Feedback Control of CLLLC Resonant DC-DC Converter using Deep Reinforcement Learning

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***Abstract*—This paper presents a novel approach to control the bidirectional power flow of an asymmetric resonant DC-DC converter by leveraging deep reinforcement learning (DRL). Unlike traditional symmetric designs, this converter employs a non-unity ratio between primary and secondary resonant capacitances, to meet the desired output voltage range within a narrow switching frequency bandwidth thus offering higher power density. Traditional control design require intensive mathematical modeling of the 9$^{\text{th}}$ order converter which is often cumbersome and requires linearization, potentially losing critical dynamics. To overcome these limitations, this research leverages DRL, which uses real-time state measurements (output voltage) to learn optimal control policies. The agent's reward function is specifically designed to achieve accurate voltage tracking by dynamically adjusting the converter's switching frequency. The proposed control strategy is validated through comprehensive simulations of the asymmetric CLLLC converter in MATLAB/Simulink, demonstrating superior voltage tracking performance and robust bidirectional power flow capability.**

***Index Terms*—DC-DC Converter Control, Deep Reinforcement Learning, CLLLC Resonant Converter, TD3 Agent, Voltage Gain Equation.**

I. Introduction

In recent years, resonant DC-DC converters have garnered significant attention from researchers and industry experts due to their suitability for high-power applications, including EV fast charging and renewable energy integration [1], [2]. Moreover, their inherent soft-switching characteristics lead to high power conversion efficiency and reduced electromagnetic interference (EMI), while also enabling very high-frequency operations, providing a high power-density and cost-effective solution [3]–[5]. The output of these converters is typically controlled by varying the switching frequency. The LLC resonant converter stands out among resonant converters due to its ability to handle a wide output voltage range [6]. However, this topology is restricted to applications requiring unidirectional power transfer, as it employs active switches on one bridge and diodes on the other [7], [8].

The electrification of the transportation sector and the push for clean, renewable energy systems have led to discussions about bidirectional power flow functionalities. For battery charging applications that require bidirectional vehicle-to-grid (V2G) power flow capability, CLLLC resonant converters are utilized. These converters feature an LLC network on the primary side of the transformer, similar to an LLC resonant converter, but with an additional series LC network on the secondary side [9]. The series LC tanks on either side of the transformer can be either symmetric or asymmetric. In a symmetric configuration, the reflected secondary inductance (L) and capacitance (C) are equal to the primary series-connected inductance and capacitance, resulting in a straightforward input-to-output voltage gain expression and a simplified tank design process [10].

PI compensators are widely used in variable frequency feedback control of resonant converters [9], [11]. To identify the compensator gains, an accurate small-signal model of the converter is necessary. In [11], a small-signal model was derived by taking the frequency derivative of the steady-state tank output voltage in the frequency domain. Although quite simple, this model completely ignores the non-linear effects arising from the switching actions of the output rectifier and is hence not reliable. Some other small-signal models were also proposed that were derived using phasor transformation [12], generalized state-space averaging [13], and extended describing functions (EDF) [9], [14]. These methods unify time-domain and frequency-domain analyses to accurately capture the non-linear dynamics of the converter and linearize the plant around a steady-state operating point of interest to find its small-signal model. However, the resulting models are fundamentally identical because these methods use the same sinusoidal basis functions assuming First Harmonic Approximation (FHA) [15], [16]. Among these methods, the one developed using EDF in [9] particularly stands out because of its use of easy-to-follow formulations. Nevertheless, inconsistent use of the transformer turns ratio, inaccurate evaluation of the resonant frequency, etc. make the otherwise excellent model inapplicable to asymmetric resonant converters.

The primary challenge with traditional control design lies in its heavy reliance on an accurate mathematical model of the system. To address this issue, model-free methods such as deep reinforcement learning (DRL) have been explored. DRL can adapt to system dynamics without requiring a precise