

# Chapter 1

## Introduction

### 1.1 Background

The rise of electric vehicles (EVs) is primarily driven by the global push towards reducing greenhouse gas emissions and achieving a sustainable, carbon-neutral future. This shift towards greener transportation is further supported by increasing environmental awareness and the implementation of policies aimed at promoting cleaner transportation alternatives. Some recent global agreements driving sustainability and EV adoption include the EU's 2023 CO<sub>2</sub> emission standards mandating 100% zero-emission vehicles by 2035, COP29's carbon market reforms, and the Glasgow Declaration (2021), aiming for zero-emission vehicles by 2035 in major markets. As a result, the EV adoption globally has been on the rise, with almost 14 million new electric cars registered globally in 2023, bringing their total number on the roads to 40 million. Fig. 1.15 shows the global electric car stock from 2013-2023. According to the global EV outlook 2024, nearly one in five cars sold in 2023 was an EV [1].

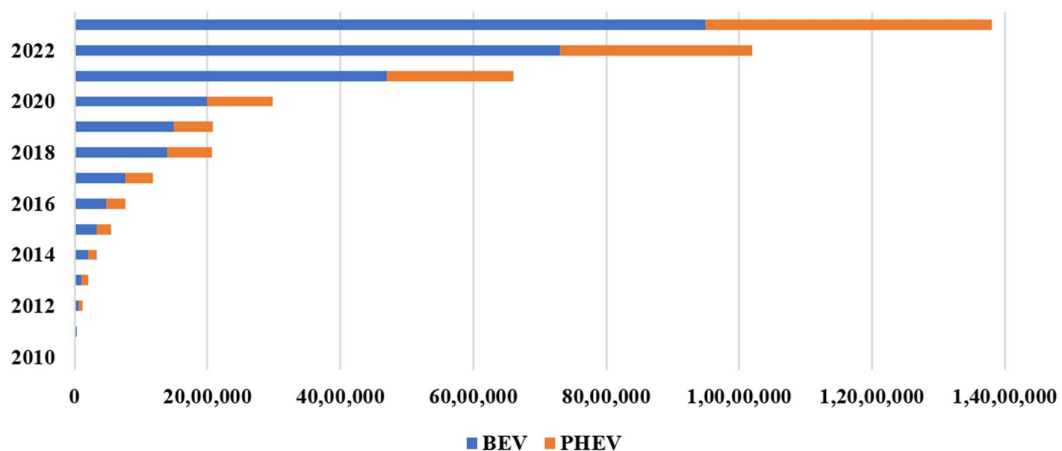


Fig. 1.1 Global electric car stock, 2013-2023 [1].

The huge global transition towards electrified mobility has necessitated advancements in EV charging technology. One of the key elements empowering this transition is the rechargeable batteries forming the primary energy source of an EV. While optimal

charging strategies are being adopted to enable efficient charging with a focus on extending battery life, fast and ultra-fast charging infrastructures are being developed to reduce charging times to a competitive range of 5-10 minutes, which is crucial for the widespread adoption of EVs. Additionally, the development of compact, cost-effective, efficient, and robust charging solutions, including both on-board and off-board chargers, is essential to support the growing number of EVs and ensure efficient energy utilization, thereby enhancing the overall sustainability of the transportation sector.

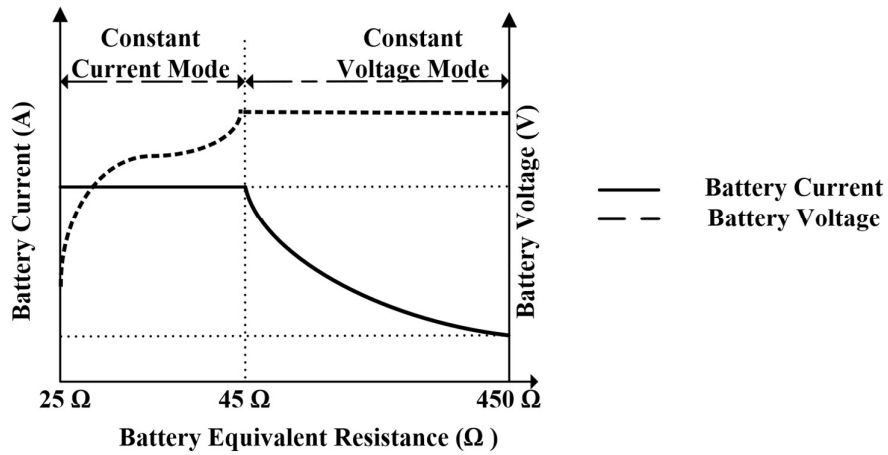
Among various available battery chemistries, the lithium-ion batteries constitute the most widely adopted technology owing to their high energy and power density, long cycle life, and efficiency [2], [3]. These batteries require single-stage or two-stage power electronics converters, constituting a battery charger to ensure efficient and reliable charging. These chargers are broadly classified into on-board and off-board charger categories. The on-board chargers are integrated into the vehicle and are typically limited by weight, space, and cost constraints, making them suitable for slower charging rates, such as Level 1 and Level 2 charging [4]. On the contrary, the off-board chargers are external to the vehicle and can support higher charging rates, such as Level 3 fast charging or ultra-fast charging, due to fewer constraints on size and weight [5].

While the converter employed in a battery charger must ensure high efficiency, high power density, light-weight, low cost, and equipment safety through isolation, an additional optimal-charging capability makes it a perfect fit for an EV battery charger. An optimal charging strategy refers to charging in a pattern that ensures fast and safe charging while also focusing on extending battery life. Moreover, the off-board charging stations with their dimensional flexibility need to attain power levels such that the battery recharging time can be made comparable to the refueling time of conventional internal combustion engine-based vehicles. Vehicle-to-Vehicle charging and EV auxiliary power demand are other prominent areas of the more recent areas attaining significant attention from the power electronics community.

## **1.2 Motivation**

Despite the sharp growth in the number of EVs on the road, the adoption of electric vehicles (EVs) faces several significant challenges hindering their widespread acceptance. One of the major underlying issues is the risk of EV battery fires, which

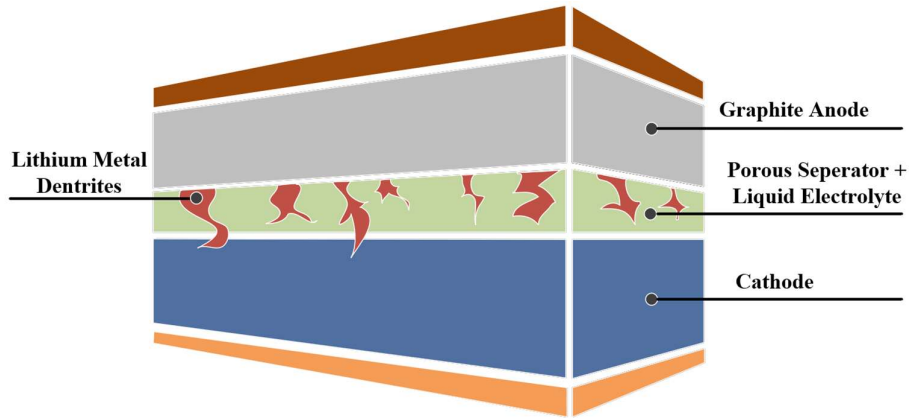
raises safety concerns among potential users and impacts consumer confidence in EV technology [6]. Additionally, the lack of ultrafast charging stations is a critical barrier, as it limits the convenience and practicality of using EVs for long-distance travel. The development of fast and ultra-fast charging infrastructure is essential to address this issue, but it poses challenges related to efficiency, power rating, and the impact on the utility grid [7]. Another major challenge is the lack of interoperable chargers, which complicates the charging process for EV users and requires standardization efforts to ensure compatibility across different charging networks [8]. Further, range anxiety, or the fear of running out of battery power before reaching a charging station, remains a significant barrier for potential EV buyers. This consumer anxiety is augmented by the limited driving range of many EV models and the insufficient number of charging stations, particularly in developing regions.



*Fig. 1.2 Constant current constant voltage charging strategy.*

Lithium-ion batteries are largely deployed in EVs due to their high-power density and long cycle life. These batteries behave as a variable resistance during charging [9]. Initially, during the discharged state, the internal resistance of the battery is very low of the order of milli-ohms. However, as the battery state-of-charge (SOC) rises, due to the internal chemical reactions, the resistance increases significantly, as represented in Fig. 1.2 [10]. The charging time of a battery is directly related to its charging current. Faster charging requires higher current; however, at higher SOC, due to the high resistance, the

$I^2R$  losses become too high, causing significant heat generation. This heat speeds up chemical reactions, reducing the actual battery capacity and aging the battery faster. A decrease in usable capacity shortens the battery life. Further, the significant amount of generated heat poses a risk of thermal runaway, eventually leading to EV fires.



*Fig. 1.3 Dendrite formation in Li-ion battery due to overcharging.*

Additionally, during charging, the lithium ion tends to move from the anode to the cathode. Abnormal conditions, such as overcharging, lead to lithium ions crowding around the anode. They eventually deposit themselves on the surface of the anode and create small lithium dendrites, as shown in Fig. 1.3. creating an internal short circuit between the electrodes, leading to catastrophic failures and even fires. To conclude, overcharging significantly impacts the battery's life, as it can significantly reduce the battery's ability to hold a charge. Additionally, overcharging can cause the battery to produce excess heat and, in extreme cases, can even lead to an explosion. Therefore, the Lithium-ion batteries require precise charging profiles to ensure optimal performance and maximum battery life.

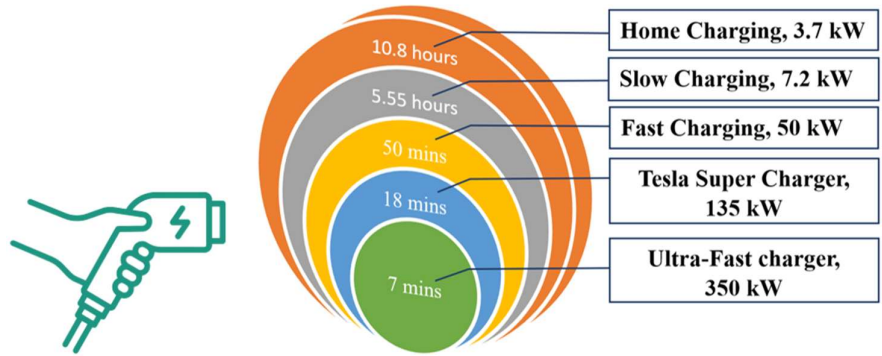
Constant current (CC) charging is a simple strategy with easy control where a constant current is fed to the battery. However, a small charging current would lead to longer charging time, whereas a high current poses the risk of easy overcharging towards the end of charging. Another popular method is the constant voltage (CV) charging, which regulates a predefined constant voltage to charge batteries. Its main advantage lies in circumventing overvoltage and its irreversible side reactions towards the end of charging,

thereby prolonging battery life. However, during the initial stage of charging, at a lower state of charge (SOC), a higher current value is required to provide a constant terminal voltage. This current value is significantly higher than the nominal battery current, which often causes shock to battery plates, leading the battery lattice frame to collapse. To address these challenges, a hybrid CC-CV charging approach that combines the benefits of fast early-stage charging of the CC strategy and overcharging protection of the CV strategy, facilitating reduced charging time while prolonging the battery life, is widely adopted for Li-ion battery charging [11].

In the CC-CV charging strategy, a constant current is fed into the battery until a predefined voltage is reached, and then the charging continues at constant voltage while the current gradually decreases, indicating the end of charging [12], as shown in Fig. 1.2. The CC-CV strategy facilitates reduced charging time while prolonging the battery life [13], and protecting the battery from overcharging [14], [15]. Further, by ensuring a smooth transition between the constant current and constant voltage stages, the CC-CV method helps in maintaining the thermal stability of the battery, thereby reducing the likelihood of thermal runaway, a common cause of battery fires.

Another major challenge hindering the mass adoption of electric vehicles is their longer charging time [16], [17], [18]. The time taken to charge a battery of a given capacity is directly related to its charging current. The recent advancements in electric vehicle (EV) charging technologies have garnered significant EV adoption among short commute range customers. However, their acceptance among long-travel range customers remains hindered due to the range anxiety, limited charging infrastructure, and longer charging time [19]. Consumers accustomed to 5 minutes of refueling time for a full tank face long waiting times with the existing battery proficiency and charging facilities. The lack of charging infrastructure, fueled by prolonged charging time, leads to driving range anxiety and deters consumer confidence in EV reliability.

One of the ways to address the range anxiety issue is to increase the battery capacity. However, it leads to an increase in the price and weight of the vehicle. Therefore, a probable solution to improve the charging infrastructure and reduce charging time is the development of ultra-fast charging (UFC) stations [20]. It refers to significantly large power-rated charging, aimed at reducing the charging time and making it comparable to the traditional refueling time [17].



*Fig. 1.4 Charging time and power rating of existing EV charging solutions to add 200 km of driving range to a Tesla SP90D.*

A representative diagram of the charging time taken by various commercially available chargers to charge a Tesla Model SP90D (having energy consumption of 20 kWh/100 km at constant power), for a range of 200 km, is shown in Fig. 1.4 a 7-kW slow charger needs 5.5 hours, a 50 kW fast charger needs 50 minutes, a 135 kW rated Tesla supercharger takes 18 minutes, while a 350 kW UFC needs only 7 minutes, which is comparable to the refueling time of conventional vehicles. However, large power handling associated with UFC requires a highly efficient converter, as even a percent of efficiency decay could mean 35 kW of loss, which is a significant amount of heat. This imposes larger heat sinks and cooling requirements due to high conducting current and increased thermal stress. Further, UFC demands high-voltage and high-current rated devices that are costlier and impose limits on the converter design and performance. These challenges hinder the development of an efficient and cost-effective ultra-fast charging facility.

With the targeted upsurge in its fleet, electric vehicles are expected to cover longer routes, hitting the diverse urban and rural roads. However, the voltage and power level of the charging network vary in a wide range from highway to city/town due to their different nature of utility. To make the best use of this diverse charging network, an intersecting solution to make the well-established battery standard compatible with a wide network of charging options is necessary. Further, as the number of charging stations is limited and many times may not align with the travel route, the fear of being stranded with a discharged EV battery is a major concern that hinders EV adoption.

Additionally, the EVs operate with low voltage (LV) loads on board, such as lighting, cooling, power steering, dashboard, music system, wiper, etc., that are necessary to

ensure safe and comfortable travel [21]. These LV loads are usually supplied from the high-voltage main battery through an auxiliary power module, which comprises an isolated DC/DC converter. However, an additional converter contributes to the increase in size and weight of the system, and increases the cost of the overall system. Therefore, integrating the LV load capability with a main charger is an attractive way of achieving a complete solution to all onboard needs [22].

These challenges collectively hinder the mass acceptance of EVs, despite ongoing research efforts aimed at overcoming these barriers. Addressing these issues, though, improved power electronics systems are crucial for developing a more sustainable and widely accepted EV ecosystem. To address these issues, this thesis investigates various converter topologies and control approaches to implement efficient CC-CV charging, the evolution of ultra-fast charging, and the approaches to achieve multi-functional behavior, and their key challenges are discussed.

### **1.3 Literature Survey**

This section discusses various power converter topologies already reported in the literature for optimal battery charging. Additionally, recent literature regarding ultra-fast charging and charging technology for EV applications is also discussed in this section.

#### **1.3.1 Resonant Dual Active Bridge Converters for Optimal Battery Charging**

A DC/DC converter is the prime element of a battery charger. While it must possess features such as bidirectionality, galvanic isolation, soft switching, higher power-density, and paralleling capability for a reliable, and efficient charging, it must be capable of varying its output in a wide range to match the stringent battery charging requirements as desired in CC-CV charging strategy to ensure fast charging and maximum battery life [11], [23], [24]. However, the implementation of CC-CV charging strategy faces challenges in terms of control complexity, converter design, light load efficiency, and soft switching [25], [26]. A CC-CV charger primarily consists of a DC/DC converter whose output can be varied in a wide range to match the stringent battery charging requirements.

One such state-of-the-art converter is the voltage-fed dual active bridge (DAB) DC/DC converter shown in Fig. 1.5. A DAB can equivalently be represented as in Fig. 1.6.

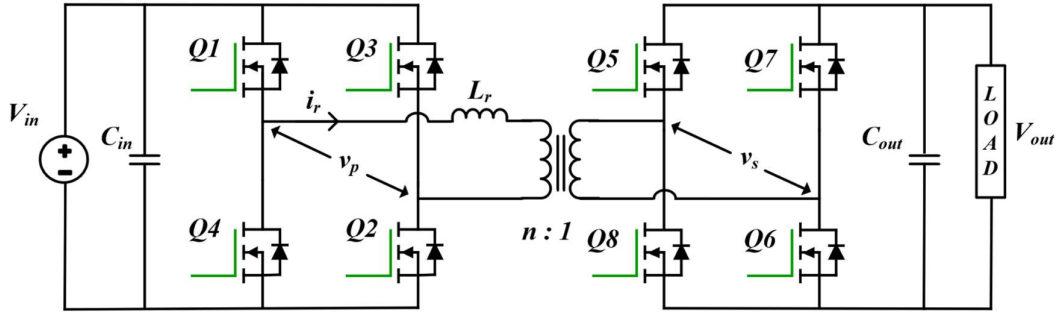


Fig. 1.5 Conventional dual active bridge converter [27].

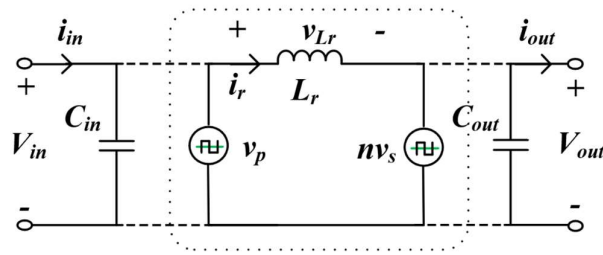


Fig. 1.6 Equivalent circuit of the conventional dual active bridge converter.

It ensures bidirectional power flow suitable for vehicle-to-grid (V2G) and grid-to-vehicle (G2V) operation, and provides high-frequency isolation that ensures safety and significantly reduces the size of magnetics [18]. In addition, it offers many advantages such as symmetrical structure, zero voltage switching (ZVS) for all switches, small filter requirements, and improved power density [19], [20]. However, the soft-switching range is limited by system gain, and efficiency deteriorates at light load operation [30], [31].

To improve the ZVS range and efficiency many modulation techniques such as Dual phase shift (DPS) in [32], triple phase shift (TPS) control to improve transient current optimization [33], [34], multiple phase shift control proposed in [35] combines the benefits of TPS during light load and DPS to reduce circulating current at medium and heavy load thus improving efficiency. The key waveform corresponding to each modulation strategy is shown in Fig. 1.7. The load-adaptive control strategy proposed in [36] utilizes DPS for switch current stress minimization in CC mode and DPS with inner phase shift control in CV mode to improve light load efficiency. In these modulation techniques, power transfer is mainly controlled by three independent control variables, the two-bridge inner phase shift ratios and the phase shift ratio between the two bridges.

With the increase in the number of adjustable control variables, the designed model for decision making becomes complex [37], [38].

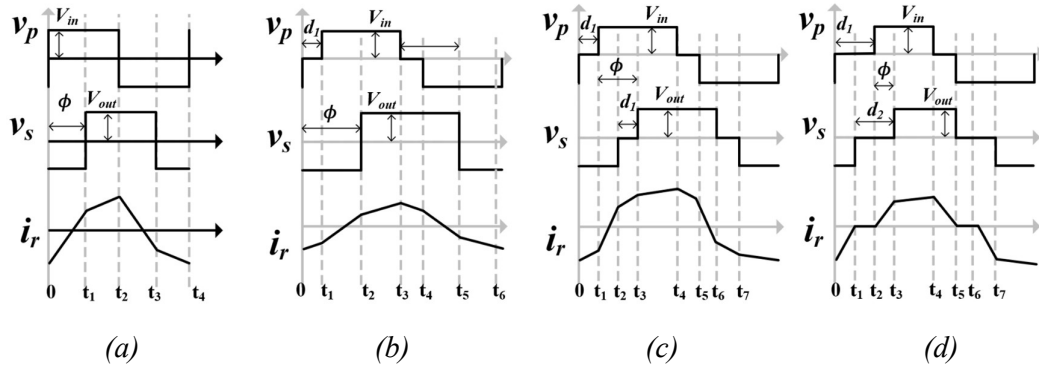


Fig. 1.7 Key waveforms of (a) Single phase shift modulation. (b) Extended Phase shift modulation (c) Dual phase shift modulation. (d) Triple Phase Shift modulation.

DAB converters employing a resonant tank have been widely explored in existing literature due to a wide soft switching range, better efficiency, and utilization of transformer non-ideality [39]. With the resonant tanks, high-frequency components of the current can be reduced making the shape of the current waveform closer to a sine thereby reducing the peak value of current. The most common resonant DAB includes adding capacitor in series with leakage inductor to obtain LC resonant tank for sinusoidal current [40], [41], [42]. With LC network, although lower RMS current with reduced turn-off current is obtained but the ZVS range still remains compromised, with significant reactive power [43], [44].

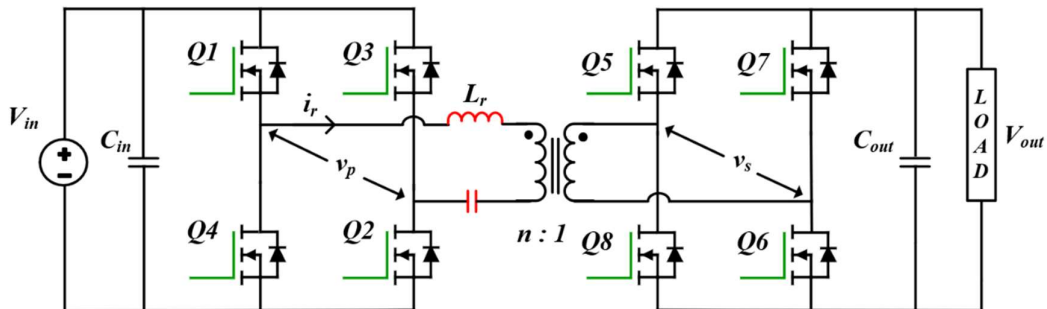


Fig. 1.8 Series LC resonant dual active bridge converters.

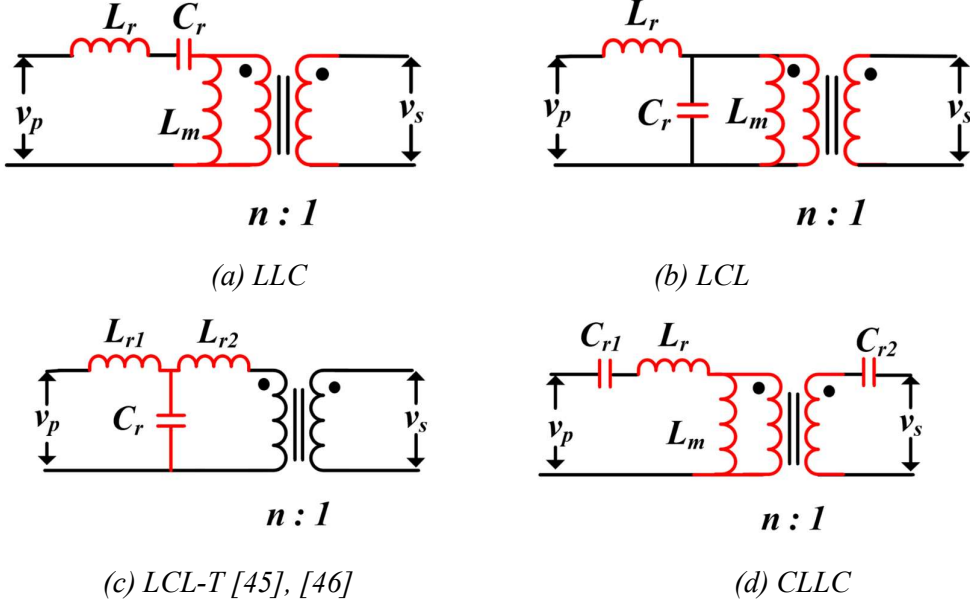


Fig. 1.9 Higher order resonant tank circuits for modified dual active bridge converter.

To further improve the switching performance, a dual-control-based resonant DAB is proposed in [47] which combines the advantages of phase-shift modulation and pulse frequency modulation to minimize the switching losses. However, the use of frequency-based modulation techniques requires a wide variation in frequency for the CC-CV charging application. This causes the magnetics to be designed for the lowest frequency, leaving the design bulky and underutilized. This also results in high circulating current, loss of soft switching, and reduction in efficiency, unstable operation at frequencies away from the resonant frequency [48], [49].

One of the acclaimed solutions towards the reduction of control complexity is the fixed-frequency operation of a resonant converter. A solution to reduce the complex frequency variations has been proposed in [50], where a duplex control is implemented to avoid secondary resonance and improve efficiency. An LCL-T resonant network is proposed in [51] where the design of the passive components has been simplified using fixed frequency operation while ensuring high efficiency in both CC and CV modes. Interleaving a PWM rectifier with an LLC to obtain wide voltage regulation is proposed in [52]. Another approach is the use of reconfigurable circuits [53], where instead of frequency variation, switches activate partly in different modes to operate as voltage multipliers of varied gain to cover a significantly wide output voltage range as required in the case of EV charging. In [54], a hybrid LLC converter is proposed that utilizes

multiple modulation schemes, transitioning the converter to operate in three different modes, i.e., as full-bridge, dual-phase half-bridge LLC, and single-phase half-bridge LLC. This configuration eliminates the need for redundant elements during different modes and provides better soft switching and efficiency compared to other topologies. Although fixed frequency operation simplifies the control, the extra switching elements can further increase losses.

Another way of simplifying the control is to utilize the load-independent points of the converter output to behave as a current source and a voltage source to operate in CC and CV mode [55], [56], [57]. Higher order resonant circuits such as LLC, LCC, CLLC with multiple resonant frequencies allow load independent operation for both CC and CV mode at different resonant frequencies [58], [59]. Series-series and series-parallel both tanks offer constant output voltage and constant output current operation [14]. Therefore, combining the fixed frequency operation at the resonant point, with phase shift modulation for power transfer can result in an efficient and simple way of achieving CC-CV operation. However, the additional elements in a higher-order resonant circuit bring in the added component cost and weight to the converter.

In addition to the above, most voltage-fed high-frequency converters draw rectangular or triangular current at the input [60]. A significant amount of high-frequency ripple can flow back to the source if the source impedance is not large enough. This can introduce significant EMI and losses, as well as degrade the DC source/battery connected at the input. Typically, to absorb these current ripples, a bulky input bypass capacitor is placed at the input. However, the use of electrolytic capacitors limits the reliability of the converter as it has a shorter life span and degrades over a period of time. They suffer due to relatively high equivalent series resistance (ESR), low ripple current ratings, and wear-out issues due to evaporation of electrolyte. In contrast to the electrolytic capacitor, the metal film capacitors provide a well-balanced performance for high voltage applications (e.g., above 500 V) in terms of cost and ESR, capacitance, ripple current, and reliability [61].

In contrast to the voltage source converter, the current source converter employs a high-reliability inductor as the DC link energy storage component [62]. Further, its source inductor limits the rate of rise of current, providing inherent short-circuit protection, thus improving the reliability of the system [63], [64]. The inductors in the current-fed

converter can withstand high voltage ripple without affecting their performance and hardly suffer from degradation [65], [66]. Hence, they provide a longer mean time between failure (MTBF), which is suitable for high-voltage DC applications. In [67], a current-fed series resonant converter operating at fixed frequency is proposed that solves the problem of input current ripple, has simple PWM control, and offers wide voltage regulation. However, in addition to the input inductor, it uses an auxiliary inductor on the primary side for achieving ZVS of the primary switches, which can increase current stress and degrade power density.

### 1.3.2 Fractional Power Processor for Ultra-Fast Charging

A typical UFC charging system architecture is shown in Fig. 1.10, the three-phase AC from the grid feeds the low-voltage DC bus through multiple galvanically isolated single-phase modules, comprising an active front-end stage and an isolated DC-DC stage [68]. Further, a DC/DC converter is required to interface the available low-voltage DC (LVDC) bus to the EV battery. This DC/DC converter handles a significantly large power of the order of 350 kW, to charge the battery in a few minutes.

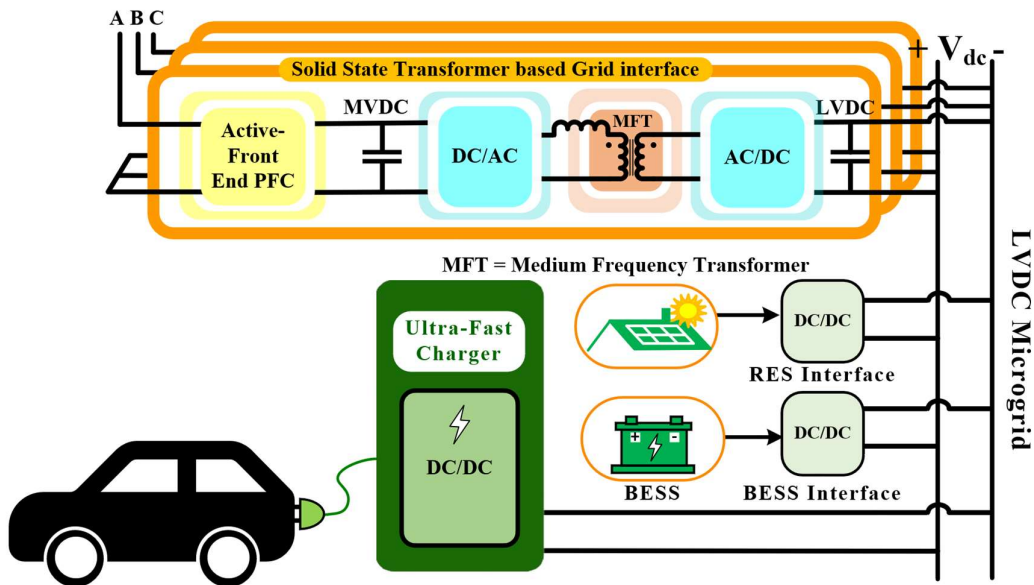
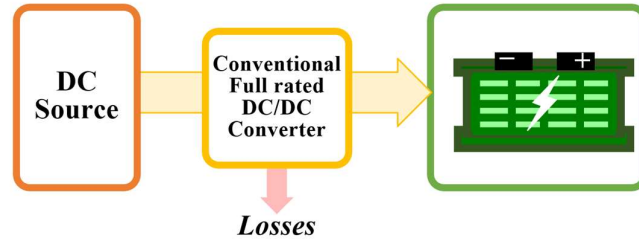


Fig. 1.10 The solid-state transformer-based UFCs architecture, interfacing RESS and BESS.

The conventional approach of ultra-fast charging widely uses full-rated power converters, i.e., the total power flows through the converter components, as in Fig. 1.11. With the further advent of GaN and SiC-based switching devices, DAB performance for

high power rated battery charging applications has improved significantly [69], [70]. However, due to the full power processing approach each of the switch in both the inverter and rectifier bridge is subjected to full voltage stress of source and battery terminal, respectively. This demands the power converter to be rated at-least at the maximum deliverable power of the UFC which results in high voltage and current stress in the switching devices and the passive elements. [71].



*Fig. 1.11 Block diagram representation of conventional full power processing scheme.*

In [72] and [73], the authors describe a reduction in the size of passive components and stress optimization by incorporating multiple interleaved stages and multi-level topologies, respectively. However, such topologies suffer due to the drawback of a larger number of components with a high KVA rating to power the UFC level. In [74] A UFC configuration, with a reduced number of series-connected input stages, is achieved by using high-voltage 3.3 kV SiC. However, the cost of components increases with an increase in the power rating, and their commercial availability becomes a major challenge. Also, in a full power processing approach, the entire battery delivered power is subjected to the converter losses. But at UFC power level, decay of even a percent of converter efficiency means impractically large kW of loss (viz., 35 kW for 99% efficient 350 kW charger). Also, the filter and magnetic components constitute a significant converter size, as the design needs to be done for the full current and voltage rating.

A probable solution to these problems is the concept of fractional power processing (FPP). In this arrangement of power transfer, the converter carries only a fraction of the power to be processed, whereas the rest of the bulk power is transferred through a series direct in-feed path, as shown in Fig. 1.12. This splitting of power transfer between two paths causes a significant reduction in losses and charger cost [75]. Additionally, a reduction in switch current and voltage stress leads to a decrease in temperature rise and heat dissipation, thereby minimizing the heat sink requirement.

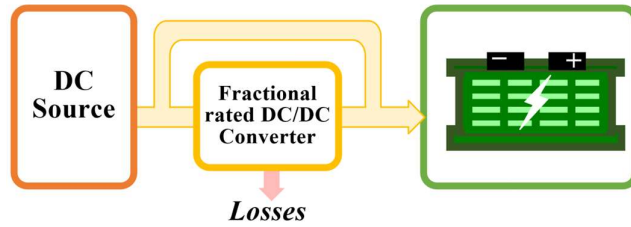


Fig. 1.12 Block diagram representation of the fractional power processing scheme.

### The Fractional Power Processing Architecture

Assuming  $V_{dc}$  and  $V_{bat}$  represent the DC source voltage and the terminal battery voltage, respectively. Table I lists all the possible architectures for implementing a fractional power processing-based bidirectional power converter interface. To implement any architecture, the converter can be connected in such a way that one of the voltage combinations from Table I is applied across its input and output terminals.

Each of the architectures has its discrete advantages that are suitable for particular applications. Depending upon the application, any feasible architecture can be selected. However, the selection of input voltage is also critical to ensure a reliable operation of any of the listed architectures. It is necessary to ensure that the voltage at dc port is positive. Moreover, any architecture must adhere to Kirchhoff's voltage law (KVL) to prevent accidental short-circuits, which retains the need for galvanic isolation of the fractional rated converter.

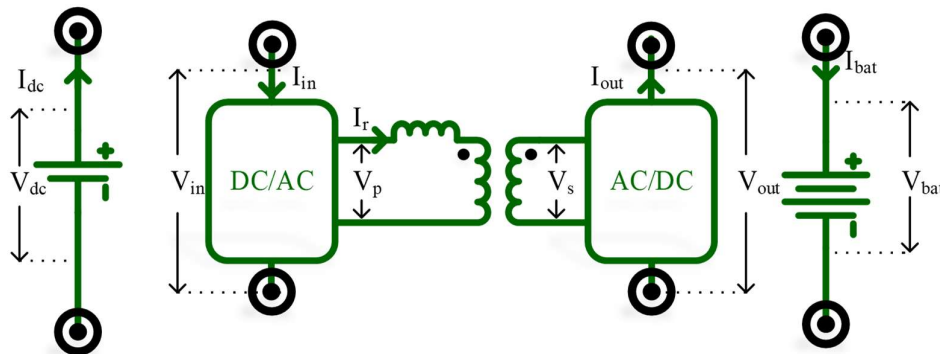


Fig. 1.13 Representative diagram of interconnecting terminals to achieve FPP architecture.

Table 1.1 Possible Architectures for Fractional Power Processing Implementation for Battery Charging

<i>DC Voltage Input</i>	<i>DC Voltage Output</i>	<i>Constraints</i>
$V_{in}$	$V_{out}$	
$V_{dc}$	$V_{dc} - V_{bat}$	$V_{dc} > V_{bat}$
$V_{dc}$	$V_{bat} - V_{dc}$	$V_{dc} < V_{bat}$
$V_{bat}$	$V_{dc} - V_{bat}$	$V_{dc} > V_{bat}$
$V_{bat}$	$V_{bat} - V_{dc}$	$V_{dc} < V_{bat}$
$V_{dc} - V_{bat}$	$V_{dc}$	$V_{dc} > V_{bat}$
$V_{dc} - V_{bat}$	$V_{bat}$	$V_{dc} > V_{bat}$
$V_{bat} - V_{dc}$	$V_{dc}$	$V_{dc} < V_{bat}$
$V_{bat} - V_{dc}$	$V_{bat}$	$V_{dc} < V_{bat}$

The FPP concept have previously been applied to a variety of systems finding application in current balancing and better voltage regulation in photovoltaic (PV) systems [76], battery energy storage owing to high power handling and low cost [16], and fast charging systems due to high efficiency [79]. In [80], a flyback converter based FPP architecture is realized for efficient battery charging. Most of these literatures presented FPP based on voltage-fed converters suffers from high current-stress, and high switching ripple. These FPPs also exhibit high ringing, duty cycle loss and require snubber across second diode, which are undesirable.

Although, the existing FPP based EV chargers fairly addresses step-down voltage applications [79], [80], [81], [82], [83], [84] for facilitating UFC power levels, the battery manufactures are moving towards higher voltage level to reduces the conductor size and  $I^2R$  losses that presents needs for step-up FPP chargers [85]. So far, the FPP topologies have widely been applied to phase-shifted full bridge (PSFB) converters [79], [81], [86], however PSFB converters are unidirectional, and cannot facilitate EV as a source capability for future UFC stations. In addition, the converter switches are hard-switched and have poor light load efficiency that degrades the charger performance for wide battery voltage range. To facilitate bi-directional operation, dual-active bridge (DAB)

based FPP chargers have been presented [82], [83], [84]; however, it has a narrow soft-switching range.

The series resonant DAB presented in [82], [83] only achieves ZVS for secondary switches, and suffers from loss of soft-switching for wide load range and poor light load efficiency. Notably, these performance challenges are critical in FPP based battery charging application as power handled by the converter varies with battery voltage and converter light load operation can span over significant charging duration. In addition to the above challenges, high current applications such as UFC calls for swift battery current regulation. Further, the FPP based chargers presented in existing literature requires dedicated controllers to regulate the output behavior and achieve multi-stage constant current (MSCC) behavior as required in FC [87]. This adds to the system complexity, design challenges, and also increases the cost of the charger.

### **1.3.3 Inter-Operable Multi-Utility Charger with V2Aux, V2V and Fast-Charging Capability**

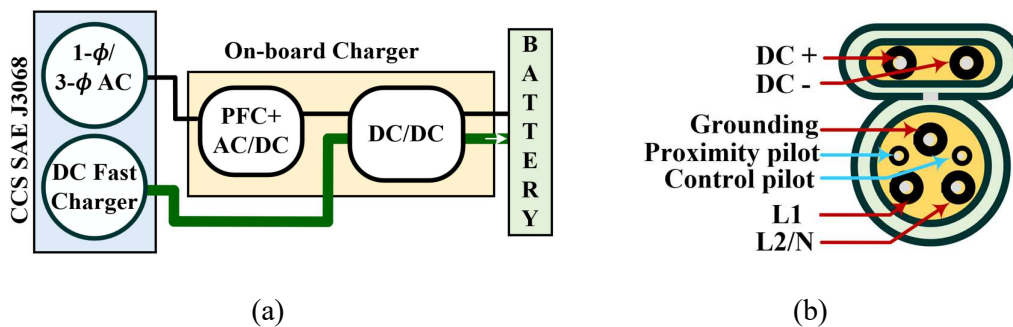
While charging capacity, cost, compact design, and efficiency of the battery charger are the major driving force of technical advancements in the past-decade, other paradigms of the new-generation battery chargers focus on their inter-operability and multi-utility nature [88]. Inter-operability refers 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 [89].

Evidently, the charging time of a battery is governed by the power handling capability of the charger, which for an on-board charger (OBC) is limited due to the compact space availability, weight constraints and cost of the vehicle [5], [90]. In addition, the size of the charger's converter is governed by the component count, their rating and the heat sink requirement, limiting the OBCs capability further only to slow charging. To reduce the size of the OBC, [91] introduced a full bridge with resonant dc/dc converter reducing stresses, [92] proposed switched inductor Cuk converter with high dc link voltage for high power density, [93] presented a series resonant converter to facilitate fast charging. However, the cost of the components with increasing voltage level becomes impractical

to be used for power level exceeding level 2 OBC, and thereby limiting their minimum charging time.

A solution to above OBC limitations is a fast charger (FC), stationed at dedicated charging facility and rated at significantly high-power owing to the flexibility of size, and space off-board. These high power fast-chargers are rated at high voltage to reduce the current at same power to minimize the conductor size and conduction losses [94]. Currently, the highest charging voltage offered by any DC fast charging station is 1000 V as on 2024, provided by CHAdeMO 2.0 or CCS Combo 2 [95]. These fast-charging facilities offers great relief to charge time and range anxiety. However, at such high power, the converter losses increase significantly and efficiency becomes very critical.

Further, the converter components need to be rated at high voltage and current, leading to impractically higher cost and heat sink demands. Additionally, the high power fast-chargers are rated at high voltage (1000 V from CHAdeMO 2.0 or CCS Combo 2 [95], [96]), to reduce the current and minimize the conductor size and conduction losses for a given power [94]. However, the significantly higher voltage of the charging station needs to be interfaced to the battery pack voltage, which is commonly available at 400 V and 800 V ratings. Further, the range of battery voltage available in the market for EVs varies widely, and it becomes a challenge to interface them at public DC charging stations. These crucial challenges call for solutions to equip the EV's OBC with FC capability while retaining OBC benefits and providing a cost-effective and efficient fast charging facility.



*Fig. 1.14 (a) Inter-operability scenario of onboard charger for slow ac charging and dc fast charging. (b) CCS SAE connector 1/3-phase AC as well as DC charging interface.*

A solution to these challenges is an interoperable charger which basically indicates an OBC that performs slow ac charging as well as can facilitate dc fast charging, by

bypassing the front-end ac/dc stage, as in Fig. 1.14 (a) [89]. Such chargers use a combined charging system (CCS) connector defined under class SAE J1772, shown in Fig. 1.14 (b). In [97], the authors introduce an integrated charger combining the benefits of both on-board and off-board charging by utilizing the motor windings. However, this approach requires additional diodes and the converter needs to be rated for high-power fast charging. In [98], the authors, exploring the future trends of OBC, highlight one of the critical challenges of interoperability; i.e., the charging power for interfacing DC fast charging remains limited to the power level of the onboard DC/DC converter, as shown in Fig. 1.15. This limits the use of existing AC charging-rated on-board chargers for FC applications.

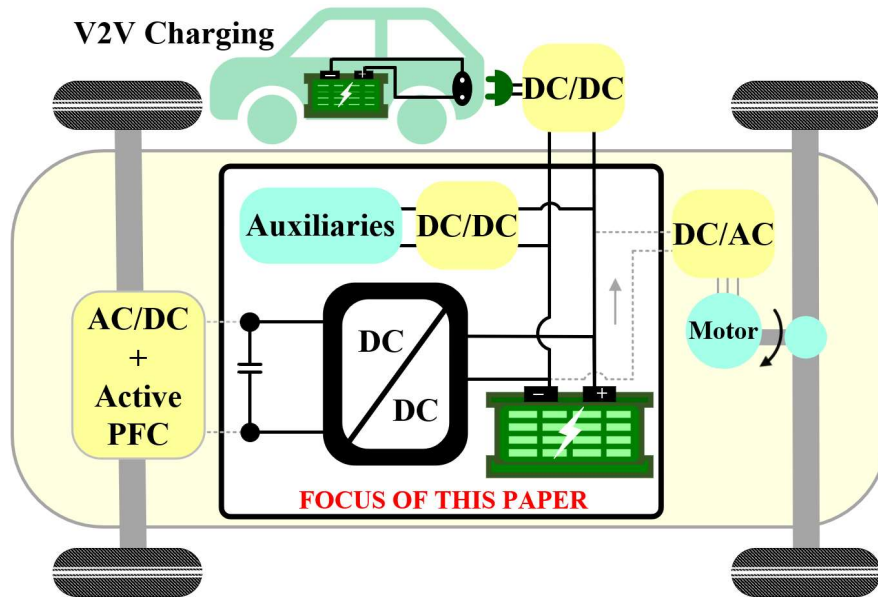


Fig. 1.15 Representative diagram of conventional OBC serving multi-utility functions.

A probable solution to the challenge of low power handling capability of existing OBC is the concept of fractional power processing (FPP) [99], [100]. Here, the same converter that is designed for low power-OBC handling can be utilized for high power FC without incurring excessive current and voltage stress on the converter components. This can be achieved because in FPP configuration, only a part of charging power, comparable to OBC power is processed through the converter, while the rest of the power can be transferred through a bypass connection interfacing dc source and battery [101].

However, a multi-utility charger strictly demands a bidirectional converter that can be controlled to both charge and discharge the battery for its respective application. The existing FPP-based FCs, also already discussed in the previous section, widely use a

diode that cannot be used for a multi-utility charger due to their unidirectional nature [78], [99]. In [83], the authors describe FPP applied to a full-bridge boost converter for OBC. However, the switches undergo hard-switching, which degrades the overall performance of the charger. In [102], resonance is employed with DAB-based FPP FC to improve the zero-voltage switching (ZVS) range; however, only secondary switches achieve ZVS, hindering the superior performance of FPP.

Further, in conventional OBC, the auxiliaries of EV, i.e., air conditioner, heater, entertainment system, headlight, automatic seats, power window, etc., are supplied by an additional auxiliary power module (APM) comprising of dc/dc converter [103], as shown in Fig. 1.15. However, a separate APM further limits the size and cost optimization of OBC. To address these challenges, integration of APM with OBC is widely explored such as integrating an auxiliary port by adding an additional winding to the transformer to generate a multi-port converter [104], [105]. [106] describes a three-port DC/DC converter for OBC, eliminating the need for a separate APM. Another method of integrating APM is by utilizing the dc/dc stage of OBC as a rectifier in charging mode and step-down converter in cruising mode to power up auxiliaries [22]. However, the existing approaches require a dedicated controller in each mode to obtain a constant voltage and achieve the current regulation required by auxiliary loads.

Additionally, vehicle-to-vehicle (V2V) charging has been another prominent application of on-board battery charger helpful in alleviating the range anxiety and providing emergency backup, while increasing the resiliency of the EV fleet. A versatile DAB-based charger incorporating V2V application is presented in [107]. However, power processing through multiple charging stages makes V2V a slow charging operation. In [108], authors describe interconnecting OBC negative rail and motor winding neutral to form integrated bi-directional converter for V2V charging. In [109], a direct connection to achieve dc V2V charging, eliminating multi-conversion stages is discussed. However, it has dominant switching losses at higher frequencies that deteriorate efficiency.

Therefore, a solution to elevate the problem of low charging power (slow charging speed) of the existing class of OBCs is necessary. It further eliminates the complex controller required in the existing state-of-the-art multi-functional converters to achieve different operating modes, and make use of the existing component capacity to facilitate V2Aux mode and V2V mode charging mode.

### **1.3.4 Quad-Operative Fractional Processor with Step Up/Down Capability for Wide Voltage EV Charging Applications**

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 a wide range of battery voltages available across different EV models in the market. This diversity in battery specification creates a strong demand of power processors capable of efficiently delivering wide voltage range loads [110]. 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, collectively referred to as a quad-operative battery charger, is identified.

As discussed earlier, the high-power battery chargers are playing a crucial role in escalating EV adoption. While traditional full power processors have reached their performance limit due to the physical and operational constraints, fractional power processing is seen as the newest solution in increasing the power handling capability and battery charging speed. Based on the input and output configuration, various literatures classify the fractional processor configuration as parallel current regulators (PCR) and series voltage regulators (SVR) [111]. The main advantage of PCR comes from processing only the amount of power caused by current mismatch [112], generally finding application in PV, however, not preferable for high power applications [113]. In contrast, SVR regulates the power based on the difference between the input and output voltage. Further, the SVRs, based on the selection of input or output as a series or parallel port, respectively, are classified as step-up or step-down FPP converters.

While the existing fractional power processor solves the problem of slow charging speed by allowing higher power to be delivered to battery compared to power processed, a bottleneck of this approach is the limited range of battery voltage. Evidently, the limit is imposed due to the differential voltage appearing at the series-connected port, which limits the power flow due to the unipolar nature of the connected bridge. To extend the charging voltage range of FPP processors to both step up and step-down capability, researchers resort to different methods such as regulating the dc link voltage, to match the required battery voltage or using auxiliary converter to extend the charging range. However, in applications with renewable and BESS integrated dc links such as microgrid,

etc., this approach may result in an unstable dc link. The current approach might bring further need for stabilization and layers of control, adding undesired complexity to the system.

To affirm the suitability of fractional power processing converter for a wide range of battery charging applications i.e., both 400 V and 800 V application range, the authors in [114] compared two approaches of achieving buck and boost voltage using a single fractional power processing converter. One with the unfolding circuit in combination with FPP system while other considered using bipolar switches in dc/dc converter to accommodate both positive and negative differential voltage. The conclusion from the analysis establishes the superiority of using bipolar switches in terms of charger performance and efficiency over using a separate voltage unfolding circuit. With this approach, a two-switch forward converter with MOSFET connected back to back with diode, reported in [115] is the simplest approach to achieve step up/down operation with FPP converter, when transmitting power unidirectionally.

To enhance the voltage regulation range of FPP based system, [116] introduced a step up/down series connected partial power converter applied to PV system. The authors established that to achieve the desired voltage range, the step-up/down FPP converter processes half the active power compared to a standalone step-up or step-down fractional power processor with reduced size. As the power processed can be reduced the dc/dc converter design can be further optimized. However, the presented solution can only perform a step-up operation in forward mode and a step-down operation in reverse power flow mode, limiting its four-quadrant operation.

Analyzing further, the authors in [117] categorized the employed partial approaches as truly partial or just partial active processing topology based on analytical methods and established that the flyback based series-regulator processes the same amount of power as that processed by conventional non-isolated boost converters and cannot be considered a fractional-power topology, contradicting the earlier published conclusion on feasibility of flyback converter for FPP approach. Further, the full-bridge series regulator can perform a true FPP, and therefore can be a considerable candidate for high efficiency battery charging. To enable fast charging application, [118] presents a step up/down FPP topology implemented by utilizing a three winding transformer and two series LC resonant tank. Another approach utilizing resonant tank based converter for four quadrant

operation in [119] presents a CLLC resonant tank based partial power processor. However, both approaches require additional components, incurring design complexity and component cost. Also, the performance of the approach is not experimentally verified.

Moreover, the above fractional power processors are reported based on voltage-fed topology; however, the current fed DABs are reported to have better performance and reliability[65]. In [120], authors introduced a step up/down partial converter based on current-fed topology to extend the converter's capability to operate with both voltage polarities. Another work [121] reported use of a current source full bridge converter with two-quadrant switches; however, the hard switching operation degraded the efficiency of the converter, reducing the overall efficiency. A step up/down partial power processor based on an isolated current source converter presented in [122] gave superior voltage regulation with four-quadrant operation and soft-switching, however, the control approach for output current regulation is not discussed. It is to be noted that although some works employ half-bridge architecture to reduce the number of active switches, the increased voltage stress at the full voltage (Parallel) port diminishes the advantages of reduced switch rating obtained with FPP, especially when implemented at a parallel-connected high-voltage port. Further, the use of multiple electrolytic capacitor would degrade the converter reliability due to its limited life cycle.

Additionally, in [121], [123] the diode conduction over the entire cycle of negative voltage results in voltage drop and additional losses that suppress the efficiency benefits of fractional power processing approach. Therefore, there is a need to develop a fractional power processing-based quad-operative power processor that can charge the battery with super high efficiency while overcoming the major drawback of the fractional power processing approach by accommodating the buck boost and forward reverse power flow.

## **1.4 Challenges with the Existing System**

With the emergent EV revolution, driven by advancements in battery and converter technology, government incentives, and a global shift towards sustainable energy solutions, the need for safe, reliable, cost-effective, and efficient charging solutions has tremendously increased. Moreover, setting up a highly-efficient, robust, and accessible

network of charging stations has become not just a modernization approach but a necessity to alleviate range anxiety and instill confidence among EV owners.

Although researchers have developed solutions towards charger topology that covers a wide range of operation and serve the stringent battery charging requirements, there are still challenges that persist with existing approaches. These challenges are briefly discussed below:

❖ For Efficient Optimal Battery Charging

- Wide variation in load current and voltage leads to loss of ZVS and poor light-load efficiency.
- Frequency control suffers from the efficiency drop and poor magnetic design due to sharp changes of the switching frequencies.
- Additional components to meet both CC and CV behavior from a single converter add to the size and cost of the converter.
- Complex controller circuits are required to implement CC-CV and to enable a smooth transition from a single converter.
- Increased computational cost, memory requirement, power loss, and overall response time of the system.
- Electrolytic capacitor reduces the life span and degrades the reliability of the converter.

❖ For Ultra-fast Charger

- Full power processing results in high current and voltage stress across switching devices, leading to large conduction losses and bulk heat sink requirements.
- The converter needs to be rated for the maximum deliverable power of the charger, leading to high cost, limited component availability, and design challenges.
- Reported FPP-based EV chargers largely address step-down voltage applications. However, they fail to cater to the higher battery voltage requirements that are gaining popularity to reduce the conductor size and conduction losses.

- The existing FPP topology has been implemented with unidirectional converters limiting EV as a source utilization, as well as suffers from hard switching and poor light load efficiency.
  - Dedicated load current regulation is required for implementing multi-step CC charging, required in case of ultra-fast charging.
- ❖ For Interoperable Multi-Utility Fast Charger
- Charging power for interfacing dc fast charging remains limited to the power level of onboard dc/dc converter.
  - The cost of the component required to extend the input voltage acceptability and enhance power capability becomes impractical for an on-board charger.
  - Integrated auxiliary power module results in poor efficiency during V2Aux mode due to light load operation.
  - Reported solutions for V2V charging involve multiple conversion stages that deteriorate the efficiency.
  - Switching between fast charging, V2Aux, and V2V mode required additional relays, a complex control strategy, and a dedicated controller in each mode.
- ❖ Quad-Operative Fractional Processor with Step Up/Down Capability for Wide Voltage EV Charging Applications
- The charging voltage range for FPP chargers was restricted to either step-down or step-up due to the unipolar nature of the differential bridge.
  - Use of an unfold circuit to achieve buck and boost operation resulted in efficiency degradation.
  - Reported works suggested the use of a diode to enable bi-polar operation for accommodating buck and boost mode, but only enabled unidirectional operation.
  - The reported solutions so far lack soft-switched solutions that enable step-up/down operation using the FPP approach.

## 1.5 Objective of the Thesis

The primary goal of this thesis is to develop power processors based on resonant dual active bridge converter to address the major challenges in EV adoption relating to

- ❖ Optimal battery charging with minimal control to ensure EV safety;
- ❖ Efficient and cost-effective ultra-fast charging solution;
- ❖ Enhancing the capability of the onboard charger to fast charging level, while enabling EV auxiliary support, and providing vehicle-to-vehicle charging without any reconfiguration.
- ❖ Extending the voltage range of the fractional power processing converter to enable both buck and boost mode charging and discharging operation.

The literature review that served as a foundation of this work established that the dual active bridge converter is the most commonly used power converter in EV charging applications due to its several performance and topological benefits. However, DAB lack in features such as simple CC-CV control, which is necessary to achieve optimal battery charging. Further, its application for very high-power applications such as ultra-fast charging is limited as the entire power will be processed through the converter, which results in high losses, degraded power density, and makes the charger cost impractically high. Moreover, the distinguished benefits of DAB, such as bidirectionality and simple configuration, can be leveraged to enhance the slow charging capability of the on-board charger to a fast-charging level, as well as enabling V2Aux and V2V functions from a single converter, making it a complete EV solution onboard.

In order to address these identified research gaps relating to optimal battery charging, this thesis aims to develop a current-driven bi-frequency resonant dual active bridge converter that operates at two different but fixed frequencies to behave as a current source and a voltage source. The aim is to eliminate the dedicated controller, improving the cost, magnetic design and performance of the charger for optimal battery charging. In addition, soft-switching of the converter switches in each of the modes to improve the overall efficiency of the converter. Also, the developed charger eliminates the input current ripple and has improved reliability compared to the conventional charger.

To address the issues related to ultra-fast charging this thesis aims to develop a current-fed fractional power processor that handles only a fraction of power, reducing the

required converter component rating significantly, facilitating high efficiency battery charging. The converter achieves ZVS for the entire range of battery voltage and fractionality ratio, ensuring high efficiency throughout the charging range. In addition, it achieves simple yet robust battery current regulation and a significant reduction in the size of the input inductor due to the differential current at the input. Due to the charger's step-up configuration, it is suitable to charge high voltage-high power batteries and support bidirectional power flow to cater to the futuristic UFC applications.

To address the challenges of slow charging speed, inter-operability issue and compact space relating to on-board chargers, this thesis aims to develop an inter-operable multi-utility fast charger based on fractional power processing approach, where a single converter perform slow AC charging, enable DC fast charging, supply auxiliary loads and support vehicle to vehicle charging when required. The aim is to operate the converter as a full-power processor to perform slow AC charging.

In fast charging mode, the aim is to operate the converter in fractional power processing configuration such that only the onboard charger's rated power is processed through the converter to achieve significantly higher charging power capability of up to four times the onboard charger's rated power. To supply the constant voltage required by EV auxiliary loads, the converter aims to operate in reverse power flow mode and half resonant frequency to behave as a voltage source. To supply another vehicle, the aim is to operate the converter in reverse power flow mode at resonant frequency to obtain current source behavior for quick V2V charging. All of the converter operations can be seamlessly achieved without any additional components or a dedicated controller.

To extend the range of fractional power processing converters, the aim is to equip the converter with bipolar switches and operate them with a specific PWM to allow both positive and negative voltage operation at the converter output. This enables high efficiency operation for a wide range of battery voltages while only processing a fraction of the power through the converter.

## **1.6 Organization of the Thesis**

The present thesis contains six chapters. The background, motivation and literature survey with research gap and the objective of the thesis are described in Chapter 1.

Chapter 2 presents a current-driven bi-frequency resonant dual active bridge converter for efficiently charging a battery in constant current–constant voltage (CC-CV) mode. 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 cause 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 a single step change in frequency and thus, offering dual source property at its output. This results in a 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 the replacement of an electrolytic capacitor with a resonant film capacitor. The behavior of the converter is analyzed through state-plane analysis, and the trajectory of each interval with the closed-form solution is presented. A performance comparison of the proposed charger with the earlier reported literature is also presented in this chapter. To 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 modes.

In Chapter 3, a novel current driven fractional power processor with resonant DAB converter, suitable for efficient ultra-fast charging applications, is presented. The processor configuration allows only a fraction of power to be processed through the converter, thus 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 operation of the converter and its performance as UFC are discussed in detail with a 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 chapter.

Chapter 4 presents a novel interoperable multi-utility charger capable of performing high efficiency fast charging (FC), supplying EV auxiliaries (V2Aux), and charging vehicle to vehicle (V2V). In FC mode, the dc/dc converter is configured such that only the onboard charger (OBC) rated power is processed through the converter while the bulk power is transferred directly through a series path. Thus, facilitating the OBC to perform FC 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 FCs. 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 FC 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 the resonant frequency with reverse power flow to support quick CC V2V charging. The versatile nature of the proposed charger to operate in FC, 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 detail, and the design criterion is discussed. The proposed concept is verified with a laboratory-developed 1 kW charger with the efficiency of 98.87 % in fast charging mode, 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 in this chapter.

Chapter 5 proposes a novel quad-operative fractional power processor that extends the charging voltage range of traditional step-up or step-down resonant dual active bridge-based FPP systems to enable charging and discharging of the battery in both buck and boost modes. The proposed charger with its simple control logic achieves seamless transition between buck-boost and forward as well as reverse power flow mode, enabling the four-quadrant operation of the proposed FPP system, all while processing only a fraction of the total power through the converter. The flexibility to operate in four quadrants with a wide voltage range makes the proposed system a suitable choice of converter for application in high-power, fast, and ultra-fast charging stations. The converter performance is verified through simulation and a scaled-down laboratory-developed prototype.

Chapter 6 contains the conclusion of this research work carried out in this thesis and the scope of future work in this area.