

Bidirectional CLLC DC–DC Converter Based on Adaptive Excitation Inductor

N. VK Chakravarthy Naik¹, N. Rajesh Kumar Gowd²

^{1,2}Assistant Professor, Dept. Of Electrical and Electronics Engineering, Sri Krishnadevaraya University College of Technology, SK University Anantapur. AP, India, 515003.

ABSTRACT

Bidirectional DC–DC converters are important in modern energy systems because they allow efficient power transfer between sources and storage. Conventional LLC and CLLC resonant converters can experience efficiency degradation when a wide voltage-gain range and bidirectional operation are required.

The project proposes a CLLCLC resonant converter using an adaptive excitation inductance. An Lp–Cp series branch replaces the fixed excitation inductance so that the equivalent excitation inductance changes with operating frequency. This reduces circulating current and improves energy-transfer efficiency.

A hybrid control approach using frequency modulation and phase-shift control is considered to maintain soft switching. The proposed topology is intended for energy-storage charging/discharging systems, electric vehicles, DC microgrids and UPS applications.

- Adaptive excitation inductance changes with operating frequency.
- Wide voltage-gain operation is achieved with a narrower operating-frequency range.
- Soft switching such as ZVS/ZCS reduces switching losses.
- The proposed structure uses a relatively simple resonant network and reduces control difficulty. The original report states that a 200 W experimental prototype achieved maximum transmission efficiency of about 97.8% in forward mode and 94% in reverse mode. □

INTRODUCTION

Renewable energy sources such as solar, small wind and wave generation are intermittent and unpredictable. Energy-storage systems help compensate for the mismatch between generation and demand and therefore require efficient and reliable charging and discharging.

Bidirectional DC–DC converters provide two-way energy transfer without changing the polarity of the input and output voltages. Compared with using two separate one-way converters, bidirectional converters can reduce size, weight and cost while providing good dynamic performance.

Pulse-frequency modulation is widely used in resonant converters, but a wide voltage-gain range can force a large change in switching frequency. Other strategies include phase-shift modulation, PWM and resonant-frequency modulation. Hybrid modulation can reduce the required frequency range, but additional components and control complexity may result.

Transformer optimization is also important. Planar and matrix transformers can improve power density and reduce losses, but transformer capacitance and magnetic design must be considered.

The main problem addressed by this project is the trade-off between wide voltage gain and high efficiency. The proposed CLLCLC converter replaces the fixed excitation inductance with an Lp–Cp branch, allowing the equivalent inductance to adapt to operating frequency. □

PROPOSED TOPOLOGY

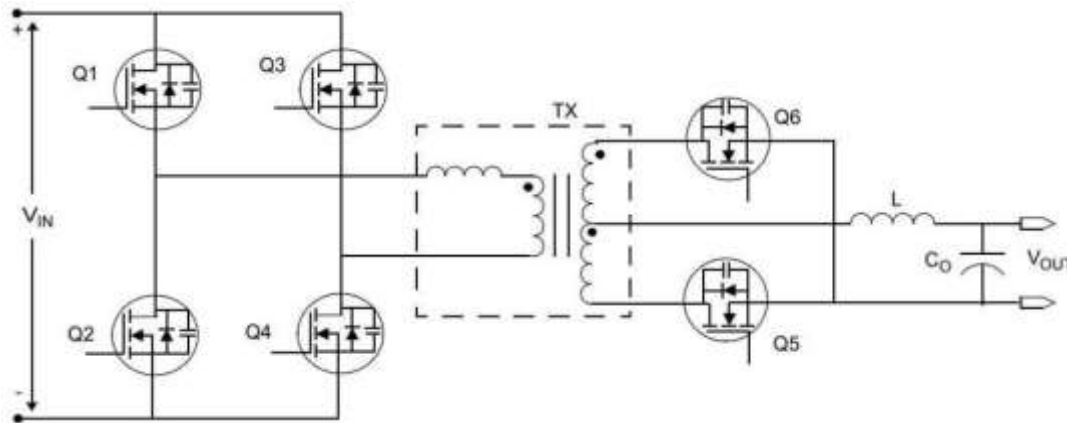


Fig. 1 Typical isolated circuit diagram.

The proposed bidirectional resonant DC–DC converter is based on the conventional CLLLC topology. The energy-conversion modules on the primary and secondary sides can operate as inverter or rectifier depending on the direction of energy flow.

In the conventional CLLLC converter, the resonant network contains L_r , C_{r1} , C_{r2} and the transformer excitation inductance L_m . In the proposed converter, an Lp–Cp series resonant branch replaces the fixed excitation inductance.

- Split capacitors C_{r1} and C_{r2} reduce current stress on a single capacitor and can improve EMI behavior.
- The equivalent excitation inductance increases with resonant frequency.
- At low input voltage, lower switching frequency gives lower equivalent inductance and higher gain.
- At high input voltage, higher switching frequency increases equivalent inductance and reduces excitation/circulating current.
- The topology aims to combine wide voltage gain with improved rated-point efficiency. The original report identifies the main difference as the use of the equivalent excitation inductance L_{meq} formed by the Lp–Cp branch.

FUNDAMENTAL ANALYSIS

A bidirectional resonant converter can transfer power in both directions and can operate as a buck or boost converter depending on the energy-flow direction. Resonant operation enables soft switching and high efficiency.

- Bidirectional power flow: power can move from source to load or from storage to source.
- Soft switching: ZVS and ZCS reduce switching losses.
- Wide voltage range: suitable resonant designs can operate over varying input/output voltages.
- Applications: EV charging, battery charging/discharging, DC microgrids and isolated DC conversion.

- Common topologies: LLC, CLLC, CLLLC and DAB.

For isolated conversion, galvanic isolation means there is no direct metallic conduction path between input and output. A transformer normally provides the isolation barrier while transferring energy electromagnetically.

The source report emphasizes that isolation provides safety and can also help eliminate ground-loop problems. □filecite□turn0file0□L192-L218□

Design considerations include transformer design, resonant frequency selection and an effective control strategy for stable operation over the required voltage range.

ISOLATION AND SYSTEM APPLICATIONS

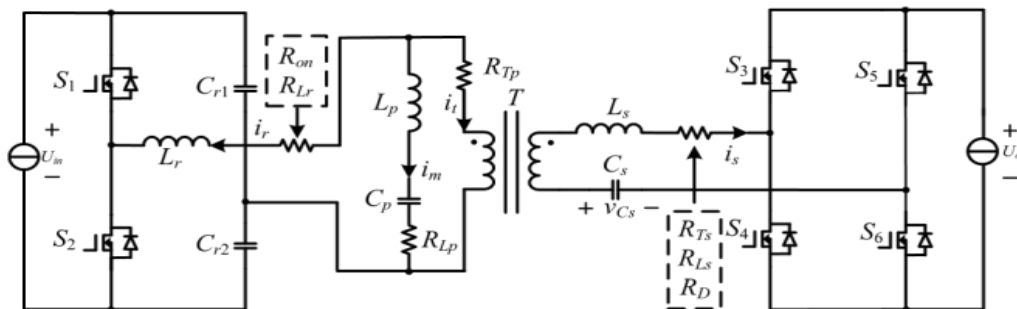


Fig. 2 Simplified loss model of CLCL converter.

In an isolated converter, the input and output have separate grounds. Isolation is generally created using a transformer and electrical insulation. Feedback and control signals crossing the isolation boundary must also be isolated; the source report mentions small-signal transformers for AC signals and optocouplers for DC signals.

- Functional/operational insulation – used for operational reasons and does not provide shock protection.
- Basic insulation – provides shock protection through a single insulation layer.
- Supplementary insulation – additional insulation used with basic insulation.
- Reinforced insulation – a single barrier providing protection comparable to double basic insulation.

Isolated supplies can be useful where safety isolation is required. The report also discusses intermediate-bus converters and point-of-load converters in multi-rail systems, particularly in telecom and high-performance computing applications. □

OPERATING DIRECTIONS AND CONTROL

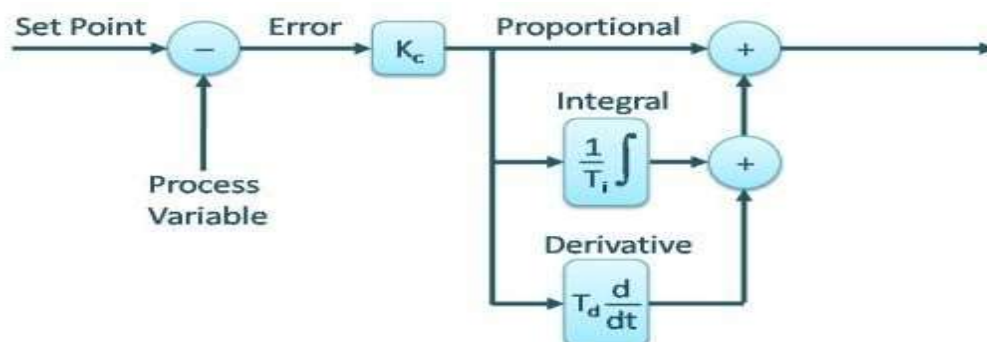


Fig. 3 Non interactive Algorithm.

The proposed CLLCLC converter has forward and reverse energy-flow directions. According to the source report, in step-up/backward operation S1 and S2 form a half bridge and generate a square wave at switching frequency f_s with approximately 50% duty cycle. A small dead time prevents simultaneous conduction of the upper and lower switches.

In the step-down/forward direction, PFM is used for the secondary switches S3–S6 while the primary switches S1 and S2 are turned off and their body diodes provide rectification.

- Step-up/backward: primary half-bridge produces the high-frequency excitation.
- Step-down/forward: secondary-side PFM controls the conversion process.
- Dead time is inserted to avoid shoot-through.
- The resonant network enables soft switching and efficient energy transfer.

The original report states that the corresponding control arrangement enables high-efficiency energy conversion over a wide voltage-gain range. □

OPERATION PRINCIPLES – MODES 1 AND 2

For the analysis, switches, inductors, capacitors and voltage sources are treated as ideal, and transformer leakage inductances are neglected. The proposed converter has operation similar to the conventional LLC resonant converter. □

□

MODE 1 (t_0 – t_1): S1 is ON and S2 is OFF. The body diodes of S3–S6 provide full-bridge rectification. Energy is transferred through the transformer to the secondary side. The output capacitor maintains the output voltage approximately at V_o . Cr1, Cr2 and Lr participate in resonance.

During Mode 1, the resonant current i_r , excitation current i_m and resonant capacitor voltage vary according to the resonant network. The primary-side reflected voltage is related to the transformer turns ratio and secondary output voltage.

MODE 2 (t_1 – t_2): As excitation current increases, the resonant current reaches the excitation current at t_1 . At this instant, no net energy is transferred to the secondary side. The equivalent L_p – C_p branch is no longer choked by the output capacitor and L_p and C_p participate in resonance together with L_r and C_r .

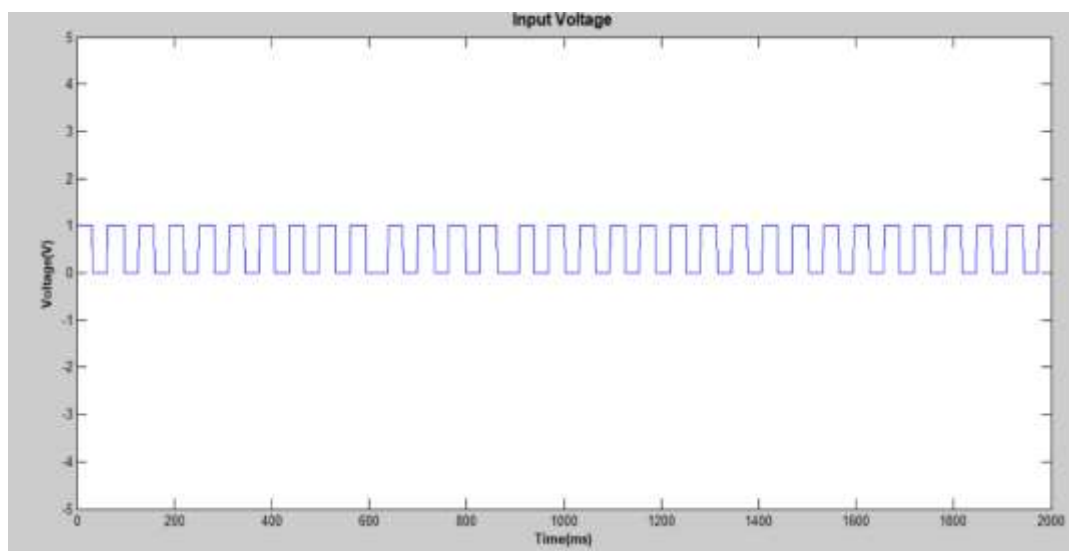


Fig. 4 Input voltage

These two intervals demonstrate how the adaptive branch participates differently depending on the instantaneous resonant current and voltage conditions.

OPERATION PRINCIPLES – MODES 3 AND 4

MODE 3 (t_2 – t_3): S1 is turned OFF and S2 is turned ON. The secondary body diodes again form a full-bridge rectifier. Energy is transferred to the secondary side. The reflected primary voltage changes polarity, and the excitation current decreases. Cr1, Cr2 and Lr remain in resonant operation.

MODE 4 (t_3 – t_4): The resonant current and excitation current meet again at t_3 . No energy is transferred to the secondary side during this interval. The equivalent excitation branch is not choked by the secondary voltage, so Lp and Cp participate in the resonant process, similar to Mode 2.

- Modes 1 and 3 are the main energy-transfer intervals.
- Modes 2 and 4 are intervals in which the adaptive excitation branch participates in resonance.
- Continuity of inductor current and capacitor voltage is used at mode boundaries.
- The source report states that step-down analysis is similar and is therefore not repeated.

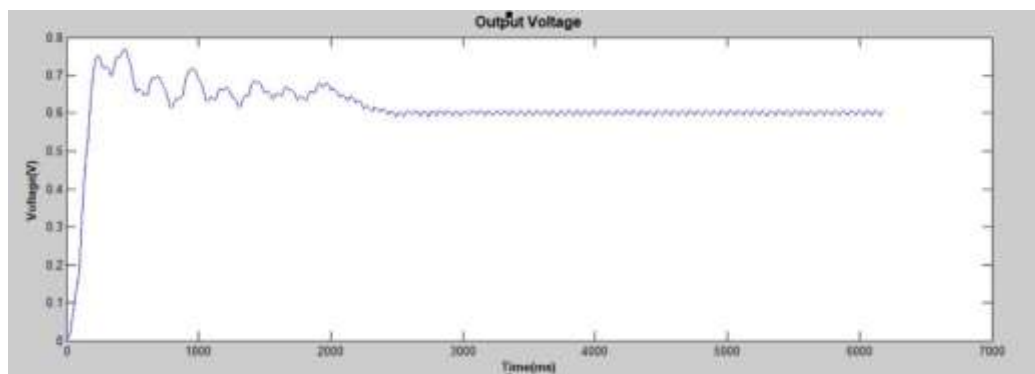


Fig.5 Output voltage

The four-mode sequence explains the resonant current path and the role of the adaptive excitation branch over one switching cycle. □

DESIGN OF THE PROPOSED CLLCLC CONVERTER

For a wide-input resonant converter, the gain–frequency characteristic is established first. The source report identifies three main calculation approaches: extended describing-function (EDF), fundamental harmonic approximation (FHA), and numerical methods such as simulation/modal analysis.

FHA simplifies the LLC gain calculation and reduces iteration time, although accuracy decreases when the operating frequency moves far from resonance. EDF and numerical approaches provide higher accuracy but require greater computational effort.

After FHA, the equivalent model contains resonant elements and an equivalent primary resistance R_{ac} . Two resonant frequencies arise because the excitation inductance can participate or not participate in resonance depending on the rectifier state.

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \quad (6)$$

$$f_{r1} = \frac{1}{2\pi\sqrt{(L_r + L_m)C_r}} \quad (7)$$

The resonant tank is characterized by the quality factor Q and inductance ratio k . The report states that larger k increases the interval between the two resonant frequencies, while a larger Q corresponds to lower resonant-tank current and higher efficiency.

ADAPTIVE EXCITATION INDUCTANCE AND LOSS MODEL

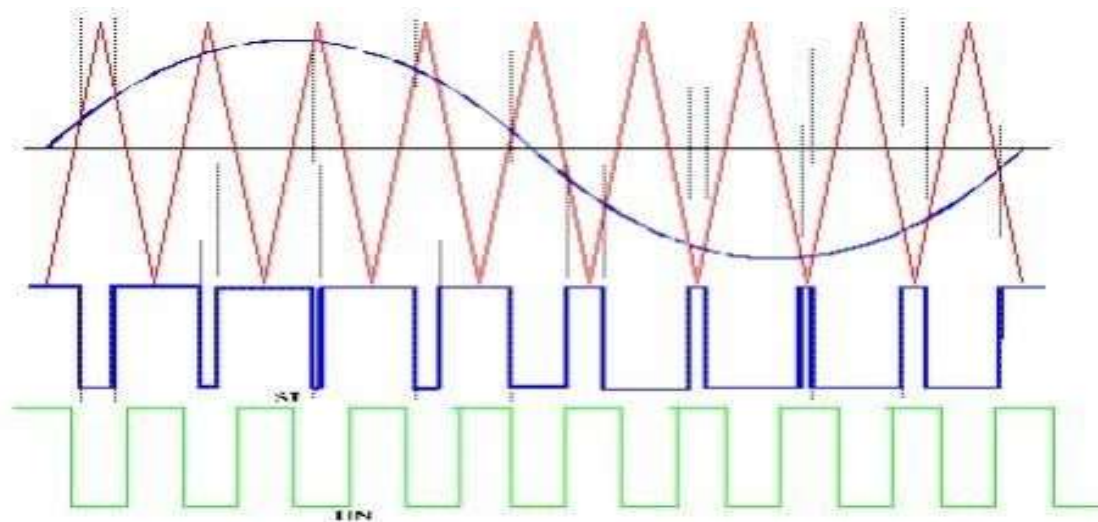


Fig. 6 UN modulated, sine modulated pulses

In a conventional CLLLC converter, L_m is fixed. At reduced operating frequency, the fixed excitation inductance can result in higher excitation current and increased power loss. Replacing L_m with an L_p - C_p branch gives the excitation network a frequency-dependent impedance.

The design of C_p and the equivalent excitation inductance L_{meq} at the minimum operating frequency is important. A smaller C_p can provide higher L_{meq} and lower excitation current. To preserve the maximum-gain requirement, the equivalent excitation inductance at the minimum operating frequency is selected in relation to the original fixed L_m .

The source report compares the proposed converter with other resonant converters and states that it can achieve a wide gain while maintaining high efficiency, with a narrower operating-frequency range under the same input voltage and load conditions. □filecite□turn0file0□L467-L492□

Power-loss estimation is required for thermal design and efficiency optimization. The reported loss components include conduction loss, switching loss, ferrite/core loss and other losses associated mainly with the gate-drive circuit and PCB equivalent series resistance. □

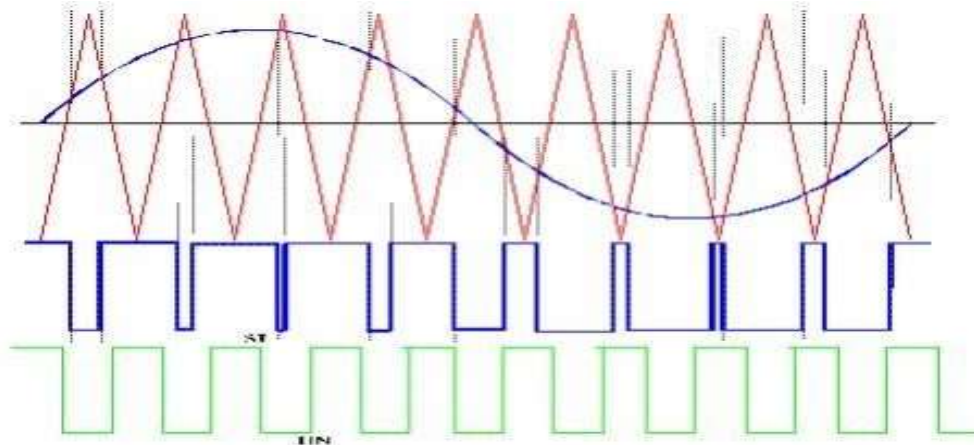
CONTROL – PID AND PWM BASICS

$$L_{meq}(f_s) = L_p - \frac{1}{(2\pi f_s)^2 C_p} \quad (13)$$

The report includes PID control as a supporting control concept. A PID controller combines proportional, integral and derivative actions. The proportional term responds to present error, the integral term accumulates past error, and the derivative term responds to the rate of change of error.

- P action: output is proportional to the instantaneous error; excessive gain can cause instability.
- I action: accumulates error and removes steady-state error, but can increase overshoot.
- D action: responds to the rate of change of error and can improve transient response, but is sensitive to measurement noise.

PWM controls the average conduction time of power switches. The report describes fixed-frequency PWM generation by comparing a modulating signal with a saw-tooth waveform. A comparator produces the switching pulses according to the relative magnitude of the two signals.



These control concepts support the broader converter-control discussion, while the proposed resonant converter primarily uses frequency-based control together with bidirectional switching arrangements.

□filecite□turn0file0□L562-L628□

These control concepts support the broader converter-control discussion, while the proposed resonant converter primarily uses frequency-based control together with bidirectional switching arrangements. □

□

CHAPTER 4 – MATLAB / SIMULINK IMPLEMENTATION

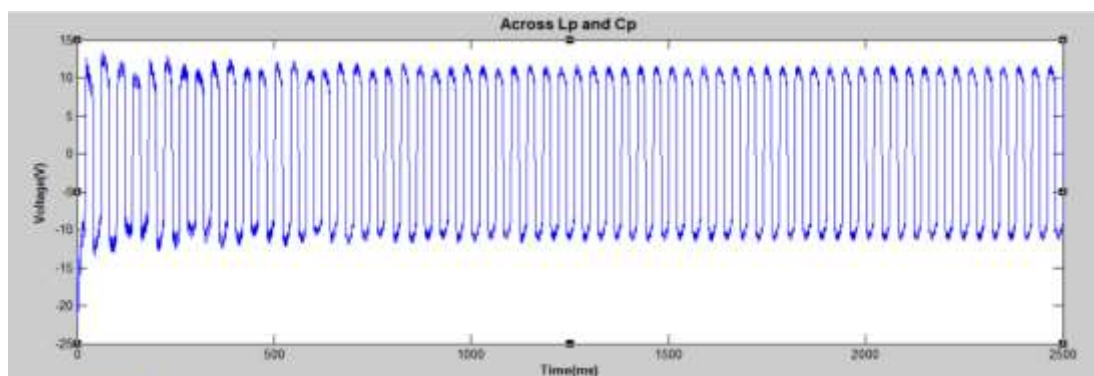


Fig.7 Voltage across Lp and Cp

MATLAB is used in the project for technical computation, modeling, simulation, data analysis and visualization. The report describes MATLAB as an interactive environment based on array and matrix operations, with facilities for programming and graphical analysis.

Important Simulink blocks used in the reported model include source blocks, voltage/current measurement blocks, scopes, three-phase RLC loads, breakers, integrators, trigonometric functions and power-electronic switches.

- Source block: represents a balanced voltage source with internal R–L impedance.
- V–I Measurement: measures circuit voltages and currents.
- Scope: displays simulation signals versus time.
- Three-Phase Series RLC Load: represents a balanced RLC load.
- Breaker: controls opening and closing of the electrical path.
- Integrator: produces the integral of its input.
- Switch/IGBT-Diode model: represents a power-electronic switching device with antiparallel diode.

The source report includes a Simulink model and simulation-result pages. In the 15-page version, the detailed generic MATLAB descriptions and repeated block explanations have been compressed while retaining the blocks directly relevant to the simulation. □

SIMULATION / EXPERIMENTAL RESULTS

The original report contains dedicated Simulink model and simulation-result pages. The detailed plots are retained in the source report, but the repeated blank/result pages are not reproduced in this condensed version.

The principal technical outcome reported for the proposed CLLCLC converter is improved wide-range operation through adaptive excitation inductance. The Lp–Cp branch changes its effective impedance with operating frequency, reducing circulating current at higher-frequency operation while preserving gain capability at lower frequency.

- Forward-mode maximum transmission efficiency: approximately 97.8%.
- Reverse-mode maximum transmission efficiency: approximately 94%.
- Experimental prototype power: 200 W.
- The converter is intended for energy-storage charge/discharge systems and related applications.

The reported conclusion states that ZVS is achieved for the power devices and that the adaptive branch reduces resonant circulating-current loss. □ □

CONCLUSION AND REFERENCES

CONCLUSION

The project presents a bidirectional CLLCLC DC–DC converter based on an adaptive excitation inductor. The operating principle is analyzed for forward and reverse modes, and the resonant network is designed to support soft switching. Replacing the fixed transformer excitation inductance with an Lp–Cp branch allows the equivalent excitation inductance to vary with switching frequency.

This adaptive behavior helps reduce circulating current and improves efficiency while allowing a wide voltage-gain range. The source report also notes that the transformer turns ratio and excitation inductance become decoupled, simplifying transformer design. A 200 W prototype is reported with maximum efficiencies of about 97.8% in forward mode and 94% in reverse mode. □

SELECTED REFERENCES

1. X. Sun, Y. Shen, Y. Zhu, and X. Guo, “Interleaved boost-integrated LLC resonant converter with fixed-frequency PWM control for renewable energy generation applications,” *IEEE Trans. Power Electron.*, 2015.
2. Y. Xuan et al., “A novel three-level CLLC resonant DC–DC converter for bidirectional EV charger in DC microgrids,” *IEEE Trans. Ind. Electron.*, 2021.
3. Y. Shen et al., “A bidirectional resonant DC–DC converter suitable for wide voltage gain range,” *IEEE Trans. Power Electron.*, 2018.
4. X. Ma et al., “A bidirectional LLCL resonant DC–DC converter with reduced resonant tank currents,” *IEEE Access*, 2020.
5. Y.-F. Wang et al., “Analysis and design of a 1-MHz bidirectional multi-CLLC resonant DC–DC converter with GaN devices,” *IEEE Trans. Ind. Electron.*, 2020.
6. M. A. Saket, N. Shafiei, and M. Ordonez, “LLC converters with planar transformers: Issues and mitigation,” *IEEE Trans. Power Electron.*, 2017.
7. S. De Simone et al., “Design-oriented steady-state analysis of LLC resonant converters based on FHA,” *SPEEDAM*, 2006.
8. C.-S. Wang et al., “A 5-kW isolated high voltage conversion ratio bidirectional CLTC resonant DC–DC converter,” *IEEE Trans. Power Electron.*, 2019.
9. Y. Wei, Q. Luo, and H. A. Mantooth, “A novel LLC converter with topology-morphing control for wide input voltage range application,” *IEEE JESTPE*, 2022.
10. Y. Wei, Q. Luo, and H. A. Mantooth, “An LLC converter with multiple operation modes for wide voltage gain range application,” *IEEE Trans. Ind. Electron.*, 2021.