PEDG 2022 Tutorial Proposal

1. Title of Tutorial

Design Automation and Optimization of LLC Converters for Energy Harvesting Applications

2. Instructor Team

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3. Abstract

Efficiency and power density are two crucial targets for power converters. There are many approaches to improve the power converters' performances. During the design stage, optimal design methods can effectively improve the power converter efficiency performance based on the theoretical power converter electric and power loss models. After the power converter is implemented, hybrid control strategies can be adopted to further improve the power converter performances. Due to the nature of renewable energy sources, a very wide voltage gain operation range is required for the power converters, which challenges on the power converter design and optimization. In this tutorial, the popular LLC resonant converters are selected for the energy harvesting applications. Due to the circuit complexity, the power converter modelling and optimization becomes challenging. This tutorial will overview the existing modelling and optimal design methodologies for LLC resonant converters. The developed simulation tools and automated optimal design tools for LLC resonant converters will be discussed. In addition, the challenges and solutions for LLC resonant converters with wide voltage gain range applications are reviewed and discussed.

4. Tutorial Outline

The outline of this tutorial is detailed as follows:

4.1 Background and Motivation. Estimated time: 15 min

In this Section, the energy harvesting application background is introduced and the challenges for power converter optimizations are discussed. The comparisons among different popular dc/dc converters are given. The basic topologies and operational principles for LLC converters are introduced.

4.2 Design Automation for LLC Resonant Converters. Estimated time: 75 min

4.2.1 Comparisons between traditional frequency domain analysis and time domain analysis. Estimated time: 15 min

In this Subsection, a comprehensive comparison between frequency-domain and time-domain analysis for LLC converters from converter design, circuit parameters, and efficiency are implemented [1, 2]. The high accuracy characteristic of time-domain analysis is demonstrated.

4.2.2 Simulation tools design for LLC resonant converters. Estimated time: 30 min

In this Subsection, the time domain modeling for all LLC converter operation modes and topologies are presented. Then, based on the modeling results, accurate and complete simulation tools for LLC converters are developed. Introductions and comparisons of the developed simulation tools and commercial simulation software are made [3]. Fig. 1(a) shows the developed open-loop simulation tool for LLC converters. It mainly includes the following parts: 1) topology selection; 2) circuit parameters; 3) output voltage and simulation speed; 4) simulation waveforms; and 5) circuit voltage and current values. Fig. 1(b) shows the simulation results and comparison with PSIM simulation software. **Please note that these tools will be lively demonstrated, and attendees are available to download and play with them.**

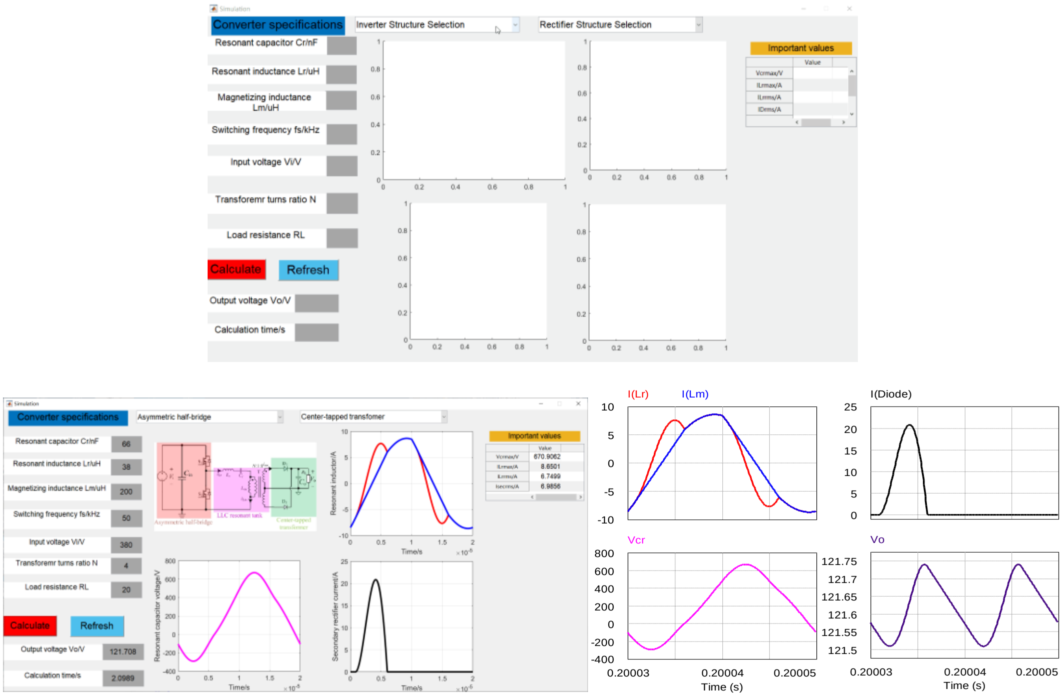

Figure 1 Developed simulation tools.

4.2.3 Automated Optimal Design Tools. Estimated time: 30 min

In this Subsection, some automated optimal design tools are developed and discussed [4, 5]. Resonant capacitor Cr (which is related to quality factor) and inductor ratio K (the ratio between the magnetizing inductance and resonant inductance) are important parameters for LLC converters. Thus, an optimal design methodology is proposed based on the Cr-K plane, the circuit power loss is selected as the optimization objective. The converter is limited to operate in below resonant frequency to reduce the computation complexity. Fig. 2 shows the developed optimal design tool based on this optimization strategy.

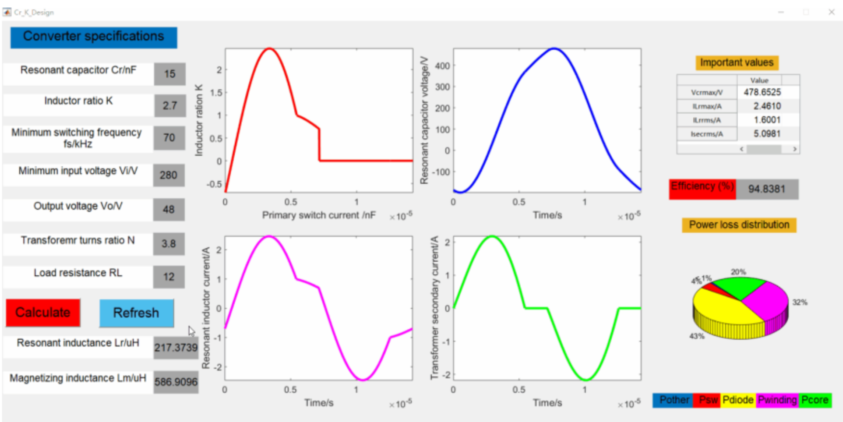

Figure 2 Power loss based optimal design tool for LLC resonant converter operating in below resonant frequency.

Another automated design algorithm is proposed based on the circuit root-mean-square (RMS) current. This optimal design method is general and applicable for most scenarios. The converter operating switching frequency range, maximum resonant capacitor volatge, and soft switching operation are ensured. The optimal design candidate can be automatically found, and the advanced optimization algorithms (genetic algorithm and particle swarm optimization) are adopted to facilitate the execution process. Fig. 3 shows the developed RMS current based automated optimal design tool. Experimental comparisons between the proposed optimal design tool and conventional design method will be conducted.

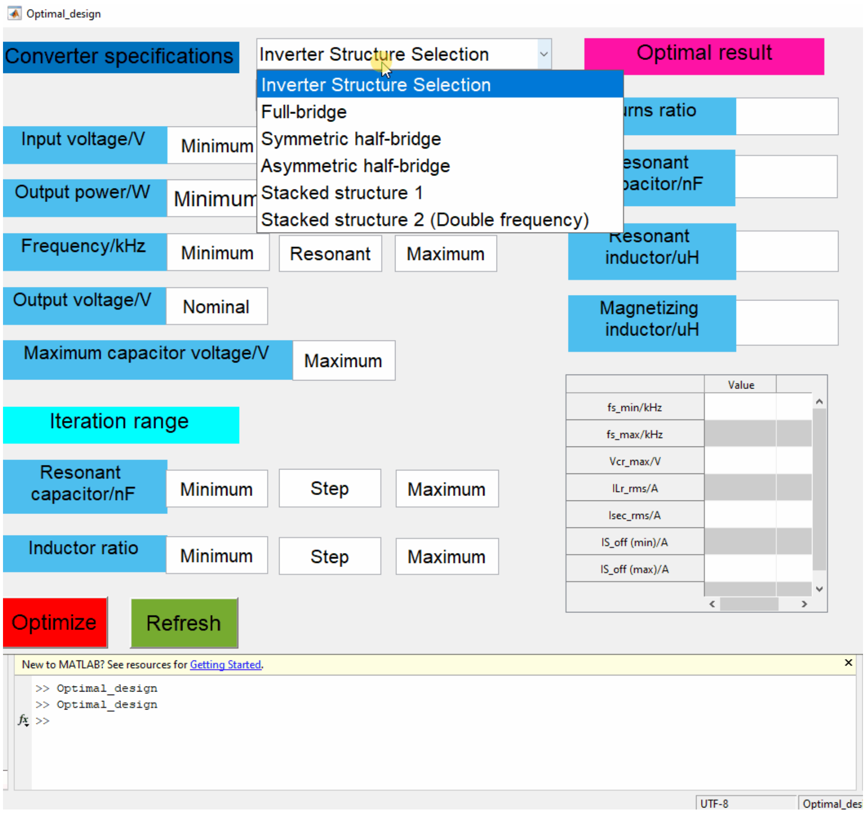

Figure 3 RMS current based automated optimal design tool for LLC resonant converters.

There will be interactions between the presenters and audience. Suggestions from audience will be collected for the future development of the tools. For example, we would like to ask what design restrictions you care, and should we included in the tools, what else should we considered to make the tool more practical.

4.3 Hybrid modulation strategies for LLC resonant converters. Estimated time: 75 min

4.3.1 Generation mechanisms for LLC converter modulation strategies. Estimated time: 15 min

In this Subsection, based on the traditional simple fundamental harmonic analysis (FHA) model of the LLC converter, the modulation strategy generation mechanisms for LLC converters are well investigated [5], and it can be divided into the following three groups: 1) resonant tank input voltage modulation; 2) resonant tank elements modulation; 3) secondary equivalent impedance modulation. The advantages and disadvantages of each modulation strategy are summarized.

4.3.2 Magnetically-controlled LLC converters. Estimated time: 30 min

Magnetically-controlled LLC resonant converters have the advantages of simple and good electro-magnetic interference (EMI) performance. The operational principles, modeling and characteristics analysis are performed for LLC converters with magnetic control. The characteristics of variable inductor are discussed from various perspectives, which help audience understand this complicate non-linear component. Typical applications of magnetically-controlled LLC resonant converters are discussed [6]-[8]. (On-board battery charger, interleaving operation, multiple-output operation, hold-up operation, single stage AC/DC power conversion, etc.)

4.3.3 LLC converters with hybrid modulation strategies or multiple operation modes.

Estimated time: 30 min

To satisfy the wide voltage gain requirement, there are some hybrid modulation strategies for LLC resonant converters. To resolve the issue of large transients, a frequency feedforward based smooth mode transition strategy is proposed [9, 10]. Some novel LLC converters with hybrid modulation strategies will be discussed [11]. Based on these discussions, the existing solutions for LLC resonant converters with wide volatge gain range applications can be summarized.

4.4 Summary. Estimated time: 15 min

Finally, we will summarize the tutorial. LLC resonant converters are the most popular power converters for energy harvesting applications due to their wide soft switching range characteristic. However, the challenges for the LLC resonant converters in these applications are the degraded converter performances caused by wide volatge gain operation requirement. The audience will learn the following aspects regarding LLC resonant converters: 1) a clear understanding of the issues and solutions for LLC converters for energy harvesting applications; 2) for audience from academia, novel ideas can be inspired by the tutorial such as novel modulation strategies that can be proposed based on the developed generation mechanisms, some novel topologies for LLC converters with wide voltage range application can be proposed; 3) for audience from industry, we have developed valuable simulation and automated design tools for LLC converters, which can resolve the practical issues in industry.

5. Lecture Style and Requirements

This tutorial will include traditional lecture, software demonstration (the developed simulation tools and automated optimal design tools), discussions and polls (what should be focused in designing a resonant converter). The targeted audience will be engineers from industry and researchers from academia that are are working on power converter, especially isolated resonant converters. Beginners in this research filed would also be interested in this tutorial. The difficulty of this tutorial is intermediate level. Only basic knowledge on power converter analysis is required.

6. Instructor Bios

Yuqi Wei: Mr. Wei is a visiting scholar at Kiel University from September 2021 to December 2021. Mr. Wei will receive his Ph.D. degree from the University of Arkansas, Fayetteville, AR, USA, May 2022. From April 2022, he will continue working as post-doc at University of Arkansas. He received the 2020 IEEE Power Electronics Society Transactions Second Place Prize Paper Award as First and Corresponding author. Award paper “Overview of Modulation Strategies for LLC Resonant Converter”. The received the 5th IEEE International Future Energy Electronics Conference (IFEEC 2021) best paper award. Award paper “A Wireless Power Transfer Based Gate Driver Design for Medium Voltage SiC MOSFETs”. Two best presentation awards for 2021 IEEE Applied Power Electronics Conference and Exposition

(APEC), 2021. Invited talk for 2021 Cryogenic Engineering Conference and International Cryogenic Materials Conference.

Alan Mantooth (IEEE Fellow): Professor Mantooth is the Distinguished Professor and 21st Century Research Leadership Chair. Dr. Mantooth has 21 years of academic experience in addition to eight years in industry. Dr. Mantooth has published well over 350 refereed publications as well as three books. He is an IEEE Fellow, has served on the IEEE PELS Advisory Committee since 2004 and served as PELS President in 2017 and 2018. He also serves as Editor-in-Chief of the IEEE Open Journal of Power Electronics. Professor Mantooth has been invited 12 times for Professional Tutorials at International Conferences

Publications that related to this tutorial are listed:

[1] **Y. Wei**, Q. Luo, S. Chen, P. Sun and N. Altin, "Comparison Among Different Analysis Methodologies for LLC Resonant Converter," *IET Power Electronics*, vol. 12, no. 9, pp. 2236-2244, 2019.

[2] **Y. Wei**, Q. Luo and **A. Mantooth**, "Comprehensive comparisons between frequency-domain analysis and time-domain analysis for LLC resonant converter," *IET Power Electronics*, vol. 13, no. 9, pp. 1735-1745, Jul. 2020.

[3] **Y. Wei**, Z. Wang, Q. Luo and **H. Alan Mantooth**, "MATLAB GUI Based Steady State Open-Loop and Closed-Loop Simulation Tools for Different LLC Converters With all Operation Modes," *IEEE Open Journal of Industry Applications*, vol. 2, pp. 320-336, 2021.

[4] **Y. Wei**, Q. Luo, Z. Wang and **H. A. Mantooth**, "A Complete Step-by-Step Optimal Design for LLC Resonant Converter," *IEEE Transactions on Power Electronics*, vol. 36, no. 4, pp. 3674-3691, April 2021.

[5] **Y. Wei**, Q. Luo, and **A. Mantooth**, "Overview of Modulation Strategies for LLC Resonant Converter," *IEEE Transactions on Power Electronics*, vol. 35, no. 10, pp. 10423-10443, Oct. 2020. **(2020 Second place prize paper)**

[6] **Y. Wei**, Q. Luo, J. M. Alonso and **H. A. Mantooth**, "A Magnetically Controlled Single-Stage AC–DC Converter," *IEEE Transactions on Power Electronics*, vol. 35, no. 9, pp. 8872-8877, Sep. 2020.

[7] **Y. Wei**, Q. Luo, X. Du, N. Altin, A. Nasiri and J. M. Alonso, "A Dual Half-Bridge LLC Resonant Converter With Magnetic Control for Battery Charger Application," *IEEE Transactions on Power Electronics*, vol. 35, no. 2, pp. 2196-2207, Feb. 2020.

[8] **Y. Wei**, Q. Luo, X. Du, N. Altin, J. M. Alonso and **A. Mantooth**, "Analysis and Design of the LLC Resonant Converter With Variable Inductor Control Based on Time-Domain Analysis," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 7, pp. 5432-5443, Jul. 2020.

[9] **Y. Wei**, Q. Luo, and **A. Mantooth**, "Wide Voltage Gain Range Application for Full-bridge LLC Resonant Converter with Narrow Switching Frequency Range," *IET Power Electronics*, vol. 13, no. 9, pp. 1735–1745, Jul. 2020.

[10] **Y. Wei**, Q. Luo and **H. A. Mantooth**, "An LLC Converter With Multiple Operation Modes for Wide Voltage Gain Range Application," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 11, pp. 11111-11124, Nov. 2021.

[11] **Y. Wei**, Q. Luo and **A. Mantooth**, "Hybrid Control Strategy for LLC Converter With Reduced Switching Frequency Range and Circulating Current for Hold-Up Time Operation," *IEEE Transactions on Power Electronics*, vol. 36, no. 8, pp. 8600-8606, Aug. 2021.