Hybrid Control Method of Full-Bridge LLC Resonant Converter Based on Electric Vehicle

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Abstract

The increasing demand for efficient electric vehicle (EV) charging systems has emphasized the need for high-performance DC-DC converters capable of maintaining high efficiency under wide load variations. This project presents a Hybrid Control Method for a Full-Bridge LLC Resonant Converter designed to enhance efficiency and stability in EV charging applications. The proposed approach combines Pulse Width Modulation (PWM) and Burst Control to address limitations in excitation current and narrow output voltage range under light-load conditions. By utilizing the resonant current energy during the burst-on period to support zero-voltage switching (ZVS) in PWM mode, the hybrid control achieves reduced switching losses, improved electromagnetic interference (EMI) characteristics, and a wider output voltage range. Furthermore, a PFM + PWM-Burst hybrid strategy is implemented to optimize performance under both light and heavy load conditions. Simulation results obtained using MATLAB/Simulink confirm that the proposed method effectively achieves ZVS operation, minimizes output ripple, and significantly improves converter efficiency across the full load range, making it well-suited for advanced EV charging systems.

INDEX TERMS Burst control, electric vehicle, LLC resonant converter, PFM control, PWM control.

I. INTRODUCTION

The rapid advancement of electric vehicles (EVs) has intensified the demand for efficient and reliable charging systems. The DC–DC converter, which serves as a critical component in the EV charger, must ensure high conversion efficiency across a wide load range while maintaining stable operation under varying input and output conditions. Conventional DC–DC converters, however, often suffer from large current stress, reverse power flow, and limited output voltage regulation, especially under light-load conditions.

The LLC resonant converter has attracted considerable attention due to its inherent advantages of high efficiency, soft-switching capability, and bidirectional energy transfer. It effectively minimizes switching losses and enhances power density, making it suitable for EV charging applications. Nonetheless, maintaining high efficiency and a wide output voltage range remains challenging under light-load operation. Common control strategies, such as pulse frequency modulation (PFM), pulse width modulation (PWM), phase-shift modulation (PSM), and burst control, exhibit limitations when applied individually. These issues include restricted voltage regulation range, poor zero-voltage switching (ZVS) performance, and increased electromagnetic interference (EMI).

To address these challenges, this study proposes a hybrid control strategy for a full-bridge LLC resonant converter that integrates PWM and Burst control techniques. The proposed method aims to maintain ZVS operation, minimize switching losses, and enhance converter performance across a wide load range, thereby improving the overall efficiency and reliability of EV charging systems.

II. LITERATURE REVIEW

Several studies have investigated methods to enhance the performance of LLC resonant converters. A hybrid PFM–PWM control strategy was introduced in [13] to achieve low voltage gain under light-load conditions; however, this approach failed to improve soft-switching performance, thereby limiting voltage regulation. The Phase-Shift Modulation (PSM) technique, as discussed in [8], [14]–[16], effectively reduced transformer core losses and adjusted output voltage, but large phase shifts adversely affected soft-switching and converter reliability under light-load conditions. The phase-shedding method, proposed in [19] and [20], improved light-load efficiency by reducing the number of active transformer phases, though it was applicable only to multi-transformer systems. The Burst control technique presented in [21] and [22] converted continuous switching operation into intermittent mode, thereby reducing switching losses and input voltage stress. However, Burst control significantly increased output voltage ripple and degraded EMI performance. Some researchers combined Burst control with other modulation techniques to enhance the voltage regulation range. For example, the Burst–PSM hybrid control method in [21] offered improved regulation but increased circuit complexity. Despite these advancements, existing control strategies are unable to simultaneously achieve wide voltage regulation and high efficiency across all operating conditions. To overcome these limitations, the present work proposes a PWM-Burst hybrid control strategy, which merges the advantages of PWM and Burst control while mitigating their individual shortcomings. By utilizing the resonant current energy during the Burst-on phase to sustain ZVS in PWM operation, the proposed approach significantly enhances conversion efficiency, reduces switching losses, and ensures stable voltage regulation across a wide operating range. This makes the hybrid control method particularly suitable for full-bridge LLC resonant converters in EV charging systems.

III. CONCEPT OF THE PROPOSED SYSTEM

The proposed system introduces a hybrid control method that combines PWM and Burst control for the full-bridge LLC resonant converter to overcome the limitations of conventional control techniques. Under light-load conditions, PWM control alone experiences insufficient excitation current, preventing the converter from achieving ZVS, which leads to increased switching losses and reduced efficiency. On the other hand, Burst control can effectively reduce switching losses by intermittently operating the converter but introduces voltage ripple and poor EMI characteristics. In the proposed hybrid control method, PWM pulses are generated during the Burst-on period, allowing the resonant current energy accumulated in this period to assist the ZVS process of the PWM control. This approach compensates for the limited excitation current in PWM mode, reduces output voltage ripple, and improves EMI performance. Moreover, the hybrid method widens the output voltage regulation range and enhances conversion efficiency.

To further improve performance under various load conditions, the system integrates a PFM + PWM-Burst hybrid control strategy. In this configuration, PFM control is employed under heavy-load conditions to provide adjustable frequency regulation, while PWM-Burst control is used under light-load conditions to sustain ZVS and reduce circuit losses. This dual-mode hybrid operation ensures efficient and stable performance across the entire load spectrum, making it highly suitable for EV charging applications.

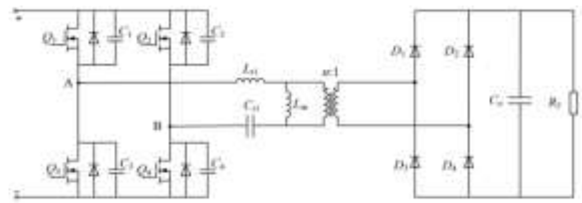

FIGURE 1. Full-bridge LLC resonant converter topology.

The proposed full-bridge LLC resonant converter consists of a full-bridge inverter on the primary side and a full-bridge rectifier on the secondary side. The inverter is composed of four MOSFET switches (Q1–Q4) that operate in complementary pairs (Q1 with Q3, and Q2 with Q4) to generate alternating voltage at the input of the resonant tank. The resonant network includes a resonant inductor (Lr), a resonant capacitor (Cr), and a magnetizing inductor (Lm), which together form the resonant cavity. On the secondary side, rectifier diodes convert the AC output from the transformer into DC, while a filter capacitor (Co) smooths the rectified output to provide a stable DC voltage. When the converter input is connected to the rated DC voltage, the full-bridge inverter generates alternating positive and negative voltages that excite the resonant network. The resonant circuit shapes the current waveform and ensures zero-voltage switching (ZVS) of the MOSFETs, thereby minimizing switching losses. The rectifier and filter stages then produce a regulated DC output voltage suitable for EV battery charging applications. The converter's design achieves high efficiency and low electromagnetic interference (EMI) by utilizing the resonance between Lr and Cr for soft-switching operation, while Lm provides energy storage and stabilizes the converter dynamics.

B. Burst Intermittent Control

Burst control, also known as intermittent control, is a method used to reduce switching losses by periodically enabling and disabling the converter's switching operation.

During the "burst-on" period, the MOSFETs conduct normally, transferring energy to the load; during the "burst-off" period, the switching activity ceases, and the output voltage is maintained by the filter capacitor.

The resonant current during the burst-on phase can be expressed as:

$$i_{r1}(t) = \frac{U_{in1}(t) - U_{out1}(t)}{jX_r} \quad (1)$$

where Xr represents the equivalent reactance of the resonant cavity, defined as:

$$X_r = \omega_s L_r - \frac{1}{\omega_s C_r} \quad (2)$$

Here, ωss is the switching angular frequency. The resonant current ir(t) varies inversely with the output voltage during the burst-on period; as the output voltage increases, the resonant current decreases. However, under low output voltage conditions, the increase in resonant current can lead to higher flux in the inductors, resulting in greater output voltage ripple and increased losses, especially under light-load operation.

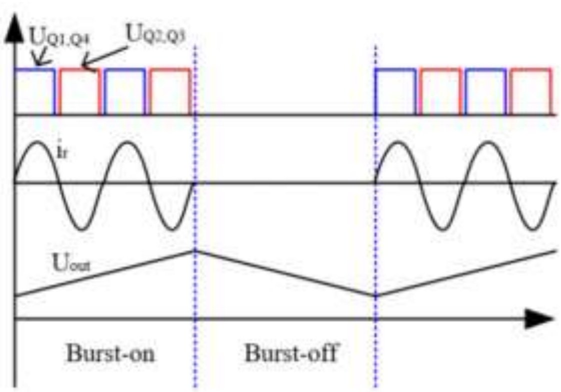

FIGURE 2. Typical waveform of Burst control

C. PWM Control

In Pulse Width Modulation (PWM) control, the duty cycle of the inverter's switching signals determines the energy delivered to the load. At high load conditions, the excitation current is sufficiently large to maintain ZVS, ensuring smooth switching transitions and reduced losses. However, at light-load conditions, the excitation current decreases, resulting in smaller duty cycles and making ZVS difficult to achieve. This can lead to hard-switching events, increased switching losses, and degraded EMI performance.

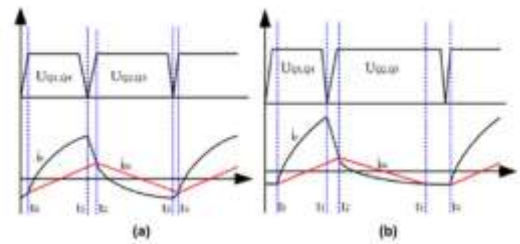

FIGURE 3. PWM control waveform.

PWM control is therefore effective under medium to heavy load conditions but becomes inefficient and unstable at light loads, necessitating an auxiliary control strategy to maintain performance.

D. PWM–Burst Hybrid Control

To overcome the limitations of both PWM and Burst control methods, a PWM–Burst hybrid control strategy is proposed. In this method, PWM control pulses are generated during the burst-on period. The excessive resonant current available during the burst-on interval provides additional excitation energy for achieving ZVS in PWM operation. This compensates for the insufficient excitation current typically encountered in pure PWM control. By partially converting the energy from the Burst mode into PWM control, the proposed hybrid strategy reduces the energy delivered to the secondary side, thereby lowering output voltage ripple and improving EMI performance. This also expands the converter's output voltage range and enhances its efficiency under light-load conditions. The hybrid control employs a double closed-loop control structure with nested PI controllers: The outer voltage loop regulates the output voltage by providing negative feedback. The inner current loop controls the resonant current amplitude. The logic unit combines the two control signals to generate a PWM–Burst control pulse that optimizes the switching behavior for each load condition.

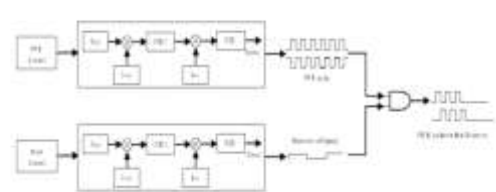

FIGURE 4. The principle diagram of PWM-Burst control.

E. PFM + PWM–Burst Hybrid Control

For full-range operation, the converter integrates PFM (Pulse Frequency Modulation) and PWM–Burst hybrid control methods. Under heavy-load conditions, PFM control is employed, using a fixed duty cycle with variable frequency to maintain high efficiency and stable ZVS operation. Under light-load conditions, PWM–Burst control is activated to reduce switching losses and maintain soft-switching characteristics.

SIMULATION AND RESULTS

The proposed PFM + PWM-Burst hybrid control method for the full-bridge LLC resonant converter was simulated using MATLAB/Simulink to verify its performance and feasibility in electric vehicle (EV) charging applications. The converter model was developed with the parameters and control structure described in the previous sections. The simulation aimed to evaluate the converter's dynamic behavior, zero-voltage switching (ZVS) characteristics, and output performance under various load and voltage conditions.

The converter was designed to operate within a wide output voltage range of 200 V to 750 V and an output current range of 0 to 75 A, reflecting typical EV charging scenarios. Three operating regions were defined according to the load conditions:

Region A (Heavy Load) – PFM control,

Region B (Medium Load) – PWM control at a fixed frequency of 150 kHz, and

Region C (Light Load) – PWM-Burst hybrid control.

During simulation, different voltage levels of 200 V, 460 V, 600 V, and 750 V were selected to represent light, medium, and heavy load conditions. Parameters are illustrated in Table 1

TABLE 1 parameters

Parameter	Symbol	Value	Description
Input Voltage Range	(U_{in})	400 V (nominal)	DC input voltage to converter
Output Voltage Range	(U_{out})	200 V – 750 V	Regulated DC output range
Output Current Range	(I_{out})	0 – 75 A	Corresponding load current range
Rated Output Power	(P_{out})	15 kW	Simulation model rated power
Resonant Frequency	(f_r)	153 kHz	Natural resonant frequency of LLC tank
Switching Frequency Range	(f_s)	100 kHz – 250 kHz	Converter operating frequency range
Resonant Inductor	(L_r)	(From optimized design	Part of resonant tank circuit
Magnetizing Inductor	(L_m)	(From optimized design)	Provides excitation current
Resonant Capacitor	(C_r)	(From optimized design)	Forms resonant network with (L_r)
Filter Capacitor	(C_o)	470 μF	Output filter capacitor
Transformer Turns Ratio	(n)	4:1	Primary-to-secondary turns ratio
Control Modes	–	PFM / PWM / PWM-Burst	Mode selection by load condition
PWM Switching Frequency	(f_{PWM})	150 kHz	Fixed frequency in PWM region
Burst Duty Range	(D_{burst})	0.3 – 0.7	Duty ratio during burst operation

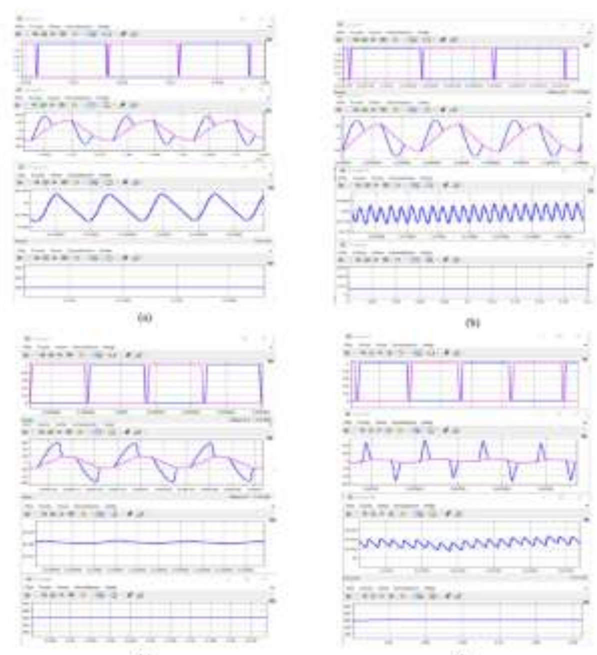

Fig 5 Simulation results. (a) 750V output voltage. (b) 600V output voltage. (c) 460V output voltage. (d) 200V output voltage.

The corresponding output currents were approximately 12 A, 27.6 A, 40.8 A, and 45 A, respectively. The results confirmed that the proposed converter achieved stable operation and maintained continuous regulation across the full voltage range. The waveforms obtained from simulation included the drive signals, resonant current, excitation current, output current, and output voltage. Under heavy load conditions (Region A), the converter operated in PFM mode, maintaining a stable output and achieving soft-switching across the bridge switches. Under medium load conditions (Region B), PWM control maintained constant frequency operation with smooth current and voltage waveforms, showing low ripple and stable ZVS. Under light load conditions (Region C), the PWM-Burst hybrid control successfully reduced switching losses while maintaining output voltage stability as shown in Figure 5 The resonant current during the burst-on period provided the required excitation energy to achieve ZVS, compensating for the low excitation current typically seen in conventional PWM control. The simulation results demonstrated that the proposed hybrid control method effectively reduces output voltage ripple, enhances EMI performance, and achieves high conversion efficiency across all load ranges. Moreover, the smooth transition between different control modes ensured stable operation without oscillation or distortion in output waveforms. Compared with traditional PWM control, the PWM-Burst hybrid method achieved better voltage regulation under light-load conditions and significantly improved soft-switching characteristics.

Performance Analysis

To further evaluate the effectiveness of the proposed control strategy, a comparative performance analysis was conducted between the conventional PWM control and the proposed PWM-Burst hybrid control under identical load and voltage conditions. The comparison was focused on key performance indicators such as efficiency, output voltage ripple, zero-voltage switching (ZVS) behavior, and dynamic stability across different load regions.

The simulation results show that under heavy-load conditions, both PWM and PWM-Burst control methods achieve satisfactory performance. However, under light-load conditions, the conventional PWM control fails to maintain ZVS due to insufficient excitation current. This leads to hard-switching operation, resulting in higher switching losses, increased device stress, and reduced converter efficiency. In contrast, the proposed PWM-Burst hybrid control effectively maintains ZVS during the burst-on interval by utilizing the resonant current energy to supplement the missing excitation current. This mechanism minimizes switching losses and enhances the converter's reliability and electromagnetic interference (EMI) characteristics.

The hybrid control strategy also significantly improves voltage regulation. The inclusion of burst intervals reduces unnecessary energy transfer to the secondary side, thereby decreasing the output voltage ripple and ensuring stable DC output even under rapidly changing load conditions. Additionally, the proposed system maintains smooth transitions between the PFM, PWM, and PWM-Burst regions without introducing current overshoot or waveform distortion, ensuring seamless operation across the entire load range.

Efficiency analysis indicates that the proposed PWM-Burst hybrid method maintains higher efficiency over a broader load range. At loads below 70% of the rated power, the PWM-Burst control exhibits noticeably better performance, maintaining efficiency close to its nominal value, while the traditional PWM control experiences a significant drop. This improvement is attributed to the reduction in switching losses and the elimination of hard-switching events during low-power operation.

Overall, the simulation results confirm that the PFM + PWM-Burst hybrid control method enhances both efficiency and dynamic stability of the full-bridge LLC resonant converter. It successfully achieves wide voltage regulation, soft-switching operation across all load conditions, and reduced EMI interference, making it a highly effective and energy-efficient control solution for next-generation electric vehicle charging systems.

CONCLUSION

This paper presented a hybrid control method for a full-bridge LLC resonant converter applied to electric vehicle (EV) charging systems. The proposed control strategy combines Pulse Width Modulation (PWM) and Burst control to overcome the inherent limitations of conventional control techniques under light-load conditions. By using the resonant current energy generated during the burst-on period to assist the PWM stage, the hybrid control enables continuous zero-voltage switching (ZVS), effectively reducing switching losses and enhancing system efficiency.

The control system further integrates Pulse Frequency Modulation (PFM) for heavy-load operation and PWM-Burst control for light-load operation, ensuring smooth transitions across all load regions. Simulation results obtained using MATLAB/Simulink demonstrate that the proposed PFM + PWM-Burst hybrid control significantly improves output voltage regulation, efficiency, and electromagnetic interference (EMI) performance compared to conventional PWM control. The converter maintains stable output operation across a wide voltage range (200–750 V) and achieves high efficiency under varying load conditions, confirming the adaptability of the control scheme.

Overall, the proposed hybrid control method provides a reliable and energy-efficient solution for EV charging converters, achieving wide voltage regulation, improved light-load performance, and enhanced ZVS characteristics. These advantages make the technique particularly suitable for modern high-efficiency, high-power-density EV charging applications and can be further extended to other resonant converter topologies in renewable energy and power electronic systems.

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