

Abstract

In the rapidly advancing domain of energy storage and power electronics, soft-switching converters have risen as transformative technologies, redefining the future of battery charging systems across diverse applications. These innovative power conversion solutions herald a new era in energy management, delivering unmatched efficiency, reliability, and precision. From powering portable electronic devices to enabling robust charging infrastructure for electric vehicles and renewable energy storage, soft-switching converters embody a leap forward in engineering. By harmonizing state-of-the-art performance with sustainable design, they lay the foundation for a smarter, more eco-friendly energy ecosystem, setting new benchmarks for the future of energy systems.

The core significance of soft-switching converters lies in their remarkable ability to mitigate switching losses, a persistent challenge in traditional hard-switching power conversion methods. In conventional power electronic systems, semiconductor switches endure considerable energy losses during the transition between on and off states, leading to heat generation and reduced system efficiency. Soft-switching converters overcome this limitation through advanced switching techniques that significantly reduce instantaneous power dissipation during these transitions. As a result, they enable substantially higher energy conversion efficiency, making them a pivotal innovation in modern power electronics.

A key innovation in this area is the bidirectional converter, which seamlessly integrates soft-switching with bidirectional power flow capabilities. This converter is crucial for applications that demand efficient energy storage and retrieval, such as electric vehicle battery charging and renewable energy storage. It enables smooth energy transfer for both charging and discharging, effectively managing power between the AC grid and the battery. By leveraging soft-switching techniques, the converter minimizes switching losses during both charging and regeneration, significantly enhancing efficiency and extending the lifespan of components. This makes it a perfect solution for next-generation energy systems requiring efficient power cycling. Specifically, the AC-DC Bidirectional Dual Active Bridge (DAB) converter further amplifies these benefits, optimizing power

conversion with enhanced efficiency, reliability, and flexibility transforming the way energy systems perform and evolve. Advanced modulation techniques play a crucial role in achieving these enhancements, enabling precise control and superior performance.

However, while these advanced modulation techniques significantly enhance the features and performance of the AC-DC bidirectional DAB converter, they also introduce added complexity at the microcontroller implementation level, such as managing a large number of control variables, utilizing multiple carriers, non-linear power relationship, necessitate close-loop to achieve power factor correction and requiring extensive analytical calculations, all of which lead to higher computational costs. This research addresses a critical gap in the literature that often overlooks minimizing computational burden a key factor in enabling the design of custom microcontrollers with lower resource requirements and reduced costs. By tackling this challenge, the study aims to strike an optimal balance between performance and practicality, paving the way for efficient and cost-effective solutions in modern power electronics systems.

To address these research gaps, an innovative triangular modulation technique (TRM) for a DC-AC bidirectional matrix-type DAB converter that overcomes challenges such as the need for multiple control variables, dependence on multiple carriers, and the complexities of non-linear power relationships, which often require closed-loop control to achieve power factor correction. The proposed method employs a sinusoidally modified variable frequency PWM, also known as an asymmetrical switching sequence, to modulate one leg of the H-bridge. This enables true soft-switching by precisely shaping the transformer current and controlling the transformer voltage. The technique simplifies implementation by utilizing a single carrier and is demonstrated digitally on the F28335 MCU, presenting its practicality and efficiency. By eliminating the reliance on complex analytical calculations, the TRM enhances performance and ensures soft-switching across the entire operating range of the converter while maintaining an open-loop power factor. Experimental validation of Method 1, tested at a power level of 500 W for the DC-AC bidirectional DAB converter, highlights its effectiveness in vehicle-to-grid (V2G) and grid-to-home (G2H) applications.

The application of the proposed TRM technique is further investigated for a distinct topology, specifically a 500 W prototype of Quasi Single Stage (Q1S) bidirectional AC-DC DAB converter with an intermediate capacitor. This exploration emphasizes maintaining performance while significantly reducing computational complexity further. By employing an asymmetrical switching sequence-based TRM, the study highlights how minimizing the number of distinct PWM signals can simplify control strategies. The approach stresses the importance of aligning modulation techniques with the

chosen topology to optimize control performance and achieve enhanced benchmarks. Implemented on the Texas Instruments TMS320F28335 microcontroller, this method demonstrates its capability to improve efficiency without compromising essential factors such as soft-switching performance and power quality, further setting a new benchmark in modulation design.

Another key challenge addressed in this research pertains to the high RMS current that leads to increased conduction losses, particularly under light load conditions, which affects both the proposed TRM and other existing TRM modulation techniques. While the phase-shift ratio exhibits a linear relationship with power transfer, the RMS current decreases non-linearly as the phase-shift ratio is reduced to supply power at light loads. This non-linear reduction in current results in higher conduction losses in relation to the output power, negatively impacting overall converter efficiency, especially in battery charging applications. Despite successfully achieving soft-switching during both turn-on and turn-off operations, the TRM modulation scheme still suffers from reduced efficiency at light loads due to these non-linear conduction losses. This work investigates these challenges in detail and explores effective solutions, proposing an improved Method 1 to enhance performance under light load conditions and mitigate these losses using a 500W prototype of Quasi Single Stage (QS^2) bidirectional AC-DC DAB without an intermediate capacitor. Additionally, the proposed modulation significantly reduces total harmonic distortion and current stress at light loads, ensuring better performance.

This research further explores the DC charging system, featuring an innovative adaptive optimal power management scheme for a hybrid energy input-based DC charging setup. This scheme efficiently integrates different energy sources, optimizing power distribution to significantly enhance system efficiency and overall performance. A key highlight is its capability to optimize photovoltaic (PV) power, reducing grid power consumption while ensuring seamless transitions between various modes without disrupting load demand. Additionally, the system supports DC fast charging for Erickshaw batteries, providing rapid dynamic control and high-quality power. This idea is verified on a technology readiness level -6 prototype with a peak rating of 10 KVA.

These works offer an innovative approach to power conversion and energy management, focusing on TRM techniques for bidirectional DC-AC DAB converters, optimizing computational complexity, TRMs realization and enhancing soft-switching performance. They also highlight the integration of adaptive power management in DC charging systems, optimizing photovoltaic power, and improving efficiency in light-load conditions. With a focus on system efficiency, power factor optimization, and renewable energy integration, this research provides key insights into the future of power electronics.

