LLC RESONANT FULL-BRIDGE DC–DC CONVERTER WITH LC ANTIRESONANT CIRCUIT

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Abstract—*An LLC resonant circuit-based full-bridge dc–dc converter with an LC antiresonant tank for improving the performance of pulse frequency modulation (PFM) is proposed in this paper. The proposed resonant dc–dc converter, named as LLC-LC converter, can extend a voltage regulation area below the unity gain with a smaller frequency variation of PFM by the effect of the antiresonant tank. This advantageous property contributes for protecting over current in the case of the short-circuit load condition as well as the start-up interval in the designed band of switching frequency. The circuit topology and operating principle of the proposed converter is described, after which the design procedure of the operating frequency and circuit parameters is presented. The performances on the soft switching and the steady-state PFM characteristics of the LLC-LC converter are evaluated under the open-loop control in experiment of a 2.0-kW prototype, and its actual efficiency is compared with an LLC converter prototype. For revealing the effectiveness of the LLC-LC resonant circuitry, voltages and currents of the series and antiresonant tanks are analyzed, respectively, with state-plane trajectories based on calculation and experiment, whereby the power and energy of each resonant tank are demonstrated. Finally, the feasibility of the proposed converter is evaluated from the practical point of view.*

Index Terms—Antiresonant tank, buck and boost voltage regulations, LLC resonant converter, LLC-LC resonant converter, over current protection (OCP), pulse frequency modulation, zerocurrent soft switching (ZCS), zero-voltage soft switching (ZVS).

I. Introduction

An asymmetrical half-bridge *LLC* resonant dc–dc converter has been gaining the popularity in a variety of switching power supplies encompassing from a small power ICT equipment, LED lighting, battery chargers for electric vehicles, to a dc microgrid power distribution system due to a soft-switching operation over the wide range of load power: zero-voltage soft switching (ZVS) of active switches and zero-current soft switching (ZCS) of rectifier diodes [1]–[11]. The wide range of softswitching operation in the *LLC* converter is attractive for a full-bridge dc–dc converter topology as well, while a typical phase-shift pulse-width-modulation (PWM) full-bridge circuit topology suffers from a severely limited range of soft switching for load power variations.The steady state performances on the voltage and power regulations of the *LLC* converter are theoretically described in Section II, whereby the low sensitivity of PFM for the buck voltage regulation is pointed out by the relevant characteristic curves.

The circuit configuration and operation principle of the proposed *LLC-LC* converter are explained in Section III, after which the series and antiresonant frequencies are explained in conjunction with the resonant tank impedances as well as the input impedance of the proposed converter. The design procedure of the circuit parameters and resonant frequencies are described in Section IV. The essential performances on the wide range of output voltage and power regulations with soft switching are demonstrated by the time-domain analysis with both the calculation and measured state-plane trajectories under the various load conditions including the short load in Section V, and compared with the *LLC* converter. Finally, the experimental verifications ate summarized; then, effectiveness of the multi element resonant dc–dc converter topology is originally revealed from a practical point of view in Section VI.

II. PFM CHARACTERISTICS OF *LLC* RESONANT DC–DC CONVERTER

The circuit diagram of *LLC* resonant full-bridge dc–dc converter is depicted in Fig. 1. The series inductor *Ls* includes the leakage inductance of the HF transformer, while the resonant capacitor *Cs* is additionally inserted in the primary-side HF inverter. The steady-state characteristics of the *LLC* converter can be derived from the fundamental harmonic approximation (FHA)

III. PROPOSED *LLC-LC* RESONANT DC–DC CONVERTER

A. Circuit Topology and Operating Principle

The proposed *LLC-LC* resonant full-bridge dc–dc converter is schematically depicted in Fig.4 [22]–[24].The antiresonant tank (*LpCp*) is employed in series with the series-resonant network (*LsCs*) in the primary-side HF inverter.

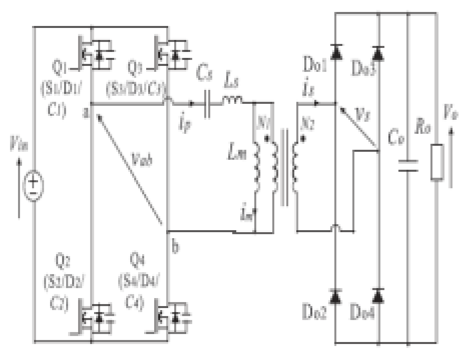

Fig 1 LLC resonant dc dc converter

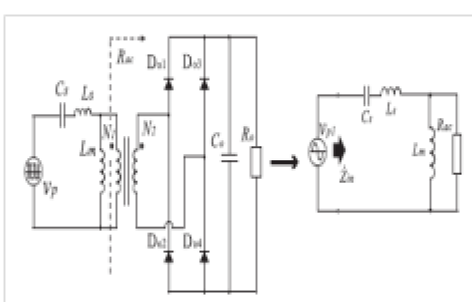

Fig 2 equivalent circuit of resonant converter

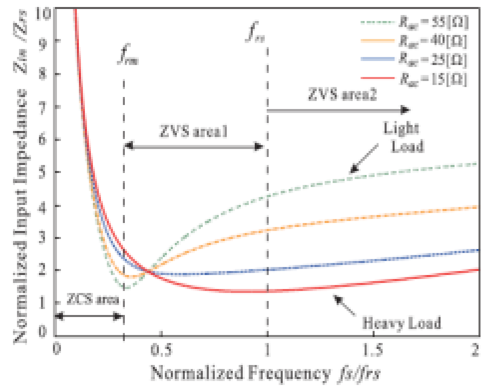

Fig 3 Input impedance characteristics of LLC resonant converter

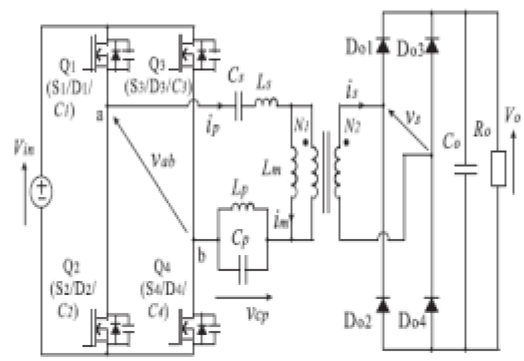

Fig 4 proposed LLC resonant converter

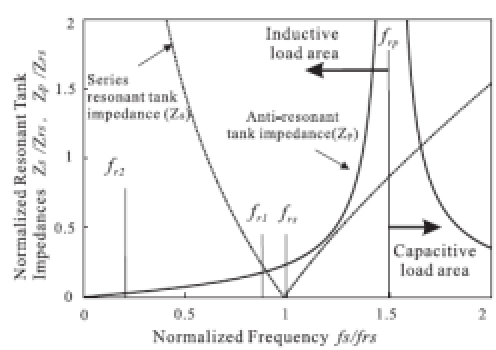

Fig 5 Theoretical characteristics of proposed resonant converter

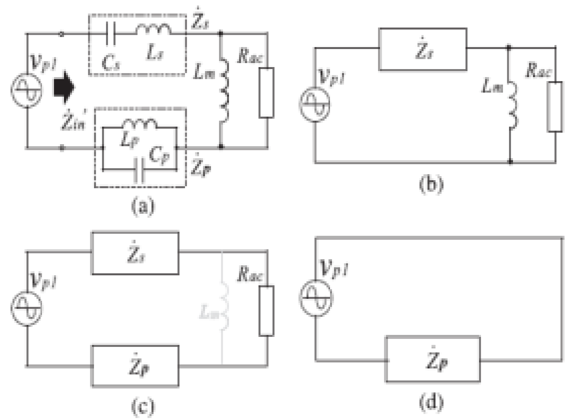

Fig 6 simplified equivalent circuits of proposed resonant converter for various modes

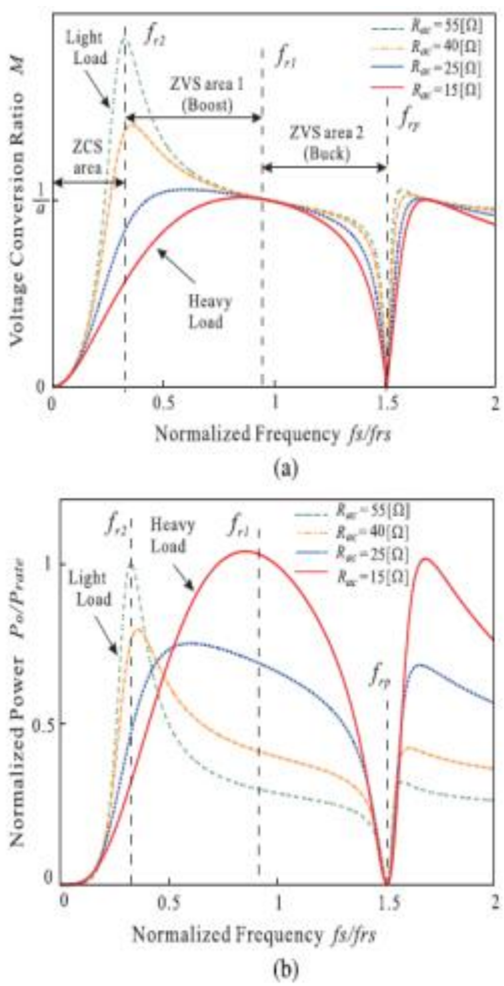

Fig 7.theoretical characteristics of proposed resonant converter

IV. DESIGN PROCEDURE OF CIRCUIT PARAMETERS

A. Resonant Frequencies

The first resonant frequency fr_1 and the second resonant frequency fr_2 of the proposed *LLC-LC* converter are designed as close to *f*rs and *f*rm of the *LLC* converter, respectively. The antiresonant frequency *f*rp should be set well less than three times fr_1 for precluding the harmonics from *ip* , while the switching frequency variation from fr_1 should be small as much as possible for a better response of the OCP. This idea on setting the resonant frequencies leads to a design guideline of *f*rp = 1.5fr_1 .Once *f*rs and *f*rm are set as 90 and 30 kHz in consideration of the wide-range ZVS operation in the *LLC* converter, the antiresonant frequency *f*rp can be designed as

frp = 1.5 fr_1 = 135KHz ------------------ 1

V.EXPERIMENTAL RESULTS AND EVALUATIONS

A. Specification of Prototype

The performances of the proposed *LLC-LC* converter are evaluated in experiment using a 2.5-kW laboratory prototype by comparison with an *LLC* converter prototype.

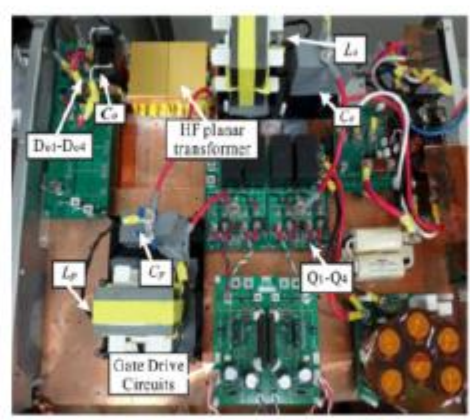

Fig 8 Experimental setup of proposed resonant converter

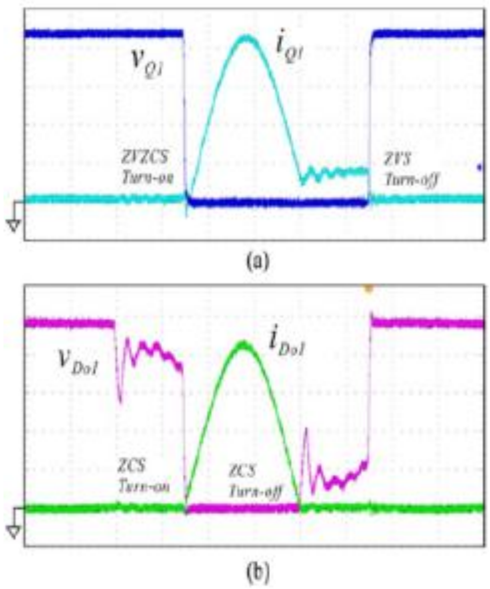

Fig 9 Practical wave form of proposed resonant converter

B. Soft-Switching Performance

The switching waveforms of the *LLC-LC* converter prototype under a heavy-load condition (80% output power) are shown in Fig. 9. ZVS and ZCS commutations can be actually confirmed from those results.

C. Steady-State Characteristics

The steady-state characteristics of the proposed converter are compared with the *LLC* converter under the open-loop control in the experiment.

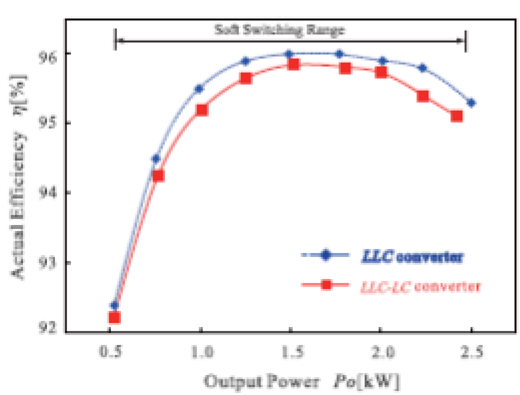

Fig 10 Comparison of conventional and proposed resonant converter

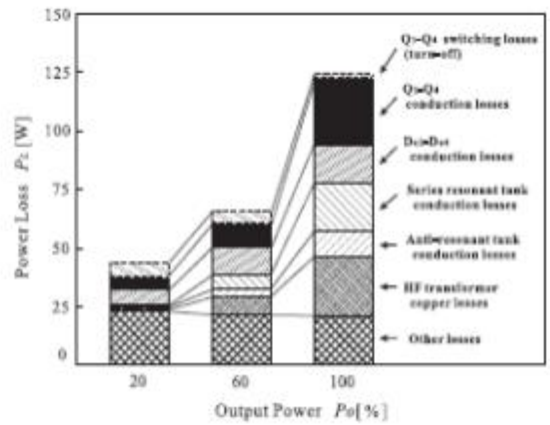

Fig 11.Output power versus power loss of proposed resonant converter

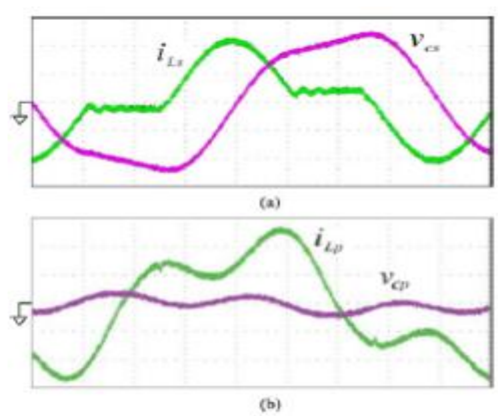

Fig 12 Experimentally obtained wave form of proposed resonant converter

E. State-Plane Analysis of Resonant Tanks

The power and energy levels of each resonant tank can be portrayed by the state-plane trajectory, which helps to understand the proprieties of the *LLC-LC* resonant tanks.

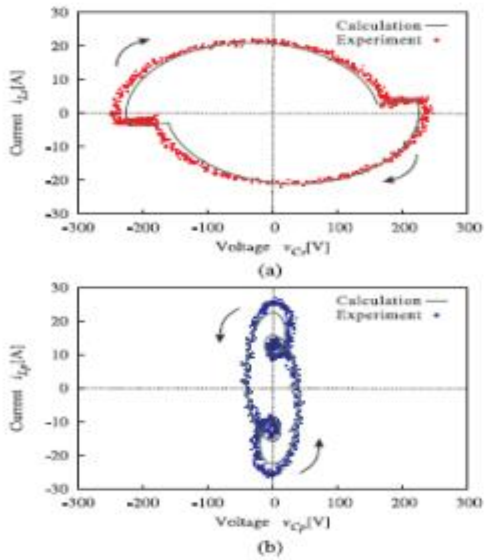

Fig 13 State plane trajectories of resonant tank

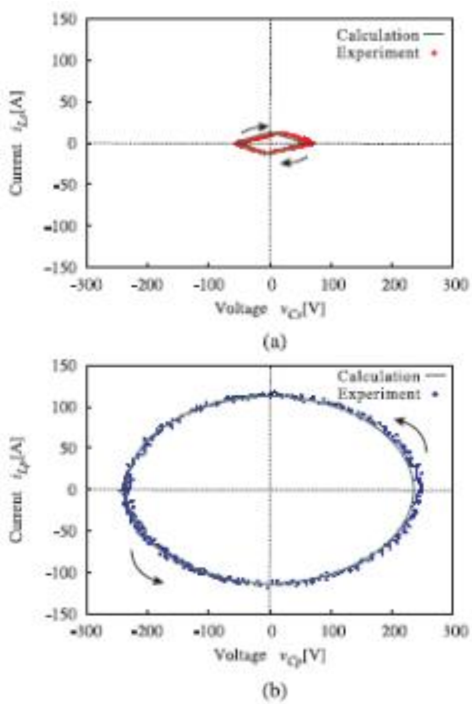

Fig 14 state plane trajectories of proposed resonant converter under load conditions

VI. CONCLUSION

This paper presents an *LLC-LC* resonant soft-switching dc– dc converter with the sensitivity-improved PFM scheme. The OCP for the short-circuit load condition as well as a start-up interval can be ensured in a smaller band of switching frequency, which is designed on the basis of the series- and antiresonant frequencies. The circuit topology and the PFM scheme are also effective for extending the voltage regulation area especially in the buck mode, which is advantageous for realizing a single stage buck and boost voltage regulations in the resonant converter. Implementation of a high-performance controller and evaluations on the transitional behaviors of the *LLC-LC* converter will be a future challenge of this research.

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