Abstract

Despite the sharp growth in the number of EVs on road, the adoption of electric vehicles faces several significant challenges hindering their widespread acceptance. Challenges pertaining to battery charging include stringent current and voltage regulation requirements for lithium-ion (Li-ion) batteries, prolonged battery charging time, range anxiety among long route travelers, lack of flexible and ultra-fast charging infrastructure, diversity in urban and rural charging networks, and concern over fleet reliability, etc. In addition, the lack of efficient power conversion for on-board demands and the need for solutions to enable EVs as a load form some of the major areas attracting academia and industry research interest in recent years.

Li-ion batteries form a core component of an EV and have been a focal point of research in recent years. However, maintaining precise current and voltage regulation is essential as poor regulation can accelerate battery degradation and increase the risk of thermal runaway, potentially leading to EV battery fires. Its implications also raise safety concerns among potential users and impact consumer confidence in EV technology. To ensure proper regulation, traditionally, charging is done at constant current (CC) or constant voltage (CV). However, CC charging at low current results in longer charging time, whereas higher current towards the end of charging results in high conduction losses arising from exponential rise of battery internal resistance. In contrast, CV charging has a challenges of battery damage due to high inrush current at the beginning of the charging period.

To prevent these adverse occurring, optimal charging strategy such as the constant current constant voltage (CC-CV) charging is deployed where the battery is initially charged at constant current to ensure faster charging time while it is switched to constant voltage charging towards end to prevent battery overcharging. Traditionally, resonant dual active bridge converters are employed for battery charging due to their high efficiency, soft-switching and simpler structure. However, any converter predominantly either behaves as a voltage source or a current source and thereby require dedicated controller to obtain the constant current and constant voltage necessary to implement CC-CV charging. This controller adds to the cost, loss, complexity and delayed response time of the overall system. In addition, the converters obtained from topological modification to achieve both current and voltage source property either require additional components

or suffer from efficiency drop for wide operation range as required in battery charging. Further, the use of electrolytic capacitor makes charger reliability a cause of concern due to their relatively shorter lifetime.

Apart from the optimal battery charging, the longer charging time, limited charging infrastructure, and range anxiety significantly deters the consumer confidence in EVs. Ultra-fast charging (UFC) is the newest concept addressing this challenge by making the battery charging time comparable to refueling time, i.e., of the order of few minutes. It refers to charging power level of the order of 350 kW to quickly replenish the battery charge, typically implemented through multi-stage constant current charging approach. However, this reduced time comes at the cost of high current, likely up to 400 A which brings the disadvantage of high conduction losses across converter components, eventually requiring large heat sink and thermal management, thereby degrading the power density. In addition, the component cost, availability, and essential battery current control becomes challenging for designing converter of such high-power rating. Recent literatures established fractional power processing (FPP) as the quantum jump in improving charger efficiency and ensuring cost reduction by processing only a part of power through the converter while transferring the rest of the power directly to the battery. However, the reported approaches do not enable bidirectionality, suffers from hard-switching, efficiency drop at light load, and lacks smooth current control.

While charging capacity, cost, compact design, and efficiency of the battery charger are the major driving force of charger evolution, the new-generation of battery chargers focus on their inter-operability and multi-utility nature. Inter-operability refers to their ability to interface with any available charging facility, i.e., level 1 or level 2 ac slow charging as well as dc fast charging. Whereas, multi-utility refers to catering multiple demands of EV ecosystem, ranging from its auxiliary loads to providing emergency backup to another EV. Incorporating these multiple paradigms while ensuring affordable cost and high efficiency have been a significant cause of concern for the EV design researchers. With EVs evolving towards becoming long range travel option, a challenge in interfacing high power battery to interface with any charging facility, i.e., rural charging networks with low voltage interface or highway network rated at high voltage high power output is often faced due to the voltage range mis-match. Voltage matching between dc fast charger output and battery is achieved by operating the on-board charger (OBC) dc/dc stage as an interface. However, the onboard charger with its limited rating cannot handle the entire power. Additionally, the high voltage battery pack has to supply various EV auxiliaries (V2Aux) that is traditionally regulated through a separate dc/dc converter, which takes up additional space and adds up to the charger cost. As a solution, some recent works reports reutilizing charger's dc/dc converter to supply auxiliaries. However, operation at low voltage and light load as required in vehicle to auxiliary mode reports degraded efficiency of converter designed for high power charging. Additionally, vehicle to vehicle (V2V) charging is another approach to alleviate the range anxiety and address fear of being stranded with uncharged battery. Many works report supplying V2V through multiple conversion stages that degraded the conversion efficiency. The current literature lacks any on-board charger that offers the flexibility to charge between ac slow charging, dc fast charging and support V2Aux and V2V operation through a single converter.

Further, the increasing EV adoption has also intensified competition among manufacturers for developing innovative and efficient charging technologies. However, the absence of industry wide standardization has led to wide range of battery voltage, available across different EV models in market. This diversity in battery specification creates a strong demand of power processor capable of efficiently delivering wide voltage range loads. Moreover, with vehicle-to-everything (V2X) gaining attention as a means of improving reliability through optimal energy management and grid stabilization, a pressing need for a versatile charger that can operate in forward, reverse as well as buck and boost mode, all while operating only fraction of power to deliver significantly higher power, collective referred as quad-operative battery charger, is identified. Most of the FPP chargers either performed step-up or step-down charging due to unipolar switches at the differential voltage port of FPP charger. Some works report use of unfolder circuit and back-to-back connected diode to extend the charger capability to both buck and boost mode, however the former results in efficiency degradation while later restricts the four-quadrant operation.

In order to solve the above issues, this thesis proposes different resonant dual active bridge-based power processors to optimally charge the battery with reduced control complexity and achieve high power efficient battery charging operation. The proposed battery chargers are briefed in the following paragraphs.

A novel current-driven bi-frequency resonant dual active bridge converter for efficiently charging a battery in constant current–constant voltage (CC-CV) mode is proposed in this thesis. The novel converter gives the freedom to operate without complex control, while ensuring stable voltage and current regulation to achieve CC-CV charging. In the proposed configuration, the switching states causes the converter to form an equivalent parallel resonant tank which facilitates the proposed converter to behave as a current source and a voltage source using single step change in frequency and thus, offering dual source property at its output. This results in reduction of control complexity and the associated cost. In addition, the problem of input current ripple is eliminated and converter reliability is improved due to replacement of electrolytic capacitor by a resonant film capacitor. The behavior of converter is analyzed through state-plane analysis and trajectory of each interval with the closed form solution is presented. The performance of the proposed charger is compared with the earlier reported literatures. To further verify the behavior of the proposed converter a scaled-down 500 W experimental prototype is developed and the experimental results are presented for both CC and CV charging mode.

In order to address the challenges related to ultra-fast charging, a novel current driven fractional power processor with resonant DAB converter, suitable for efficient ultra-fast charging applications is proposed in this thesis. The processor configuration allows only a fraction of power to be processed through the converter, thereby reducing the current and voltage stress across components. This presents an opportunity to achieve reduced component rating along with decreased losses while transferring bulk power through a series path to achieve highly efficient battery charging. The proposed charger achieves zero voltage switching (ZVS) for entire range of charger operation ensuring high efficiency through-out the load range. It further offers robust battery current regulation and reduction in size of magnetics due to differential current configuration at the input. The operation of converter and its performance as UFC are discussed in details with mathematical model. The performance of the proposed converter is validated through 1.32 kW scaled-down laboratory developed prototype. Its performance is compared in details with conventional and presented in this thesis.

With an aim to develop an efficient, flexible and compact power processor this thesis proposes a novel interoperable multi-utility charger capable of performing high efficiency fast charging, supplying EV auxiliaries (V2Aux), and charging vehicle to

vehicle (V2V). In the fast-charging mode, the dc/dc converter is configured such that only the on-board charger rated power is processed through the converter while the bulk power is transferred directly through a series path. Thus, facilitating the OBC to perform fast charging by increasing the charger capability significantly (up to 4 times) while achieving reduced component rating, much lower losses, lower cost and high efficiency charging compared to conventional fast chargers. Moreover, the converter operates at resonant frequency to behave as a current source at the output facilitating multi-stage constant current (CC) charging, without requiring any complex controller, as desired in fast charging operation. In the V2Aux mode, this converter operates with reverse power flow at half the resonant frequency to behave as a voltage source and supplies the vehicle auxiliaries. Further, the same converter charges another vehicle by operating at resonant frequency with reverse power flow to support quick CC V2V charging. The versatile nature of the proposed charger to operate in fast charging, V2Aux and V2V modes without requiring additional components while only rated for OBC power makes it an efficient and cost-effective interoperable multi-utility charger. The operation of the converter in each mode is presented in details and the design criterion is discussed. The proposed concept is verified with a laboratory developed 1 kW charger with efficiency of 98.87 % in fast charging mode and 98.12 % in V2Aux and 97.2 % in V2V mode, and the performance is verified for dynamic load. A comparison with the other existing literature is also presented.

To extend the charging capability of resonant DAB based fractional power processor to wide voltage range this thesis proposes a quad-operative fractional power processor that extends the operational range of the FPP charger to four quadrants. This enables seamless handling of both charging and discharging modes, encompassing both step-up and step-down voltage conversion while maintaining the advantages of fractional power processing. The use of bipolar switches enables positive as well as negative voltage operation at the converter output, thereby allowing buck and boost operation. The converter operation ensures soft-switching of all switches and low current and voltage stress across switching components. The proposed topology enhances efficiency by reducing the processed power by 50% for same load range compared to the buck or boost FPP converter alone. Additionally, proposed charger also facilitates critical functionalities and smooth current control, thereby improving integration with modern EV infrastructure. The charger performance is validated for 50 V and 350 V battery

through simulation and initial experimental validation are presented for four quadrant operation.