Analysis and Simulation of a Bidirectional CLLC Resonant Converter

Candidate: Rebecca GIOCO ***Supervisor:*** Prof. Iustin Radu BOJOI ***Co-supervisor:*** Alessandro BADOGLIO

Abstract**—In the socio-economic scenario, the charging infrastructure for Electric Vehicles (EVs) is poised to be a crucial factor in decarbonization over the coming decades. In this context, the CLLC resonant converters are of great interest since are characterized by a bidirectional structure with great efficiency and power density. This thesis activity has been carried out at the Prima Electro S.p.A. company. The purpose is to use the results obtained as a first evaluation tool for the possible creation of CLLC resonant converters. Thanks to the FHA (First-Harmonic-Approximation), an analytical study has been performed on a converter simplified model to describe its frequency behaviour. Simulations were conducted on PLECS to verify the validity of the analytical models and as a tool to map the operating regions of the converter. Furthermore, component stresses were evaluated as an assessment tool for the future design work.**

I. Introduction

The CLLC converter is an isolated bidirectional battery charger with high efficiency and power density. This kind of converter comprises a primary side H-bridge connected to the DC-link, a resonant tank, a high-frequency transformer and a secondary side H-bridge connected to the battery, shown in Fig.1. Within this framework, the main **goals** that have been highlighted are the following:

- Analytical study of the CLLC resonant converter;
- Model validation with PLECS simulation;
- Component stress evaluation via script tools on PLECS environments.

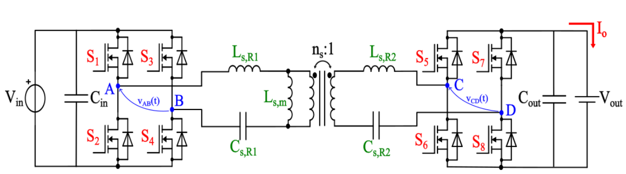

Fig. 1: Bidirectional CLLC resonant converters.

II. Analytical Study

Theory requires deriving a basic model shown in Fig.2 where the output acts like a resistance, and where the input is only the first harmonic of the square wave voltage at the input of the primary H-Bridge. The analysis in the following order was conducted:

- Derivation of voltage gain expression (step-down/step-up determination), reported in Fig.3;
- Study of inductive and capacitive behavior (Soft Switching);
- Calculation of phase shift for secondary H-Bridge control (synchronous rectification for resistive output), shown in Fig.4.

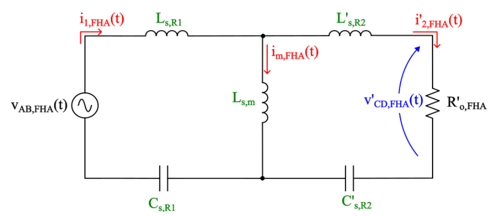

Fig. 2: Equivalent circuit of CLLC.

Subsequently, the simulation stages progressed methodically:

- Employ simplified equivalent circuit to validate phase shift formula;
- Validate analytical model with circuit using square wave generators;
- Evaluate the error led with FHA using the CLLC circuit.

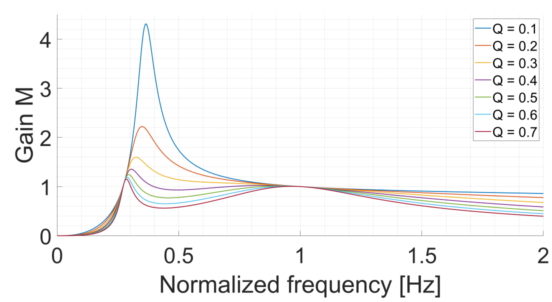

Fig. 3: Voltage gain trend of CLLC.

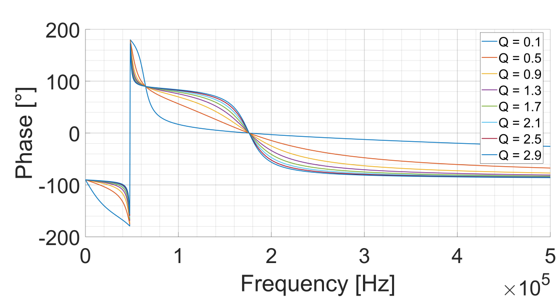

Fig. 4: Phase shift trend of CLLC.

III. Simulation Results

A. Phase Shift Formula Validation

First of all, the phase shift formula was validated using the PLECS environment by comparing the theoretical calculation and the acquired data. In Fig.5 the error between the two is reported, reaching a maximum of 0.18 ° for frequencies 2.5 times higher than the resonance frequency f_{R1}, regardless of the type of output.

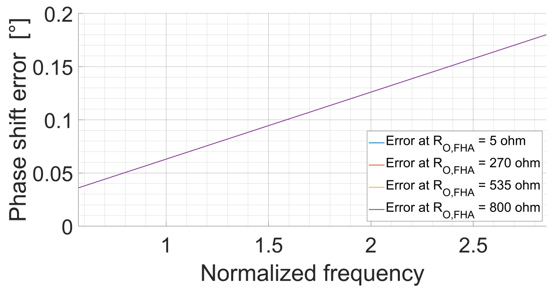

Fig. 5: Error between theoretical and obtained phase shift.

B. Evaluation FHA Committed Error

An estimation of the error committed by utilizing the FHA is derived and shown in Fig.6. For high output equivalent resistance, the FHA makes estimation errors at a frequency far away from the resonant one. Essentially, the simplified circuit effectively mirrors the converter when operating within proximity to its resonance frequency, enabling a comprehensive study of its frequency behaviour.

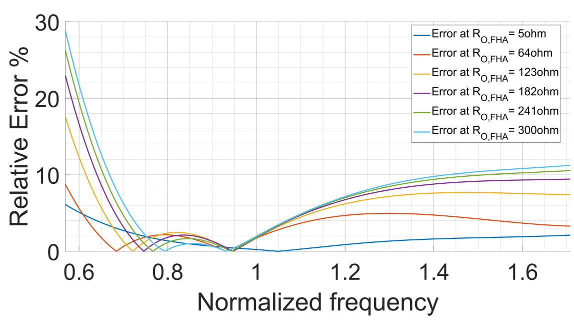

Fig. 6: Relative error with using FHA.

C. Mapping Operating Points with Gain Limits

The final step involves analyzing the maximum stresses on the inductors, capacitors, transformer, and MOSFETs in the resonant tank. Maps were generated by operating the converter at various points and recording key parameters for sizing. Fig.7 shows the power absorbed by the output load depending on the voltage gain and the operating frequency. Afterwards, by considering some limitations for operating regions the maps were elaborated to take the maximum stresses. The limitations that have been highlighted are the minimum and maximum gain and the gain limit to reach maximum power at most. To give an idea, Fig.8 highlights the maximum RMS value of the current flowing through the inductor in the primary of the resonant tank.

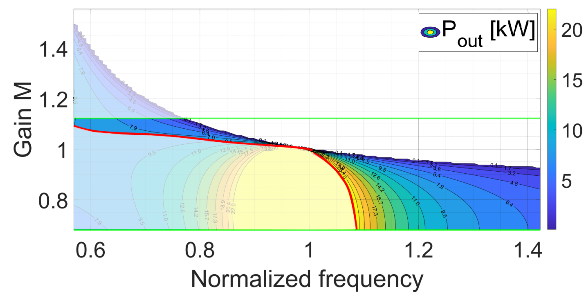

Fig. 7: Battery output power.

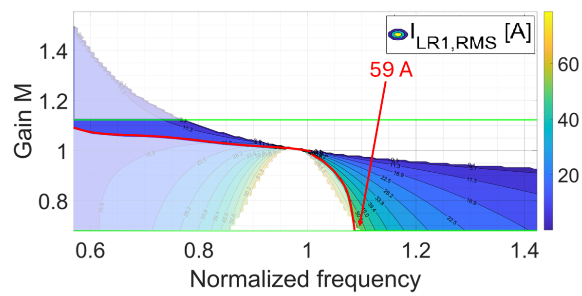

Fig. 8: Primary side inductor RMS current.

IV. Conclusions

In the light of the analysis carried out, the mathematical calculation of the phase shift could be considered satisfactory, because it reflects the frequency behaviour of the current at the secondary side. Then, this formula is unequivocally utilised to control the opening and closing of the rectifier bridge switches, ensuring synchronous rectification.

In addition, an evaluation of the validity of the treated method with the use of FHA has been done. Focusing on phenomena between 0.7 times and 1.3 times the resonance frequency, the assumptions and hypotheses offer reliable results.

Moreover, the simulation tool employed for analysing point-by-point stresses is robust and valuable, as it captures all stresses at different operating conditions, providing a comprehensive framework for the future design assessments.

V. Personal Contribution

My main contributions can be summarised as follows:

- Execution of all the aforementioned analytical studies and manipulation of the derived formulations;
- Simulations in the PLECS environment to validate the analytical model, with qualitative and quantitative evaluations conducted to assess errors and extrapolate operating regions;
- Stress maps for components derived from simulations, aiding in component sizing in the post-design phase.