$

$$H(s) = \frac{1}{\sqrt{(1 - \omega^2 L_r C_r)^2 + \left(\frac{\omega L_r}{R_e}\right)^2}} \tag{2.19}$$

The voltage gain magnitude can be written as

$$M = \frac{V_o}{V_{in}} = \frac{8/\pi^2}{\sqrt{\left(1 - \left(\frac{\omega_s}{\omega_r}\right)^2\right)^2 + \frac{1}{Q_e^2}\left(\frac{\omega_s}{\omega_r}\right)^2}} \tag{2.20}$$

Let $\omega_x = \frac{\omega_s}{\omega_r}$

$$\boxed{\frac{V_o}{V_{in}} = \frac{8/\pi^2}{\sqrt{(1 - \omega_x^2)^2 + \left(\frac{\omega_x}{Q_e}\right)^2}}} \tag{2.21}$$

2.2.2 DC voltage gain characteristics

The variation in voltage gain vs different switching frequencies for different values of R, Q can be seen by figure 2.8. To obtain these results, we have chosen same values as that of SRC : $V_{in} = 20V, L_\mathrm{r} = 84.142\mu H, C_\mathrm{r} = 481.67nF, R = 10ohms.$

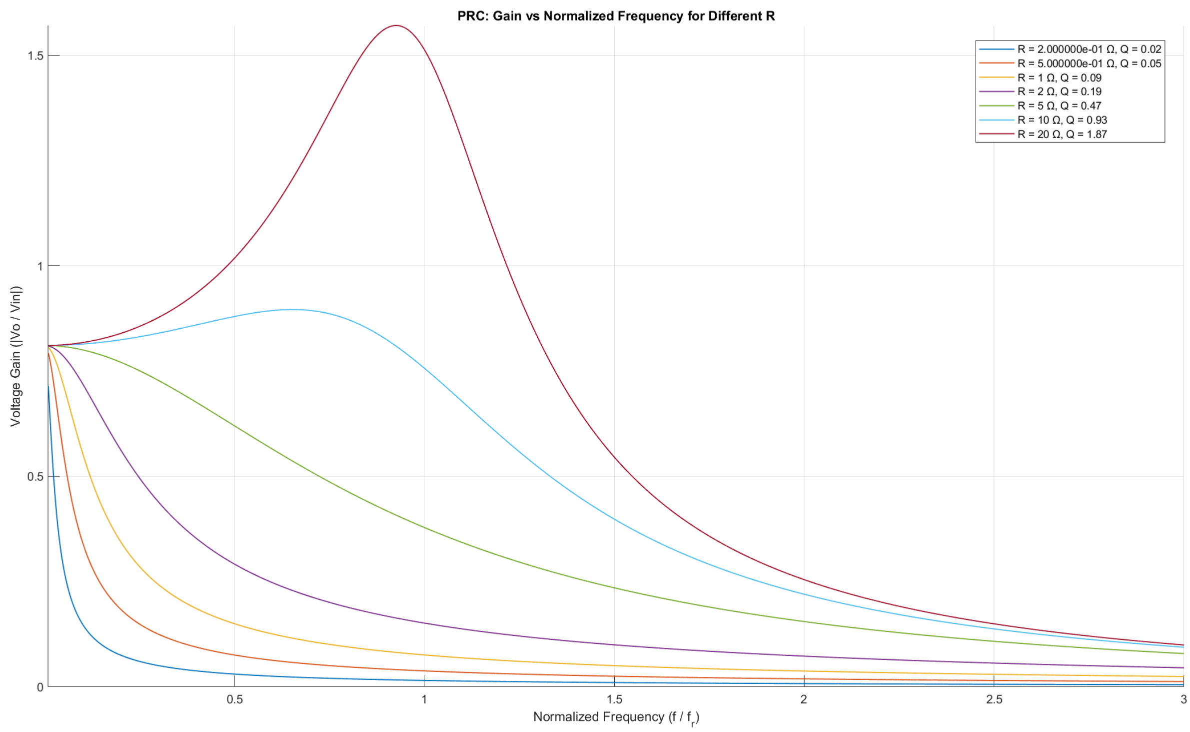

Figure 2.8: PRC Gain at different R

The resonant frequency is 25 kHz. From the figure 2.8 we can see that if we increase the switching frequency f_s above resonant frequency f_r, the voltage gain reduces for all loading conditions. When the switching frequency equals to the resonant frequency, the magnitude of the output voltage is $\frac{8}{\pi^2}$ times Q_e of the input DC voltage. This shows that PRC can have a conversion ratio that is either greater or less than 1. In essense, the gain is determined by the quality factor at resonance. Therefore, PRC can perfrom both buck and boost operation.

At frequencies close to resonant frequency, the gain is more than 1 (boost operation)

At frequencies greater or less than resonant frequency, the gain is less than 1 (buck operation)

2.2.3 Limitations of parallel resonant converter

- The main problem with PRC is large amount of circulating energy even at at light load conditions and pretty high circulating energy even when the load is zero as the load is connected in parallel with the resonant circuit.
- The output voltage at resonance frequency is the function of load and it can rise to very high values at no load condition or light load condition if the operating frequency is not raised.
- Poor efficiency at high Q values (light load) as conduction and switching loss are significantly increased.

Chapter 3

Conclusion and Future Work

3.1 Conclusion

This work analyzed SRC and PRC using the Fundamental Harmonic Approximation (FHA) method, with voltage gain expressions validated through MATLAB simulations. While simple, SRC and PRC face limitations like poor voltage regulation and high circulating current at light load, making them less ideal for demanding applications such as EV charging. These insights motivate the shift toward advanced topologies like the LLC converter, which addresses these drawbacks effectively.

3.2 Research Gaps

- Ongoing research is focused on expanding the operating range of resonant converters to handle a wider variety of load profiles. Achieving this would enhance their versatility and adaptability in real-world applications.
- Existing analytical models (e.g., Fundamental Harmonic Approximation) often neglect high-frequency harmonics and parasitics, which can lead to deviations between theoretical and actual performance.
- Control strategies for resonant converters remain complex, making implementation and real-time control challenging in practical systems.

3.3 Future Work

- Transitioning to more advanced topologies like LLC resonant converters can be considered to overcome the limitations of SRC and PRC, such as narrow gain bandwidth and limited ZVS range.
- Design and mathematical modeling of the LLC resonant converter, including detailed component selection, resonant tank design, and transformer design with soft-switching (ZVS) considerations.
- Development and implementation of effective control strategies for LLC converters to ensure robust operation under varying load and input conditions.

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[2] S. Vyapari and V. N. R, "Design Oriented Steady State Analysis of Series and Parallel Resonant Converters," 2022 IEEE International Conference on Industrial Technology (ICIT), Shanghai, China, 2022.

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