RESONANT DUAL ACTIVE BRIDGE BASED MULTI-MODE POWER PROCESSORS FOR ELECTRIC VEHICLE CHARGING APPLICATIONS

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By

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6.1 Introduction

High-efficiency battery chargers play a vital role in accelerating EV adoption. A battery charger primarily consists of a DC/DC converter, and its efficiency is predominantly affected by the semiconductor losses, that comprise of the conduction losses and the switching losses. The dual active bridge converter employing resonant tank networks forms an attractive choice of converter for EV battery charging by specifically targeting switching losses through soft-switching techniques.

However, an optimal battery charging further requires precise current and voltage control, such as CC-CV mode, to ensure fast charging time with minimal battery degradation. The traditional methods of achieving this objective require a dedicated controller that adds to the complexity, cost, and overall response delay in the system. To address this issue, a current-driven bi-frequency resonant dual active bridge converter that inherently behaves as a current source and voltage source at two different frequencies is proposed in this thesis.

Further, longer charging times result in range anxiety among long-route consumers. Whereas, the limited charging infrastructure, high establishment cost, inefficient high-speed charging demands high-power charging, such as ultra-fast charging UFC. However, with hundreds of kWs of charging power, the traditional full-power processing resonant DAB converter becomes insufficient to cope with the high voltage-current stress and high-power losses. As a solution, this thesis proposes a current-driven fractional power processor for UFC applications

Moreover, EVs evolving for long-distance and intercity travel are faced with a diverse charging network with varying available charging voltage. Also, EVs require additional converters on board to supply their auxiliary loads, and charge another vehicle from its battery to provide emergency backup. To address these, an onboard charger with bidirectional capability acting as an interface can effectively solve the problem of compatibility between the available charger and the battery, as well as eliminate the separate converter requirement to minimize system cost, size, and losses.

Further, the lack of industry-wide standardization results in a wide range of battery voltages employed in EV batteries. The fractional power processing concept is of significant importance in applications dealing with high power levels. However, its implementation in the practical EV landscape becomes challenging due to the wide range of batteries available in the market. The conventional approach to extend the available charging voltage range requires converter design to be done for relatively large power, defeating the benefits of the FPP concept. To solve the above challenges, a solution to extend the high-efficiency charging range is required. In addition, to facilitate both higher and lower battery voltage charging and discharging while fractionally processing total power, a quad-operational fractional power processor is necessary.

To address the limitations of the resonant dual active bridge converter in achieving the above objectives, this thesis proposes resonant dual active bridge-based multi-mode power processors for electric vehicle charging applications that subsequently target each of the challenges in EV adoption. This chapter summarizes the conclusions of the work carried out in this thesis. Also, a brief note about the future scope of the work is included in this chapter.

6.2 Conclusion

To curb the challenges in converter control for achieving optimal CC-CV battery charging, a current-driven bi-frequency resonant dual active bridge converter is proposed in this thesis. The proposed charger forms an equivalent parallel resonant tank and therefore inherently behaves as a current source and a voltage when operated at the resonant frequency and half the resonant frequency, respectively. To study the dual-source property of the proposed converter, the trajectories of the converter in each interval of operation are derived using state plane analysis, and the load characteristics on the normalized plane are plotted, which verifies the CC-CV behavior of the proposed charger. Its operation at two different but fixed frequencies to behave as a CC-CV charger simplifies magnetic design, and eliminates the requirement of a dedicated controller, thereby making it a suitable choice of converter for optimal battery charging. Further, the complexity in the implementation of the charging strategy, the memory requirement, the associated cost, and the delay are eliminated, along with an improvement in the converter reliability. To validate the converter's performance, a 500 W laboratory prototype of the converter is developed and tested for both CC and CV modes. The experimental results validate the current source and voltage source properties of the converter, and its dynamic performance establishes the robustness of the proposed charger during mode transition. The converter achieves ZVS turn-on for primary and secondary switches in CC mode, whereas it achieves ZVS turn-on for primary switches in CC mode and ZCS turn-on and turn-off of secondary switches in CV mode. The converter achieves an efficiency of 96.18 % at 500 W.

To address the challenges relating to UFC, this thesis proposes a novel current-driven fractional power processing-based resonant DAB converter. As the converter of the proposed ultra-fast charger handles only a fraction of the total power delivered to the battery, the converter's power rating is significantly reduced. The proposed charger achieves ZVS for the entire range of battery voltage and fractionality ratio, ensuring high efficiency battery charging throughout the range, and operates with reduced inductor size due to differential input. Further, due to its current-driven nature and resonance operation, the proposed charger offers simple yet robust battery current regulation while eliminating the need for any complex controller. The operation of the proposed charger is discussed in detail, and its performance for ultra-fast charging applications is analyzed in this chapter. The behavior of the charger and its control performance are experimentally verified through a 1.32 kW laboratory developed charger prototype. The results validate that the proposed charger has reduced current and voltage stress and achieves soft-switching for the entire range. This provides an opportunity to select low-rated, less costly, and more efficient components. Further, dynamic performance verifies that the proposed charger can efficiently charge in CC mode for a wide range, as desired in the UFC application, by varying a single control variable, thus minimizing the control requirement.

This thesis further proposes an interoperable multi-utility fast charger based on a resonant dual active bridge converter that provides the flexibility to charge the vehicle battery from any of the available charging facility, i.e., ac, dc level 2 or fast charging including both low voltage outlet in rural and high voltage interface at highway charging network.

To achieve this objective, the proposed charger performs high-efficiency fast charging by using only an OBC-rated dc/dc converter that supports EV auxiliary loads and enables quick V2V charging only by performing a single-step frequency change and phase-shift control. The proposed charger performs all the above functions without requiring additional components or over-stressing existing components. Additionally, the multi-stage CC charging strategy and smooth voltage and current regulation are achieved in each mode by utilizing simple control without requiring a dedicated complex controller. The converter achieves soft-switching for all the switches in each mode of operation, ensuring high efficiency operations and minimizing heat sink requirements. The proposed interoperable multi-utility fast charger is an efficient and versatile solution to futuristic EV applications.

To solve the challenges of fractional power processors relating to limited voltage range, this thesis proposes a novel quad-operative fractional power processor that extends the battery charging capability to both buck and boost mode operation, enabling wide voltage range for EV charging. The proposed charger can operate with both positive and negative converter output voltage by utilizing bipolar switches at its output bridge. The proposed charger utilizes the current driven resonant dual active bridge converter that ensures soft-switching of both the primary and the secondary bridge switches further eliminating the turn-on switching losses. Additionally, the converter experiences low voltage and current stress across its semiconductor switches allowing low rated switches and lesser conduction losses. The converter operation is verified through simulations for 50 and 350 V battery. Experimental validation of the proposed concept is presented using a scaled down laboratory prototype.

6.3 Scope of Future Work

- The current driven bi-frequency resonant DAB converter is tested for 500 W at laboratory scale with Si switches. Its operation at high power and SiC switches will be studied. To completely exploit the bi-directional nature of the charger it will be integrated with AC/DC PFC stage and tested for reverse power flow to ensure grid to vehicle (G2V) and (V2G) power transfer operation.
- The performance of current driven fractional power processor is verified for 120 V battery with 1.3 kW laboratory developed prototype. Its performance validation with market available EV battery of approximately 350 V will be carried out at

higher power level. Further, the stress analysis of current driven fractional power processor is studied based on current and voltage appearing across switching devices. In future, its thermal testing to understand the heat generation in converter and direct path will be studied.

- The performance of complete interoperable multi-utility fast charger will be studied including the AC/DC conversion stage and integrated prototype will be developed to demonstrate automatic mode selection between AC charging, DC fast charging, V2Aux and V2V mode.
- The quad operative fractional power processor will be studied for performance operation in wide range of fractionality ratio and the operation of converter near zero fractionality, i.e., very low output voltage will be studied.