Chapter 1

Introduction

1.1Background

Lithium-ion battery-based electric vehicles (EVs) offer numerous advantages over petroleum-fuelled internal combustion engine (ICE) vehicles, making them a more environmentally friendly and consumer-friendly option [1]. EVs produce zero tailpipe emissions, significantly reducing air pollution and greenhouse gas emissions compared to ICE vehicles, which burn fossil fuels and release harmful carbon dioxide (CO_2) and nitrogen oxides (NOx) [2],[3], [4] . These gases trap heat in the Earth's atmosphere, causing a gradual increase in global temperatures. Additionally, EVs are more energy-efficient, converting around 85-90% of their electrical energy into vehicle movement, while ICE vehicles only convert about 20-30% of their fuel energy into motion. This efficiency results in lower operating costs for EVs, as electricity is cheaper than gasoline, and the fewer moving parts in an EV mean reduced maintenance expenses [5], [6]. Moreover, the shift to renewable energy sources like solar and wind for electricity generation further amplifies the environmental benefits of EVs [7]. As advancements in lithium-ion battery technology continue to extend vehicle range and reduce charging times, EVs present a cleaner, more cost-effective, and sustainable alternative to traditional ICE vehicles [8], [9]. In India, the transportation sector emitted 155.9 Mt to 368.2 Mt of CO_2 from 2001 to 2020 [10]. Adopting electric vehicles (EVs) instead of fossil fuel-based vehicles can help reduce CO_2 emissions. However, the high cost of EVs limits their demand in the consumer market. This cost can be lowered by integrating emerging technologies into EV design. The benefits of adopting lithium-ion battery-based EVs are shown in Table 1. 1. This thesis represents a lithium-ion battery-based EV.

Table 1. 1 Benefits of the adoption of the lithium-ion-based EV

High Energy density	Lightweight	High power-to-weight ratio
High Efficiency	Long life cycle	Low self-discharge rate
Fast charging capability	Scalability	Lower environmental impact
Improved safety features.	Zero tailpipe emissions	Modularity

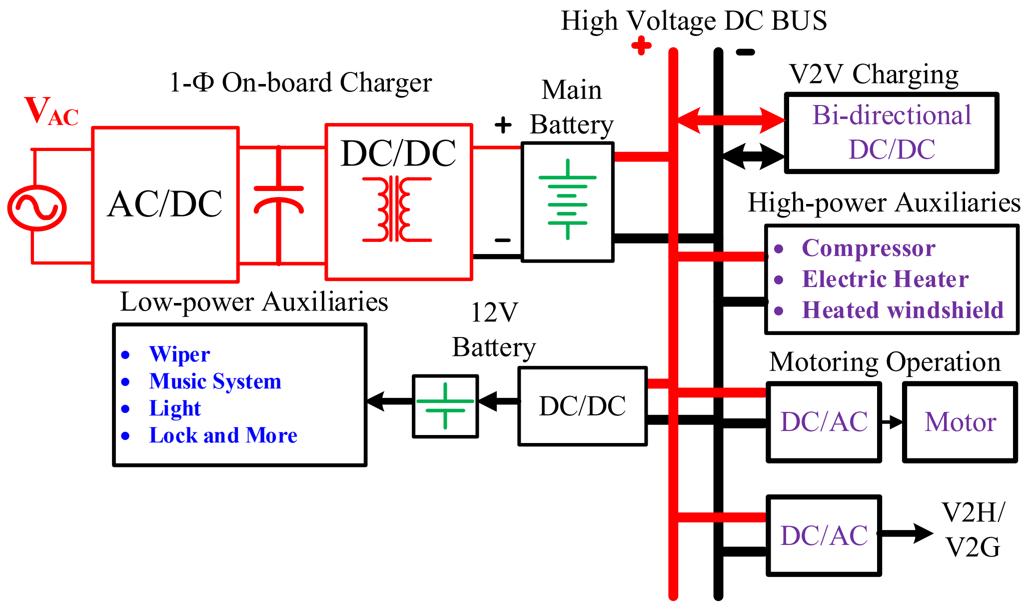

Fig.1. 1 Block diagram of the conventional EV system.

1.2Motivation:

Designing an electric vehicle (EV) is not just about creating a mode of transportation, it's about driving the future towards sustainability. Every line and every innovation in an EV brings us closer to a cleaner planet, reducing our carbon footprint and embracing the power of renewable energy. By reimagining mobility, we can design a world where efficiency, performance, and environmental responsibility go hand in hand. Let's build vehicles that not only move people but move us all towards a brighter, greener future.

The operation of an EV involves three main functions:

1) Charging,
2) Motoring, and
3) Powering the EV cabin to ensure safety and comfort.

Existing EVs have two charging options: i) Off-board and ii) On-board. The off-board charger has a high-power DC fast charger, and its installation cost is high [11]. The on-board charger, which is an AC charger, is built into the electric vehicle (EV), and its cost is already included in the overall price of the EV. In on-board charging, AC/DC and DC/DC two-stage converters are required to charge the main battery [12], [13], [14], [15], [16], [17], [18]. In a motoring operation, a DC/AC converter takes the power from the battery and switches according to the motor [19]. During all these operations, the cabin's low-power auxiliaries are supported by an additional low-voltage battery, and the high-power auxiliaries are directly connected to the high-voltage main battery [20], [21],[22],[23].

Apart from the above-mentioned properties, various converters are required for other functions, such as inverters used to drive the motor, V2G/V2H operation, DC/DC converters used for V2V charging, low-voltage battery charging, etc. [24], [25], [26]. However, all the processes are mutually exclusive. All these functions are essential to improve the charging process, which reduces the uncertain burden on the grid. The block diagram of the conventional EV system is shown in Fig.1. 1. The benefits of all these functions are as follows.

i) An additional DC/DC converter charges the low-voltage battery from the main battery or AC supply source [27], [28], [29], [30]. The low-voltage battery supports the cabin's low-power auxiliary demand, such as the music system, lock, wiper, light, and more.

ii) V2G/V2H operations can supply energy on demand during extreme environmental conditions and in rural areas, requiring an additional DC/AC converter. Additionally, they can help reduce the load on the power grid and create one dimension of energy trading [31].

iii) V2V charging enables mobile power transfer by a bidirectional DC/DC converter, helping to reduce range anxiety from the consumer's mind [32], [33].

iv) All these converters occupy significant space, which negatively impacts their power density.

v) An individual converter for the specific operation increases the cost of the EV.

Therefore, integrating these functionalities into the on-board chargers of electric vehicles can significantly reduce overall system costs and promote wider consumer adoption. This thesis presents a unified, cost-effective converter design that integrates all these functions into a single solution.

1.3 Literature survey:

Conventionally, different features with different converters increase the required space and cost of the EV. The converters used in these features work mutually exclusively. For example, the motor remains stationary during the on-board charging operation. Therefore, the on-board charger can be integrated with the converter of the motor drive.

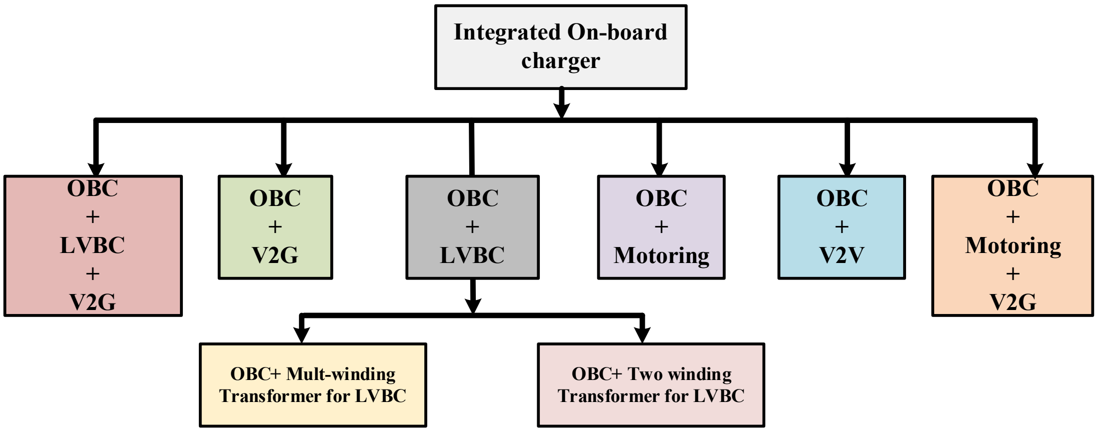

Fig.1. 2 Different possible integrated onboard chargers.

The possible integrations of various features with the on-board charger (OBC) are illustrated in Fig.1. 2. The OBC supports dual-function and multi-function configurations to enhance vehicle performance and energy flexibility.

1.3.1 Dual-Function Integration:

These configurations involve the integration of the OBC with two distinct functions, including:

- OBC and low-voltage battery charger (LVBC).
- OBC and motoring mode (MM) operation.
- OBC and vehicle-to-grid/vehicle-to-home (V2G/V2H) power supply.
- OBC and vehicle-to-vehicle (V2V) charging.

1.3.2 Multi-Function Integration:

- OBC integrated with LVBC and V2G power supply.
- OBC integrated with LVBC and MM operation.
- OBC integrated with V2G and MM operation.

1.3.2.1 Integrating the On-board charger with the LVBC:

Traditionally, the on-board charger is integrated with a low-voltage battery charger. To integrate the on-board charger with a low-voltage battery charger (LVBC), either a multi-winding or a two-winding transformer is used [34]. In [35]-[36] the on-board charger is integrated with the multi-winding transformer to charge the main battery and low-voltage battery, simultaneously. However, the galvanic isolation is missing during the main-battery charging. The galvanic isolation prevents the fault current from entering the EV from the grid. In [37], an isolated on-board charger integrated with a multi-winding transformer charges the main and low-voltage batteries, as shown in Fig.1. 3. However, the multi-winding transformer adds design complexity and affects voltage regulation during dynamic loading. In [38], [39], on-board charger integrated with a two-winding transformer to charge the main battery and low-voltage battery, as shown in Fig.1. 4. However, only two functions are integrated, with the help of 20 switches [39].

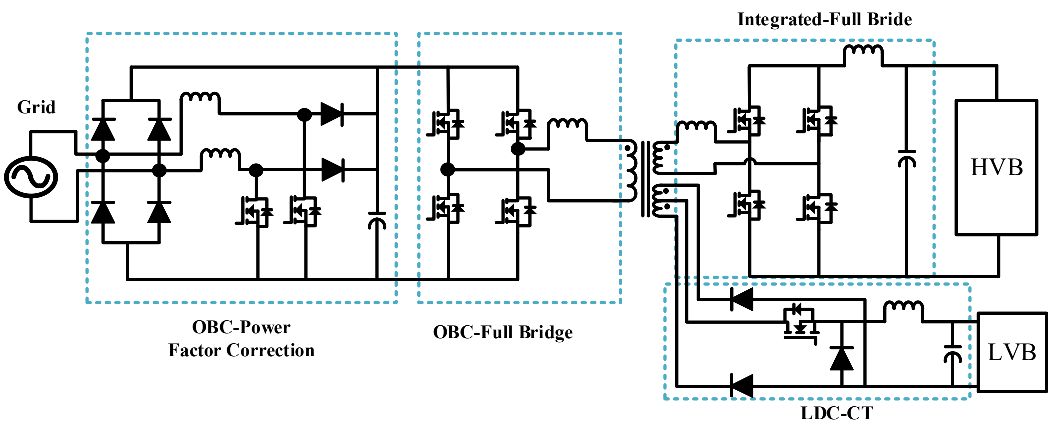

Fig.1. 3 On-board charger integrated with a multi-winding transformer for charging the main battery and a low-voltage battery.

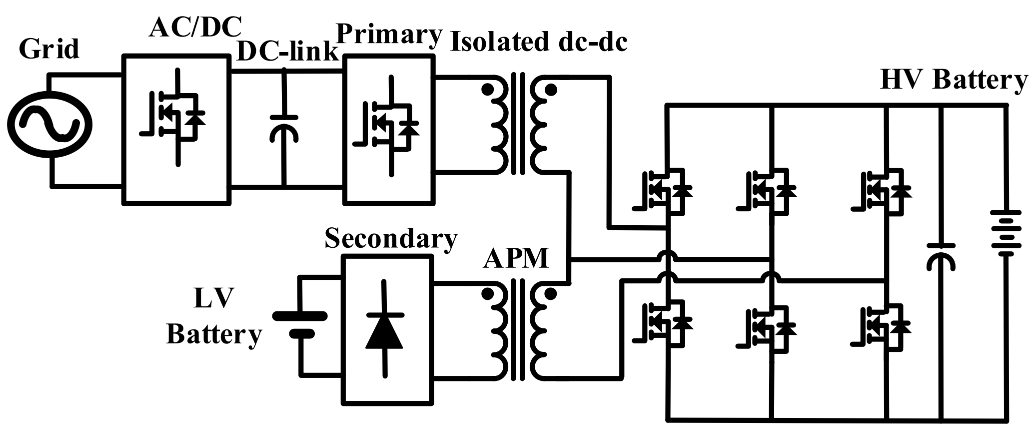

Fig.1. 4 On-board charger integrated for low-voltage battery charger with a two-winding transformer.

1.3.2.2 Integration of on-board charger with motoring mode operation

In [40], [41], [42], [43], [44], [45], [46], [47], [48] the on-board charger is integrated with motoring mode operation. The galvanic isolation is also missing in these integrated converters during the single-phase charging. However, the **IEEE standard 2405-2022** states that the AC input and DC output circuits shall be galvanically isolated from each other. In [49], the coupled magnetic-based isolated on-board battery charger is integrated for the electric vehicle's boot motor drive unit, as shown in Fig.1. 5. However, only the motoring mode is integrated with the on-board charger.

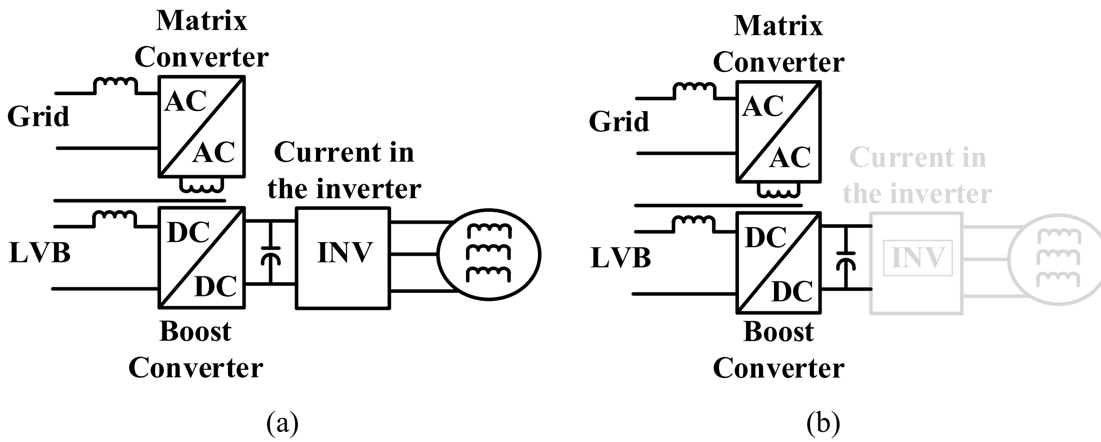

Fig.1. 5 Couple magnetic-based integrated power unit that can provide two functionalities: (a) boost motor drive and (b) OBC.

1.3.2.3 Integration of on-board charger with V2H/ V2G operation

To enable integration of the OBC with V2H/V2G power supply functionality, the system must incorporate bidirectional power flow capability [50], [51], [52], [53]. Therefore, the on-board charger is integrated with a vehicle-to-grid (V2G) power supply [54], [55], [56], [57], [58]. In [59], a bidirectional dual active bridge (DAB) is cascaded with DC/AC converter for G2V and V2G operation. However, for G2V and V2G operations, an additional DC/AC converter is required alongside the DAB. In [60], a dual active bridge with asymmetric semi-variable frequency modulation is used for the G2V and V2G operation. However, only V2G operation is integrated with on-board charger.

1.3.2.4 Integration of on-board charger with V2V charging operation

In [61], an additional converter is required along with the on-board charger for vehicle-to-vehicle (V2V) charging. However, the on-board charger can be integrated for the V2V charging[62], [63]. In [64], an integrated V2V charger is given, where the motor winding neutrals and the negative rails of the on-board drivetrains of both EVs are directly connected. However, access to the motor winding’s neutral point is essential for multimode operation, which can increase the machine design complexity. In [65], two on-board chargers are directly connected for the energy transfer between the EVs. However, eight switches are used for V2V energy exchange, which can increase the switching losses during the V2V charging, as shown in Fig.1. 6.

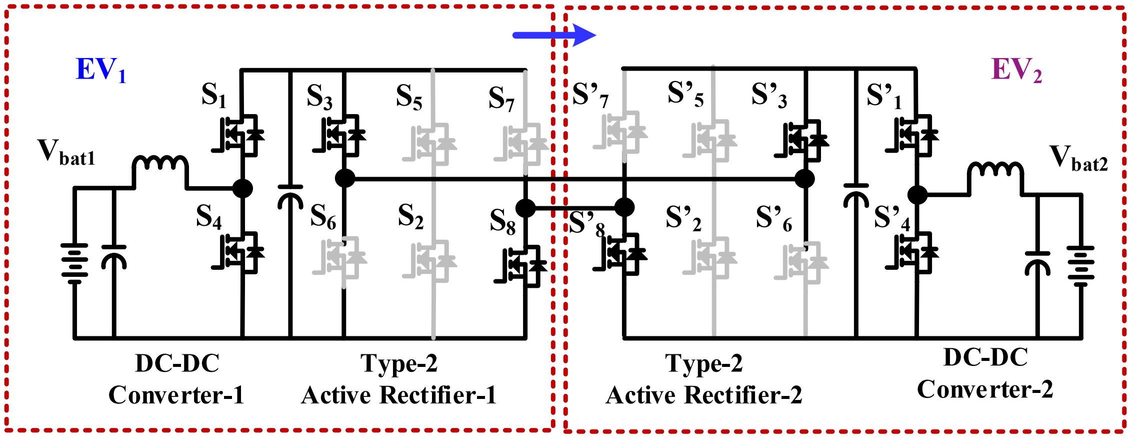

Fig.1. 6 On-board charger is integrated and used as a V2V charger.

In the configuration mentioned above, the power converter integrates only two functions into a single converter, such as G2V with LVB charging, G2V with MM, G2V with V2G, or G2V with V2V. However, there is scope for integrating two or more functions into a single converter, because all these modes of operation work independently.

1.3.3 Multi-Function Integration:

These involve the integration of the OBC with more than two functions, showcasing its versatility:

- OBC integrated with MM operation and V2V charging.
- OBC integrated with V2G power supply, MM operation, and LVBC.
- Other possible combinations involving V2H, V2V, MM, and LVBC.

These configurations demonstrate the OBC's ability to serve as a multifunctional component in modern electric vehicles, enabling efficient operation and bidirectional energy flow.

1.3.3.1 Integration of on-board charger with LVBC and V2G

In [66], [67], [68], [69] the multifunctional on-board charger (OBC) provides low-voltage battery charging (LVBC) and vehicle-to-grid (V2G) power supply. The main battery charges the low-voltage battery; however, both batteries cannot be charged at the same time. In [70], multifunctional OBC and photovoltaic (PV) power are used to charge the main and auxiliary battery simultaneously, as shown in Fig.1. 7. However, 17 switches and two transformers are used for the implementation of G2V, V2G, and LVBC operations.

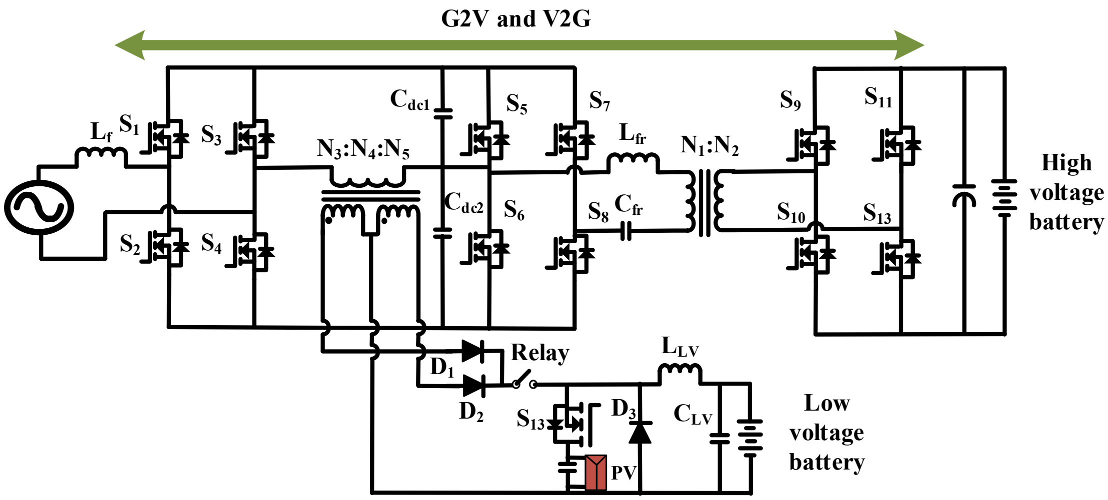

Fig.1. 7 A multifunctional power converter for G2V, V2G, and LVBC.

1.3.3.2 Integration of OBC for V2G and motoring operation

In [71], [72], [73], integrate the OBC with the V2G and motoring operation. In [72] a dual active bridge (DAB) DC-DC converter cascaded by a three-phase four-leg DC-AC converter with 18 switches to perform these operations, as shown in Fig.1. 8.

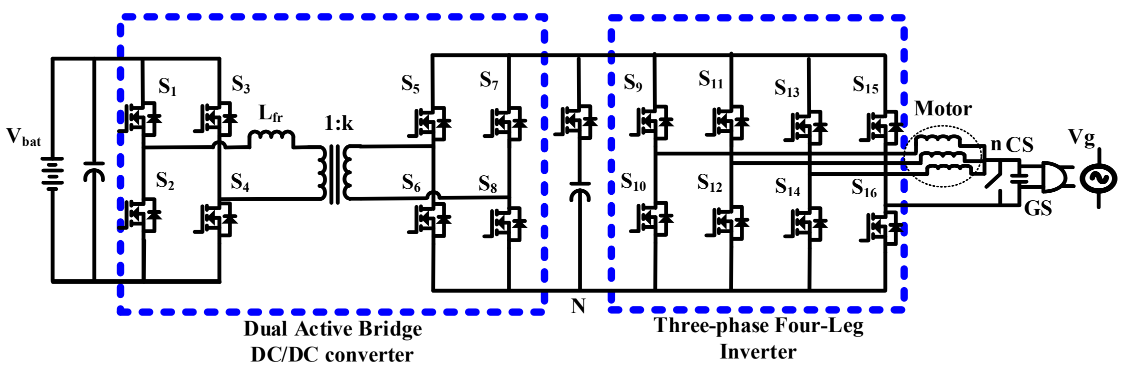

Fig.1. 8 Integrated circuit of on-board charger for G2V, V2G, and motoring operation.

1.3.3.3 Integration of OBC for V2G and V2V operation

In [74], the OBC is integrated with G2V charging, V2G power supply and V2V charging. However, for these operations, the six-phase induction motor is cascaded with a six-leg converter along with four additional changeover switches.

1.3.3.4 Integration of OBC for LVBC and Motoring operation

In [75], an integrated switched reluctance (SRM) powertrain with OBC provides G2V charging, motoring operation, and LVB charging operation, as shown in Fig.1. 9. However, three changeover switches are used for the mode transformation.

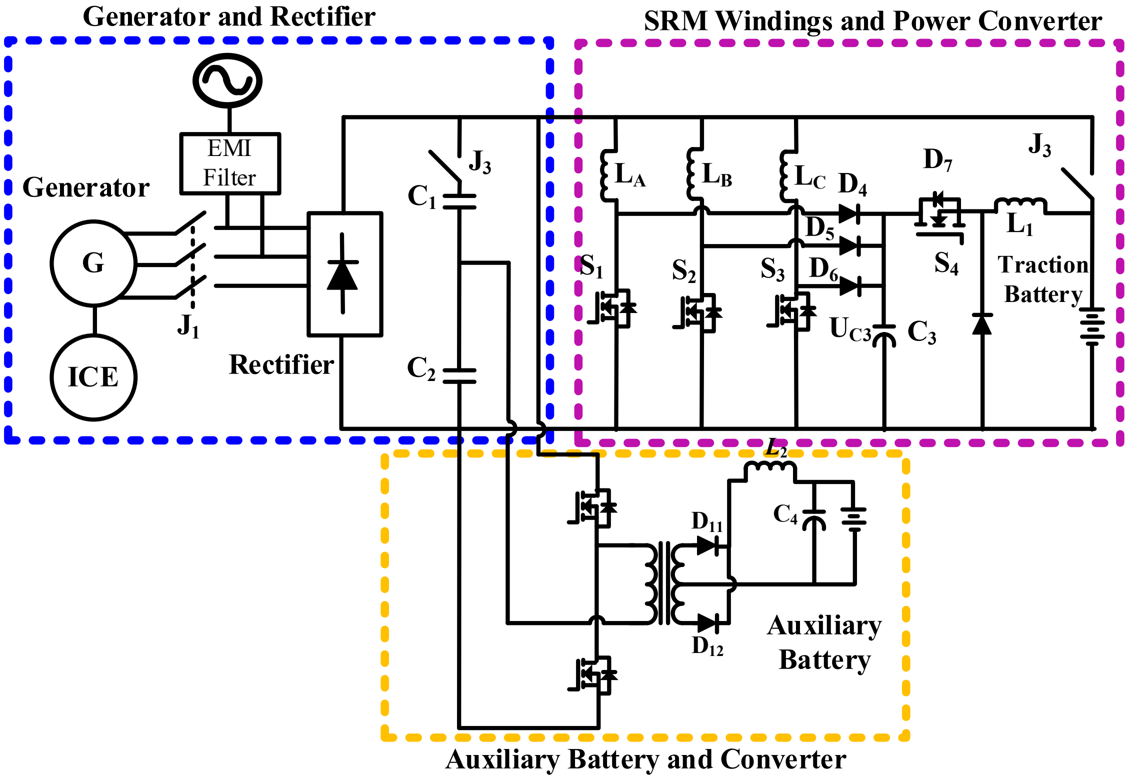

Fig.1. 9 Integrated switch reluctance power train with OBC for G2V charging, LVB charging, and MM operation.

1.4 Challenges with the Existing Similar Prior Work

Concerns about air pollution caused by gasoline-powered transportation can be alleviated by shifting toward electric vehicle adoption. Additionally, integrating emerging technologies can transform the transportation system into an eco-friendly operation. In EVs, different converters are required for various functions, which increases their cost and required space. This required space decreases the power density of the converter.

Therefore, the researchers are integrating one or more functions into an on-board charger because the cost of the on-board power converter is included in the price of EVs. Two or three functions are combined into a single unit in the integrated converters discussed above. However, they tend to have a relatively high switch count. The optimal design of an integrated power converter is crucial for enhancing electric vehicles' power density and efficiency.

From the above-discussed power electronics converter, the overall challenges observed in similar prior works are as follows

❖ Integration of the converter:

- Only two or three features of the EVs are integrated into the single power electronics converter.

- The integration is formed between the OBC and the low-voltage battery charging converter.
- OBC with the motoring mode operation of the converter.
- OBC with V2V power supply.
- OBC with V2G power supply.
- OBC with the V2G and the LVB charging converter.
- OBC with the LVB and motoring operation.
- OBC with the Motoring and V2V operation.

❖ An additional requirement of LVB and its charger

- An additional LVB (12 V) and its charger are required for the low-power auxiliaries.
- The high-power auxiliaries are directly connected to the main battery.
- The cost of the LVB is also high.

❖ High-power auxiliary supply in low-power EVs

- In EVs, high-power auxiliaries are directly connected to the main battery. Therefore, boosting the battery voltage for these auxiliaries can decrease the current demand from the auxiliaries.

❖ Switch count and the power density:

- A large number of switches have been used for these integrations.
- For more than the three functions, an additional converter is required. These additional converters acquire more space in EVs, which decreases the power density and increases the cost.

❖ Process of the mode transformation:

- The operation of the power converter is transferred from one operating mode to another with the help of the relay (changeover switech).
- The life cycle of the relay can affect the durability of the integrated power electronics converter.

1.5 Objective of the thesis:

It is concluded from the literature survey that there is not a single converter that performs G2V charging, V2G/V2H power supply, V2V/DC charging, MM operations, and auxiliary power supplies. Additional changeover switches have been used to transfer from one operating mode to another.

However, the life cycle of the changeover switch affects the durability of the integrated converter. Further, an additional LVB and its charger are required for the low-power auxiliaries, and the high-power auxiliaries are directly connected to the main battery. More converters occupy more space, increasing the power converter's size and decreasing the power density and efficiency.

In order to overcome the above challenges, the thesis aims to develop a single converter for all modes of operation without any additional relays. Along with that, the regulated multi-outputs in all the modes of operations eliminate the requirement for an additional LVB (12 V) and its charger. The proposed power processor is designed systematically in five different topologies to achieve all four different functions with auxiliary power supplies for EVs:

- The first topology is designed as a multifunction quasi-Z source-based multimode power processor for low-power EVs. In multifunction operation, it charges the battery from the single-phase AC supply and can drive a 36 V AC motor with the proposed modified sinusoidal pulse width modulation (M-SPWM) technique. The charging mode to motoring mode is reconfigured with the help of seven changeover switches. In multimode property, four changeover switches are used to form the circuit of energy supplier and acceptor vehicles for energy exchange during V2V charging.
- In the second topology, the 48 V, 1 kW BLDC motor is driven with an adaptable multifunction power processor having multimode properties. In multifunction, the proposed converter performs charging as well as motoring operations and generates auxiliary power supplies for the EV cabin. Further, in its multimode properties, vehicle-to-vehicle charging is provided by restructuring itself with three changeover switches. For driving the BLDC motor, a high-PWM low-ON switching technique is used, which reduces the commutation torque ripple.
- In the third, an on-board power processor is designed, which has inherent V2V operation with reduced components. In this design circuit, the switch count is reduced from 18 to 14, in which only three switches are used in place of seven for the mode selection. Further, for the V2V charging, the proposed power converter from both vehicles is directly connected.
- Further, a reversible multifunction multimode on-board power processor is designed, which has inherent V2G property, along with G2V, V2V, and motoring operation. The proposed power processor generates the regulated outputs for the power support of the EV cabin in all modes of operation.

- In the next topology, a designed multifunction multimode power processor enabling induction motor (IM) drive with auxiliary power supplies for high-power EVs. For the mode selection, no additional changeover switches are required. Only one connector is required for connecting the motor to the proposed power circuit.

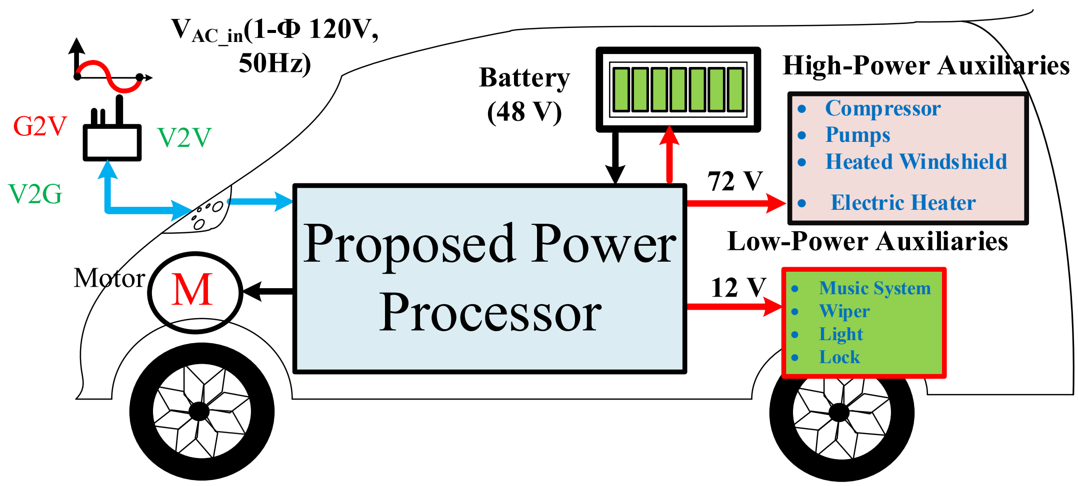

Fig.1. 10 Block diagram of the proposed power processor.

This thesis represents a laboratory-scale design of a proposed power processor, which serves as a G2V charging, V2G power supply, V2V charging, and motoring operations. Along with that, it generates the regulated power supplies for the power support of the EV cabin. The block diagram of the proposed power processor is shown in Fig.1. 10.

All the configurations are suitable for low-power EVs, like GEMe4, Mahindra e20, Wings car, Microlino, Storm R3, MG Comet, etc.

1.6 Organisation of thesis:

The present thesis contains even 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 multifunction quasi-Z source-based multimode power processor for low-power EVs. In multifunction operation, it charges the battery from the single-phase AC supply and can drive the 36 V AC motor with the proposed modified sinusoidal pulse width modulation (M-SPWM) technique. The charging mode to motoring mode is reconfigured with the help of seven changeover switches. Further, in its multimode property, it performs vehicle-to-vehicle charging. In V2V charging, the proposed power processor restructures itself with the help of four changeover switches into an energy supplier and acceptor vehicle circuits for energy exchange. In charging mode, it generates three outputs from the single-phase power supply. 1) output charges the battery with constant-current and constant-voltage (CC-CV) technique, and maintains the unity power factor at the source terminal, and the 2) and 3) outputs cater to the power demand of the EV cabin. In motoring mode, a new M-SPWM technique is proposed for three outputs: 1) a buck-boost AC output for the motor drive, and 2) and 3) outputs to power the EV's cabin. The multioutputs eliminates the requirement of an additional LVB (12 V) and its charger. A comparison analysis with similar prior work with a different function with switch count is presented. Further, a laboratory-scale prototype for the proposed concept is developed and tested at 550 W.

Chapter 3 presents a BLDC motor drive with an adaptable multifunction power processor having multimode operations. It is a single converter that performs charging and motoring operations with the auxiliary power supplies. Further, the vehicle-to-vehicle charging is performed by restructuring the power processor into an energy supplier and acceptor circuit with the help of three changeover switches. The proposed converter charges the 48 V battery from the single-phase 120 V, 50 Hz power supply and generates 12 V and 72 V to the power supply of the EV cabin. The charging mode is tested at 500 W, where the proposed converter charges the 48 V, 36 Ah battery and powers the auxiliaries of the EV cabin by a unified control loop. The proposed converter is restructured to efficiently drive the 4-pole 1000 W BLDC motor with a High-PWM Low-ON switching technique while simultaneously supplying power to the auxiliary systems of the EV cabin. Furthermore, the V2V charging is performed at 480 W. The proposed power processor's comparative analysis and cost analysis with similar prior work are listed in a tabular form. Further, the power density of the proposed power processor is calculated and compared with similar previous work.

Chapter 4 presents an on-board power processor having inherent V2V operation with reduced component count. The proposed single converter serves for single-phase on-board charging, multioutput for the auxiliaries, motoring operation, and vehicle-to-vehicle (V2V) charging operation. The proposed converter uses 14 switches, which is a smaller number of switches with respect to the number of functions compared with similar prior converters. The multioutput features of the proposed converter are utilized for functionalities of V2V charging and auxiliary supplies, along with motoring and single-phase charging. For V2V charging, no circuit modification is required. Only six active switches from both vehicles are used for the V2V charging. The converter's efficiency in single-phase on-board charging, motoring operation, and V2V charging modes is 91.88 %, 92.3 %, and 93%, respectively, nearly 90 % of its rated load. Further, the thermal stability of the proposed converter is added in the experimental section. A laboratory-scale prototype is developed, which tests 780 W in charging mode, 1000 W in motoring mode, and 480 W during V2V changing operation.

Chapter 5 presents a reversible multifunction multimode on-board power processor with inherent V2G Operation. The proposed power processor provides grid-to-vehicle (G2V) charging, vehicle-to-grid (V2G) power supply, motoring operation (MM), vehicle-to-vehicle charging, and auxiliary power supply for the EV cabin. During G2V operation, it charges the 48V battery from the 120V, 50Hz power supply and generates two more outputs of 12V and 72V to supply the low-power and high-power auxiliaries of the EV cabin. In V2G operation, the 3.5 A current is injected into a 120 V, 50 Hz AC grid system. In motoring mode, it drives the BLDC motor with a High-PWM Low-ON switching scheme and generates regulated output voltages (12 V and 72 V) from the 48 V battery. The 12 V regulated output eliminates the demand for an additional low-voltage battery (12 V), and its charger and 72 V output reduce the current demand for the high-power auxiliaries in low-power EVs. To express the novelty, comparative analysis, cost analysis, and component utilization factor have been expressed with similar prior works. To justify the proposed idea, the multifunction operation, control algorithm, and experimental results with load dynamics are presented. A laboratory-scale prototype is tested at 780 W in G2V changing operation, 1 kW during V2G operation, 1 kW in motoring operation, and 480 W in V2V charging.

Chapter 6 presents the multifunction multimode power processor enabling induction motor (IM) drive with auxiliary power supplies for high-power EVs. The proposed power processor enables G2V, V2G, V2V, and IM drive, operation, and auxiliary power supply in EVs. In this system, all the modes are transferred without any changeover switches, except in motoring mode. A connector “S” is required only for motoring mode operation to connect the motor to the proposed power processor. All the functions are implemented by only 14 switches, which is less compared to similar prior work. The proposed power processor is tested in a load transient condition, and it is found that the system is stable regardless of the variation of the load. A laboratory prototype is tested in 720 W in G2V operation, 1 kW in V2G operation, 490 W in V2V operation, and 768 W in motoring mode operation. Further, the loss analysis is determined in all the modes of operation by varying the load from 10% to 100%. The peak efficiency operation of the proposed power processor in G2V, V2G, V2V, and IM drives is 97%, 95.3%, 97.2%, and 93.5%, respectively.

Chapter 7 presents the general conclusion of the research conducted in this thesis, along with the scope for future work in this area.