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Vehicle-to-Vehicle (V2V) Power Transfer: Electrical and Communication Developments

Azizulrahman Shafiqurrahman, *Member, IEEE*, Vinod Khadkikar, *Fellow, IEEE* , and Akshay Kumar Rathore, *Fellow, IEEE*

***Abstract*—The concept of energy transfer between two vehicles and communication between them is a promising one for the future of electrified transportation sector. In response to the growing research and interest in vehicle-to-vehicle (V2V) technology, this article provides an in-depth review on the actual energy transfer between two vehicles and their communication aspects. The literature is addressed to analyze power electronics topologies for successful V2V power transfer and compare V2V charging optimization techniques. Communication protocols and standards relevant to V2V technology are also discussed with a focus on their potential applications for improving transportation safety and efficiency. Further, challenges faced by existing V2V power transfer solutions and the commercial products available for implementing V2V charging are described. In contrast to other literature surveys, this paper provides a comprehensive overview of V2V power transfer and communication technologies with implications for the future of sustainable electrified transportation. The study and discussion of over 300 papers on the topic are encompassed in this paper.**

***Index Terms*—Electric vehicle (EV); V2V power transfer; On-board charger; Off-board charger.**

NOMENCLATURE

3GPP	3rd Generation Partnership Project
ADAS	Advanced Driver Assistance System
MBNN	Bichromatic Mutual Nearest Neighbor
BSM	Basic Safety Message
CAM	Cooperative Awareness Message
CAV	Connected Autonomous Vehicles
CCA	Cooperative Collision Avoidance
CCW	Cooperative Collision Warning
CPT	Capacitive Power Transfer
CS	Charging Station
D2D	Device to Device Communication
DAB	Dual Active Bridge Converter
DSRC	Dedicated Short-Range Communication
EATC	Earliest Available Time for Charging
EMF	Electromagnetic Field
ETSI	European Telecommunications Standards Institute
EV	Electric Vehicle
EVSE	Electric vehicle Supply Equipment
FCC	Federal Communications Commission, U.S.
FCW	Forward Collision Warning
GaN	Gallium Nitride
ICE	Internal Combustion Engine
ICW	Intersection Collision Warning
IEC	International Electrotechnical Commission
ILP	Integer Linear Programming
IoV	Internet of Vehicles
IPT	Inductive Power Transfer
ITS	Intelligent Transportation System
LCW	Lane Change Warning
LOS	Line of Sight
LTE	Long Term Evolution
MED	Mobile Energy Disseminator
MIP	Mixed Integer Programming
MLGS	Message Linkable Group Signature
mm-Wave	Millimeter Wave Communications
MP	Meeting Point
MRC	Magnetic Resonant coupling
MPC	Model Predictive Control
NHTSA	National Highway Traffic Safety Administration
OBU	On-Board Unit
PR	Proportional Resonant
RES	Renewable Energy Resource
RSU	Road Side Unit
SAE	Society of Automotive Engineers
SiC	Silicon Carbide
SRM	Switched Reluctance Motor
TTC	Time-to-Collision
VANET	Vehicular Ad hoc NETwork
V2D	Vehicle-to-Device
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2R	Vehicle-to-Roadside Unit
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
WAVE	Wireless Access in Vehicular Environments
WBG	Wide Band-gap Semiconductor
WPT	Wireless Power Transfer
ZPA	Zero Phase Angle

Manuscript received July 26, 2023; revised September 02, 2023 and November 10, 2023; accepted December 05, 2023. This work was supported by the ASPIRE, the technology program management pillar of Abu Dhabi's Advanced Technology Research Council (ATRC), via the ASPIRE "VRI (Virtual Research Institute)" under Grant VRI20-07.(*Corresponding author: V. Khadkikar.*)
A. Shafiqurrahman is with the Department of Electrical Engineering and Computer Science, Khalifa University, PO Box 127788, Abu Dhabi, UAE (email: azizulrahman.shafiqurrahman@ku.ac.ae).
V. Khadkikar is with the Advanced Power and Energy Centre (APEC), Department of Electrical Engineering and Computer Science, Khalifa University, PO Box 127788, Abu Dhabi, UAE (email: vinod.khadkikar@ku.ac.ae).
A. K. Rathore is with the Electrical and Computer Engineering, Singapore Institute of Technology, Singapore 138683 (e-mail: akshay.k.rathore@ieee.org).

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I. INTRODUCTION

THE transportation sector has seen tremendous growth in recent years. Key developments include the use of electric vehicles (EVs) to reduce the carbon footprint and the shift to intelligent transportation systems (ITS) [1]. EVs are becoming economically attractive to customers because their ranges are increasing, the cost of charging EVs is far cheaper than refueling internal combustion engine (ICE) based vehicles, the reserve capacity and safety standards of Li-ion batteries are improving, and the amount of charging stations (CSs) with higher power capacities is increasing in cities worldwide [2]. The rising adoption of EVs has significant impacts on power systems in the form of high load demand at peak hours [3], nonuniform load profile [4], [5], power system stability [6], voltage stability [7], [8], energy consumption [9], power losses and line loading [10], power quality [11], and distribution network [12], [13]. Therefore, extensive research has been conducted to address these issues [14]–[19] such as optimal planning for EV battery swapping stations [20]–[22], coordination of EV charging in smart grids [23], [24] and EV-based ancillary services for the power grid, such as load balancing [25]–[27], voltage regulation [28]–[30], frequency regulation support [31]–[33], and grid congestion management [34]–[38].

EV chargers have the ability to receive or deliver power to the grid or household via connections grid-to-vehicle (G2V), vehicle-to-grid (V2G), home-to-vehicle (H2V), and vehicle-to-home (V2H) [39]. Additionally, EVs can receive power from or deliver power to another vehicle via a vehicle-to-vehicle (V2V) connection, which is the subject of this article. V2V is emerging as an essential term for transferring power and/or communication between two or more vehicles. This paper investigates both aspects of V2V technology and presents an up-to-date overview.

V2V power transfer solutions presented in the literature differ in terms of the number of conversion stages, phases, circuit topologies, rated power, power efficiency, and other aspects. V2V power transfer has been implemented at three different power levels: Level-1 slow charging (1.4-1.9 kW), Level-2 moderate charging (4-19.2 kW), and Level-3 fast charging (50-240 kW) [40]–[42].

V2V charging solutions have been developed for a variety of reasons, e.g., to address range anxiety, to allow EVs to share power in situations where neither the DC fast CSs nor the AC grid are available, to reduce energy demand, to improve grid loading, and for commercial purposes to take advantage of different energy tariffs and sell energy at higher prices during peak hours [43]–[45]. To further enhance the power system, V2V power transfer has been implemented to improve grid loading during peak hours, reduce losses between the CSs and the grid [46], minimize charging costs, optimize the utilization of renewable energy resources (RESs), move traditional power grids toward smart power grids, and reduce reliance on CSc, which significantly affect the power grid, as discussed in [47].

EVs are heavily dependent on CSs for recharging during long trips; therefore, the optimal allocation of CSs [48]–[52], CS scheduling strategies [53]–[57], and the coordination of V2G, G2V, and V2V operations at CSs [58], [59] has been studied in the literature as CSs are used as an interface between EVs. In [60], a publish/subscribe (P/S) communication framework has been suggested using public busses as data receiving/transmitting points for moving EVs to improve the communication required for optimal selection of CS with lower estimated waiting time (EWT). The P/S communication framework has been explained in more detail in [61].

Aggregators could be distributed in cities to transmit V2V power so EVs can charge and discharge without being connected to the grid [62]. This allows flexible and much cheaper direct V2V charging, also called cooperative V2V, between EVs without the need for CSs [63]–[66]. Cooperative V2V can further lower energy consumption by another 20-35% according to [67]. An additional option involves merging V2H with G2V to function as V2V, eliminating the necessity for a power grid or CS connection [39], [68]–[70]. In this scenario, one EV serves as an energy source by providing power to electrical loads via V2H, while another EV operates as an energy receiver, utilizing G2V functionality.

Gallium nitride (GaN) and silicon carbide (SiC) are wide bandgap (WBG) semiconductors that are becoming increasingly popular in V2V charging systems [71]–[73]. The main advantages of WBG switching devices include higher switching frequency, higher rated voltage, and lower switching and conduction losses, resulting in higher power efficiency [74]. WBG devices can operate at higher temperatures, require less cooling, and are smaller and lighter compared to other power switches [75]. SiC-based converters are more widely used and better suited than GaN in V2V applications due to their higher power, voltage, and temperature capabilities [76].

Techniques to optimize V2V charging include finding the optimal location among multiple CSs for multiple EVs in an appropriate manner, minimizing the traveling distances, reducing charging cost and time, individual EV user satisfaction, and coordinating V2V charging within a single CS. Controlling the flow of energy between different EVs has been studied, and several algorithms and protocols for V2V energy management have been proposed in the literature [46], [63]–[67], [77]–[89].

The weighted bipartite graph approach has been used in [46], [67], [77] to develop V2V matching algorithms with maximum weight. These algorithms aim to share V2V charge among EVs to increase user satisfaction and efficiency of the overall power distribution system. In [78], another optimization method based on the Oligopoly game and Lagrange duality has been presented to achieve the minimum cost for V2V charging. In [79], bichromatic mutual nearest neighbors (BMNN) are computed first before matching EV providers and receivers online. This process takes into account user privacy and connections created for V2V charging. The provider and receiver EVs need to communicate securely before requesting V2V charging; therefore, an authentication framework required for communication between EVs prior to V2V energy transfer has been developed in [90].

In [80], [81], mixed integer programming (MIP) has been formulated in a single CS to reduce the cost of V2V charging; similarly, in [82], [83], a MIP with the presence of RESs has been developed to coordinate and schedule V2V charging.

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TABLE I: V2V charging scheduling, coordination, and optimization techniques

Ref.	Main goal	Problem solving approach	Aggregator	Online / Offline	Objective function	Simulation & assumptions
[46]	Matching provider EVs to receiver	max-weight V2V (bipartite graph)	CS	Online, Offline	Minimize V2V charging cost	IEEE 14-bus power system
[63]	Matching provider EVs to receiver	Gale Shapley game and user satisfaction model	MP	Online	maximize V2V matching with highest average user satisfaction	20x20 km^2 area, 100 EVs, and 25 MPs.
[64]	Matching provider EVs to receiver	(1) V2V matching algorithm, (2) MP selection algorithm	MP	Online	maximize V2V matching and the best possible use of MPs	Helsinki, Finland, 4.5x3.4 km^2 area, 900 EVs, and 21 MPs.
[65], [66]	Matching provider EVs to receiver	(1) max-weight V2V, (2) EV-consumer oriented, (3) EV-provider oriented	supplier EV	Online	(1) Optimal network social welfare, (2) Optimal EV-consumer V2V matching, (3) Optimal EV-supplier V2V matching	20x20 km^2 urban network, 50 EVs, 25 parking lots, and 2 CSs
[67]	Matching provider EVs to receiver	max-weight V2V (bipartite graph)	CS supplier EV	Online	(1) maximize system benefit, (2) EV users' individual satisfaction	Java-based custom simulator, NHTS statistics
[77]	Matching provider EVs to receiver	max-weight V2V (bipartite graph)	CS supplier EV	Online	Maximize EVs matched to an energy supplier	Java-based custom simulator, Richmond metro area
[78]	Matching provider EVs to receiver	(1) Oligopoly game, (2) Lagrange duality	CS	Online	(1) Maximize revenue, (2) Minimize charging cost	PTV VISSIM traffic simulator, 6x2.8 km^2 area
[79]	Matching provider EVs to receiver securely	Privacy reserving BMNN	supplier EV	Online	Minimize traveling distance for V2V matching	1x1 km^2 area, 200 EVs
[80], [81]	Optimal scheduling of V2V (dis)charging	MIP using Benders decomposition	CS	Online	Minimize social cost	MATLAB 2012a
[82]	Optimal scheduling of EV (dis)charging	MIP	CS	Offline	Maximize EV users' satisfaction & minimize energy transactions	CPLEX 12.6.2 optimizer
[83]	Optimal scheduling of EV (dis)charging	MIP	CS	Online, Offline	Minimize charging cost	CPLEX 12.6.2 optimizer
[84]	(1) Optimal CS or MED selection, (2) Optimal routing to chosen MED or CS	Shortest path algorithm to select route for CS or MED	Supplier MED or CS	Online	Minimize travel time to reach a CS or MED for V2V	Erlangen city
[85]	Optimal CS selection through V2V	EATC	CS	Online	Minimize total waiting time	Helsinki, Finland, 4.5x3.4 km^2 area, 240 EVs, java-based ONE simulator
[86]	(1) Optimal routing, (2) Matching provider EVs to receiver	Shortest path algorithm to select route	supplier EV	Online	Minimize charging cost	5x5 km^2 area, 3 parking places with total 90 parking slots, Java Eclipse-based VanetMobiSim simulator
[87]	(1) Optimal routing, (2) Optimal CS selection for V2V, (3) Matching provider EVs to receiver	(1) Q-learning based algorithm, (2) max-weight V2V (bipartite graph)	supplier EV	Online	(1) Maximize V2V matching, (2) Minimize total waiting time, (3) Maximize aligning EVs (dis)charging through energy demand and supply matching	Nanjing city, China, 4x3.7 km^2 area
[88]	(1) Optimal routing, (2) Matching provider EVs to receiver	(1) ESTAM algorithm, (2) DP algorithm	supplier EV or CS or both	Online	(1) Maximize number of trips, (2) Maximize energy efficiency	Lower Peninsula of Michigan, each EV has 30 kWh battery, WPT-V2V efficiency assumed 90 %
[89]	Optimal trajectory of trucks	ILP using Dantzig-Wolfe decomposition	Supplier truck	Offline	Maximize EVs matched to supplier trucks for V2V	Montreal city, 54x16 km^2 area, 40 EVs, C++, and CPLEX optimizer

In [63], a comprehensive system for organizing and distributing energy among EVs has been suggested. It is a two-layer optimization approach incorporating the Gale-Shapley game and the user satisfaction model to bring EVs together for cooperative V2V charging at meeting points (MP) without needing CS. A similar solution has been presented in [64], which uses V2V matching and MP collection algorithms to reduce the amount of energy consumed by EVs. Three V2V matching algorithms are put forward in [65], [66] to improve the energy consumption profile and add further flexibility to EV charging. The algorithms are compared with traditional grid-connected charging techniques regarding energy consumption, network social welfare, and computation time.

The authors in [84] developed an approach for EVs to achieve optimal routing to the most suitable CS or energy provider buses, also called mobile energy disseminators (MEDs), using the shortest path algorithm. The EV can efficiently find and use the best available charging opportunity by selecting a CS or MED based on the shortest travel time. This approach resulted in a fourfold improvement compared to the scenario where the EV only had the choice between CS, showing the potential effectiveness of the given approach. In [85], a CS selection technique based on the earliest available time for charging (EATC) has been offered to improve user

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satisfaction further.

The optimization problem for the best parking area has been solved in [86] considering the minimum charging cost, and then optimum V2V matching pairs are selected to reduce congestion caused by EVs waiting for the energy exchange. The authors further extended their work to develop a better solution in [87], particularly within metropolitan areas using a Q-learning based technique and maximally weighted V2V using a bipartite graph.

Wireless power transfer has been implemented for V2V charging, referred to as wireless power transfer for V2V (WPT-V2V). The approach presented in [88] aims to optimize WPT-V2V by scheduling the charging process to find an optimal route path and minimize the charging time and energy loss in EVs. In [89], the authors considered a scenario with multiple charging providers, each with a fleet of trucks with large batteries to charge EVs in selected parking areas. Integer linear programming (ILP) has been employed to plan the routes for the trucks to charge the highest number of EVs through V2V charging. The results are compared with SWSPF and SDSPF heuristic algorithms in terms of performance, efficiency, and time needed for computation. The optimization techniques discussed previously are summarized in Table-I.

On the other hand, ITS is gaining popularity as a digitized version of traditional vehicular systems, where connected vehicles (CVs) are able to exchange data through the infrastructure of vehicular ad hoc networks (VANETs) [91]. The deployment of ITS in urban cities increases vehicle safety standards and improves the overall driving experience. V2V communication is the core of vehicle safety communication technology integrated into modern vehicles. Its main objectives include notifying drivers of potential accidents with the help of alert systems, collision avoidance, motion assistance, and congestion and traffic aid [92].

There are several papers in the literature that provide an overview of battery charger topologies [40], [93], [94], on-board chargers [41], [95], off-board chargers [96], DC fast chargers [97]–[99], power converter configurations for EVs [100]–[102], comparison between the characteristics of V2H, V2V, and V2G operation [39], architectures of CSs [42], [101], [103], [104], and the impact of EVs on the power grid [14], [39], [42], [47]. However, to the best of the authors' knowledge, no technical review of previous work on V2V power transfer techniques has been presented. Therefore, this paper discusses the state of the art of V2V power transfer with its communication aspects in detail.

The rest of the paper is structured as follows: Section II provides a detailed discussion on V2V power transfer, exploring existing topologies in the literature. In Section III, the communication aspect of V2V is explained, covering its standards and applications. Section IV addresses challenges in adopting V2V technology for EVs, explores commercial developments, and outlines global market-available V2V products and standards, concluding with insights into future developments.

II. V2V Power Transfer

The pictorial representation of V2V power transfer concept is illustrated in Fig. 1. In this particular example, among two EVs, EV1 acts as the energy provider, while EV2 is the energy receiver. Likewise, EV2 can be provider and EV1 can be receiver if EV1 requires energy from EV2. The V2V power transfer can be achieved using on-board converters or through an external hardware (such as, off-board converter). EVs can benefit from V2V power transfer by offering longer ranges, more flexibility, added convenience, less need for large batteries, less reliance on a limited number of CSs, and less infrastructure for recharging [67]. The power grid efficiency can also be increased by using EVs as mobile energy storage systems. This would allow EVs to store any extra energy generated by RESs, such as solar and wind power, and feed it back into the system when needed.

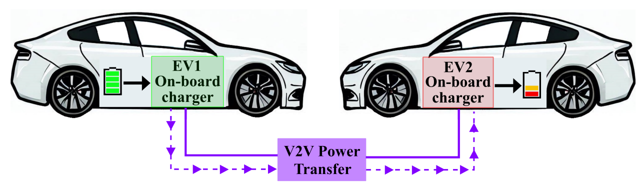

Fig. 1: V2V power transfer pictorial representation.

The connection between two EVs for V2V operation varies in design, power level, charging speed, connector type, portability, location, cost, and number of phases. In this paper, V2V power transfer is classified into two main groups: the first is based on the type of power transfer, and the second is based on the type of connection as shown in Fig. 2.

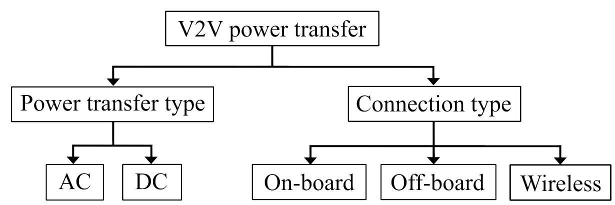

Fig. 2: V2V power transfer classification.

A. *V2V based on type of power transfer*

The first classification of V2V operations is based on the type of power transfer which can be either AC (AC-V2V) or DC (DC-V2V) with their respective conversion stages. Block diagrams of V2V power transfer presented in the literature are summarized in Fig. 4 and Fig. 5. The blue-dashed line represents the on-board charger of power-supplying EV, and the red-dashed line represents the on-board charger of power-receiving EV. The rest is the external interface or off-board charging circuitry. Most of the AC-V2V methods shown in Fig. 4 involve redundant conversion stages. This redundancy is minimized by DC-V2V charging systems, as shown in Fig. 5.

Power electronic converters are the fundamental component of V2V connections [100], and several types of converters are used for V2V charging, as shown in Fig. 3. The plug-in and WPT-V2V charging topologies [71]–[73], [105]–[125] presented in the literature are discussed in detail in this paper.

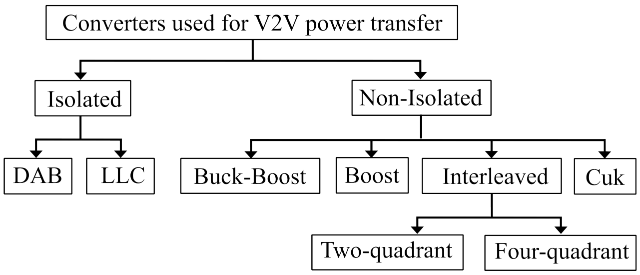

Fig. 3: Converters used for V2V power transfer.

B. V2V based on type of connection

V2V operation depends on battery chargers, which can be either on-board or off-board chargers. On-board chargers are divided into single-phase and three-phase chargers and are characterized by small size, weight, and lower cost [41], [42], [95], [126]–[128]. However, off-board are fast chargers that require additional space, as described in [96], [97], [129]–[136].

1) On-board V2V chargers: On-board chargers are mainly used for low and medium charging rates. The primary concerns associated with designing on-board V2V charging solutions are the longer charging time and low to medium power range of type-1 and type-2 chargers. However, on-board V2V chargers offer many advantages, such as the fact that no modifications to existing chargers are required, there is no additional cost other than a cable and a small controller, and they are integrated into the EV. These benefits make on-board V2V chargers a practical and cost-effective solution.

An AC-V2V solution employing single-phase type-1 on-board chargers with a 3.3 kW maximum power limit has been proposed in [105]. As depicted in Fig. 6, the two EVs are connected by a V2V cable connected to the AC terminals of both EVs through LC filters. During V2V charging, the two active rectifier stages perform rectification and inversion operations. As a result, the switches in active rectifier-1 and active rectifier-2, together with the switches in the DC-DC converter stages, jointly make a contribution to the conduction and switching losses. This process includes the conversion of DC to DC and DC to AC in EV1 and then the conversion of DC to AC and DC to DC in EV2 (assuming forward mode). Thus, according to [105], the power efficiency of V2V power transfer is only 87% as there are a total of 12 switches responsible for conduction and switching losses. The authors suggest installing galvanic isolation between DC-DC converter and active rectifier stages with a dual active bridge (DAB) converter to increase the safety and robustness of the V2V charger.

In [106], a DAB converter with an active rectifier has been used to achieve AC-V2V operation as shown in Fig. 7. The implementation of a hybrid control mechanism combining boundary conduction mode (BCM) and continuous conduction mode (CCM) with hysteretic current mode control (HCMC) resulted in system volume reduction, a significant 50% boost in power level, and sustained reliability. The power hub has achieved an efficiency of 98.3% when considering only the inverter efficiency and excluding the losses of the DAB converters.

In [107]–[109], bidirectional on-board buck-boost DC-DC converters are suggested with a direct DC-V2V connection, where two EVs are directly connected via their DC-links. The authors in [107] assumed fictitious switches sw as shown in Fig. 8 to connect the two DC-links. In [108], the two-quadrant buck-boost DC-DC converters are cascaded for direct V2V, resulting in the development of a cascaded buck-boost converter; however, access to and connection of the DC-links of both EVs requires further clarification. The on-board charger has only two terminals for accessing the battery; the first is through the battery connection, which requires a DC input, and the second is through the front-end active rectifier's AC terminal. Thus, there is no direct access offered to the battery via DC-link to charge or discharge it [137], so the approaches in [107], [108] are not feasible in practice for commercial EVs. Numerous modern EVs offer DC fast charging through their battery DC terminals, while the intermediate DC-link terminals do not support this feature. To apply the V2V approach described in [107], [108], it would be necessary to equip the on-board chargers with extra charging ports to access the DC-links.

In [109], a practical solution has been presented in which the active rectifier stage is reconfigured as the interface to connect the DC-links instead of the conventional rectification or inversion operations, as shown in Fig. 9. In this technique, the V2V power transfer occurs directly through the DC to DC stage by utilizing only four switching devices of active rectifier-1 and active rectifier-2. For example, switches S_1, S_1', S_6, and S_6' are continuously turned on to establish a connection between the two EVs. There are a total of 8 actively conducting switches responsible for the overall conduction losses in [109]. In addition, S_1, S_1', S_6, and S_6' do not have switching losses because they are continuously on and are not switched during the entire V2V operation. Therefore, [109] achieves relatively less switching and conduction losses, resulting in higher efficiency compared to other approaches. This connection allows bidirectional current flow in all possible cases where the battery voltage of EV1 is less than, equal to, or greater than that of EV2.

In [110], [111], an alternative DC power transfer approach is presented. It involves the use of a single-stage on-board charger, which is based on a bridgeless Cuk DC-DC converter, as illustrated in Fig. 10. This charger requires fewer components and is capable of functioning in both G2V and V2V modes. Here, only receiver EV on-board converters are used for the power transfer through direct connection from the provider battery terminals.

In [112], an integrated converter is designed to address the inherent slowness of single-phase charging. This integrated converter incorporates drive and charge capabilities, catering to fast charging operations across a broad input voltage range. This topology facilitates G2V, V2G, and DC/V2V charging functionalities and also enables rapid charging from both AC (single-phase) and DC sources without necessitating hardware modifications. In this work, authors utilized the phase windings of a 4-phase switched reluctance motor (SRM). Expanding on [112], in [113], the authors refined the integrated

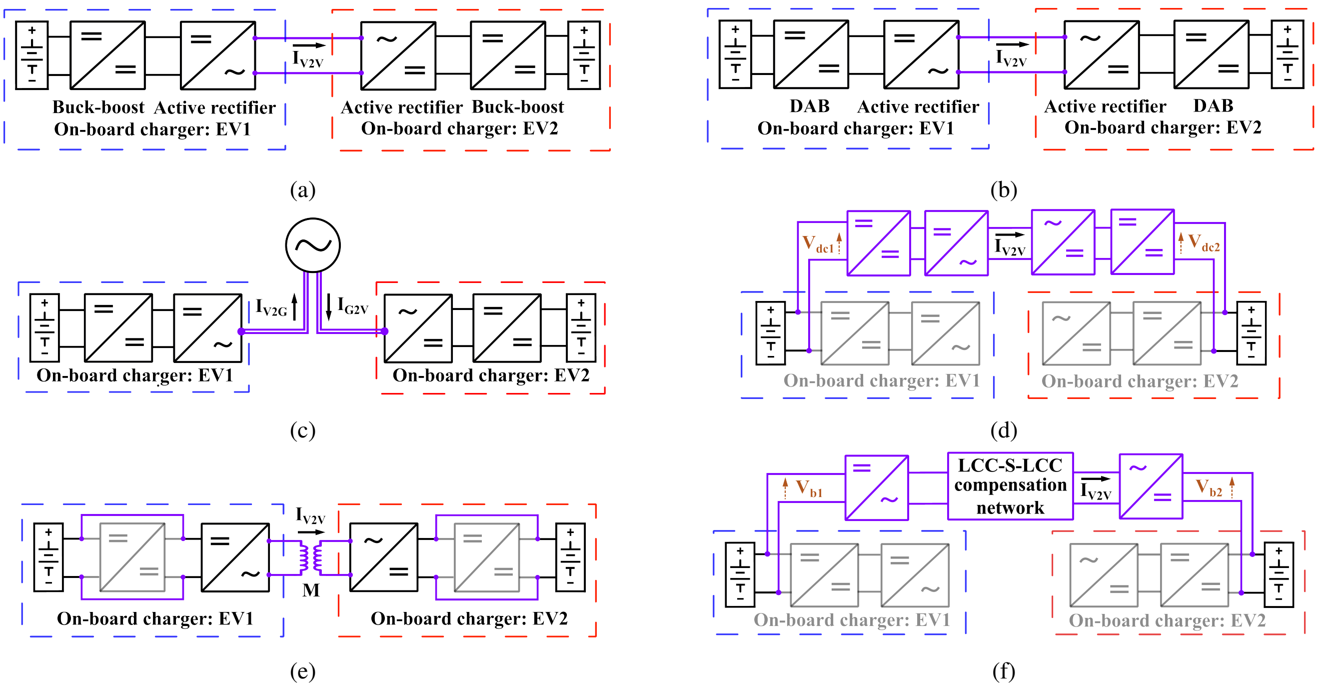

Fig. 4: AC-V2V power transfer configurations: (a) on-board with buck-boost, (b) on-board with DAB, (c) off-board grid-connected, (d) off-board with four stages, (e) wireless with LLC, and (f) wireless with LCC-S-LCC.

converter to eliminate the need for additional non-integrated components during G2V operation. The integrated converter is reconfigured into an integrated bridgeless buck-boost converter for V2V charging. This involves connecting the energy provider EV or PV to the DC-link, while the energy receiver EV (EV2 in this example) is linked to the second DC-link, as depicted in Fig. 11. Various operational modes are presented for scenarios involving $V_{b1} > V_{b2}$ and $V_{b1} < V_{b2}$. Notably, in this work, the inductors are reconfigured from the SRM's phase windings.

In [114], another approach to direct V2V charging has been suggested using the EV's drivetrain and motor windings to enable DC fast charging between the EVs as shown in Fig. 12. Instead of a typical three-phase DC-AC stage, the EV's type-2 on-board charger has been converted into a bidirectional DC-DC converter in the interleaved configuration for efficient power transfer. The results have demonstrated an efficiency of 91.53% at a high power of 130 kW, making it a promising solution for V2V power transmission.

The authors in [115] have offered a multifunctional on-board charger consisting of an interleaved DC-DC stage used to buck/boost the battery voltage level and an additional DAB converter that controls the power flow and provides galvanic isolation for each EV. The DC-AC stage is neglected; however, the overall system incurs additional conduction and switching losses, leading to ultimately lower power efficiency. The two EV chargers are connected via switches on their DC-links, as shown in Fig. 13.

2) Off-board V2V chargers: Off-board chargers are used to overcome the compact weight and size restrictions of on-board chargers and other several limitations such as low power rating, slow charging speed, and extended waiting times for EV users. Off-board chargers can transmit much higher DC-V2V power ratings up to 50 kW because off-board chargers do not have limitations on the power level. However, they need external hardware to make a connection between the batteries of the two EVs. Conventional off-board V2V charging methods typically involve four energy conversion stages of DC-DC, DC-AC, AC-DC, and DC-DC, with the connection between the two EVs being made via a power grid, which has been reported to have a low efficiency of 90.7% [107], as depicted in Fig. 4(c). To overcome the need for an external aggregator, a portable V2V device has been filed in [125], but it has redundant conversion stages, additional cost, and limited output power. As a result, recent research efforts have focused on high-power DC fast charging techniques to overcome the limitations of conventional V2V charging. Various approaches, such as those proffered in [71]–[73], [116], [117], [119], have suggested minimizing the number of conversion stages for off-board chargers, as illustrated in Fig. 5(b-h) to enhance the charging speed and efficiency of V2V charging systems.

In [116], the authors introduced an off-board charger, depicted in Fig. 14, which used a non-isolated bidirectional cascaded buck-boost converter. By minimizing the number of switches and other components, this charger achieved remarkable power efficiency. The charger's performance has been evaluated under three different conditions, encompassing both forward and reverse power flow scenarios: when $SOC_{b1} \approx SOC_{b2}$, $SOC_{b1} > SOC_{b2}$, and $SOC_{b1} < SOC_{b2}$.

In [117], the authors have developed a novel magnetic power plug that uses a DAB converter incorporating SiC power MOSFETs, as shown in Fig. 15, to provide multiple charging options, including V2V power transfer. This power connector offers several advantages, including galvanic isolation and

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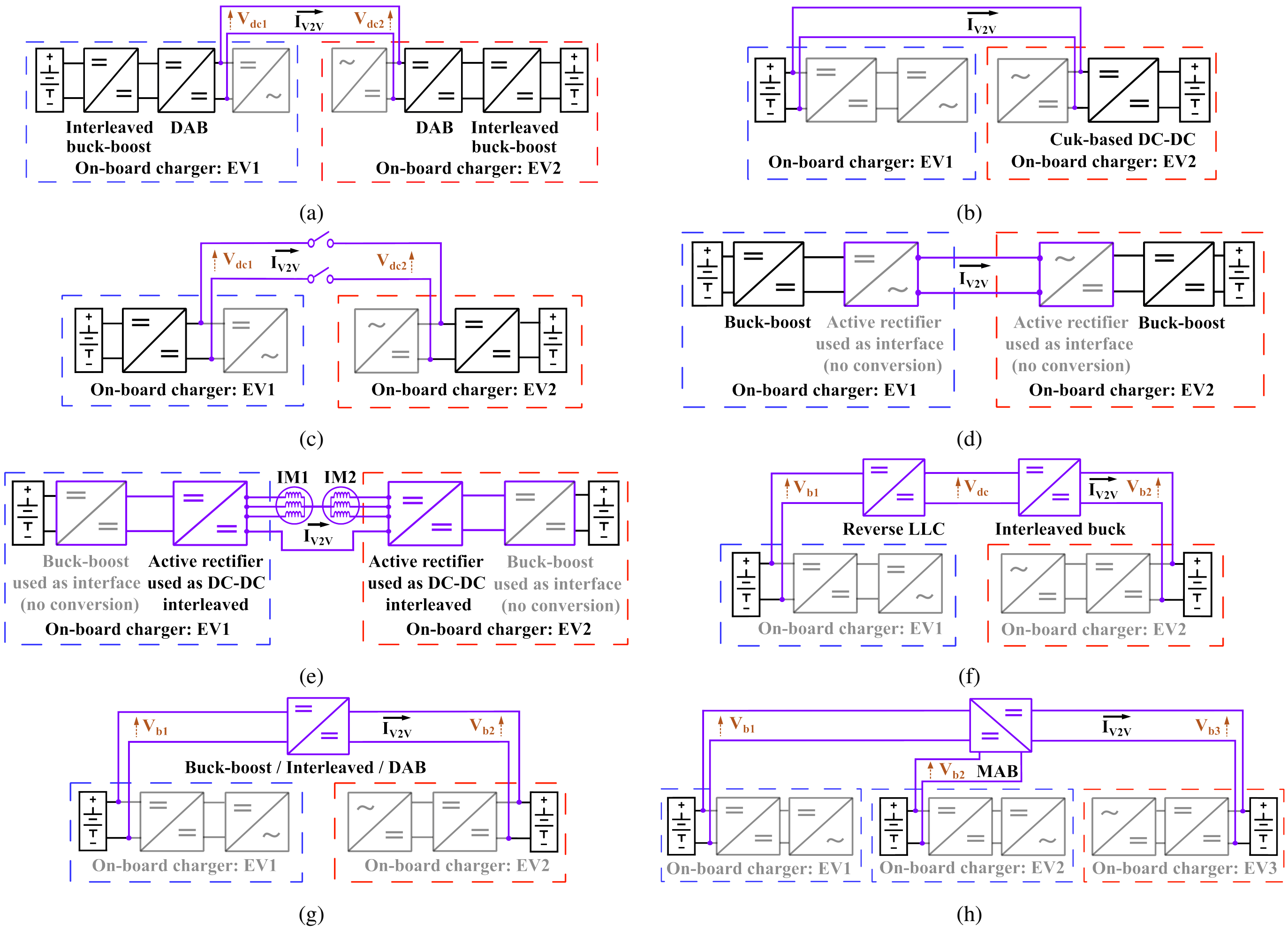

Fig. 5: DC-V2V power transfer configurations: (a) on-board with four stages, (b) on-board with one stage, (c) on-board with two stages and assumed switches, (d) on-board with two stages, (e) on-board with drivetrain and motor windings, (f) off-board with reverse LLC and interleaved buck, (g) off-board with buck-boost or interleaved or DAB, and (h) off-board with MAB.

improved efficiency of 85-90%. In [118], a multi-functional charger has been implemented for G2V, V2G, and V2V functions using an active rectifier and three-level DAB converter with 50 kW off-board charging capability as shown in Fig. 16. The rectification has been ignored for V2V operation, and the control of the DAB stage involves dual-phase shift modulation. A phase difference exists between the transformer's primary and secondary side voltages, influencing the amount of power transfer. Results show a 50% reduction in switch voltage stress for all switches compared to input and output voltages during battery charging/discharging.

In order to leverage the accessibility of multiple EVs for charging, [119] has suggested implementing an off-board, multiport active bridge (MAB) topology, enhancing the system's flexibility for both G2V and V2V charging operations as shown in 17. The MAB offers a significant advantage over traditional DAB converters by allowing multiple EVs to charge a single receiver EV rather than being limited to a single one. To stay within the scope of this paper, the G2V section of the topology is omitted and only the V2V charging portion is depicted in Fig. 17.

An interleaved DC-DC converter has been developed in [71], [72] to enhance direct V2V connections further. The authors have demonstrated the benefits of using multiple phases in the converters with single-phase, two-phase, and three-phase configurations. These phases effectively reduced current ripple, resulting in improved efficiency, which has been a key factor in optimizing V2V technology for reliability and performance. The interleaved architecture of the converters shown in Fig. 18 also enabled high current density, making them ideal for high-power applications. In addition, the compact design of the interleaved converters reduced the size and weight of the off-board charger. In [71], [72], [114], the AC-DC stage has been controlled to act as an interleaved DC-DC converter instead of operating as a conventional inverter.

A multi-purpose EV charger with V2V capability has been introduced in [73] to transfer DC power directly between two EVs. The design, which replaced the conventional DC-DC converter with a reverse LLC converter and the active rectifier with an interleaved buck converter, effectively reduced the number of energy conversion stages from four to two, as shown in Fig. 19. This resulted in several advantages, including a high efficiency of 96.1%, portability, and the utilization of SiC semiconductors. However, the design is

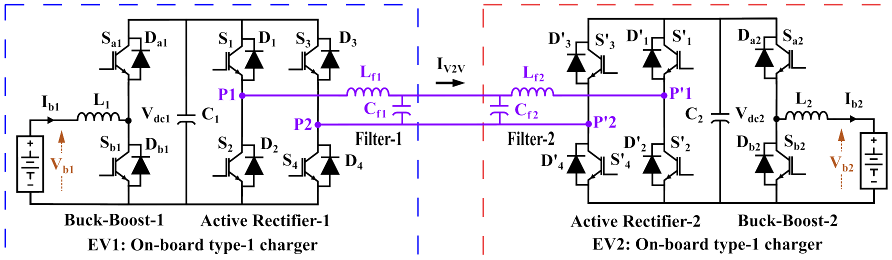

Fig. 6: Topology-1: V2V via direct on-board converters (type: AC power transfer with buck-boost and active rectifiers) [105].

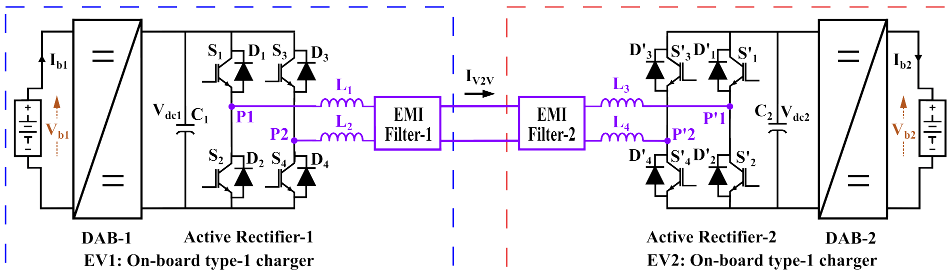

Fig. 7: Topology-2: V2V via direct on-board converters (type: AC power transfer with DAB and active rectifiers) [106].

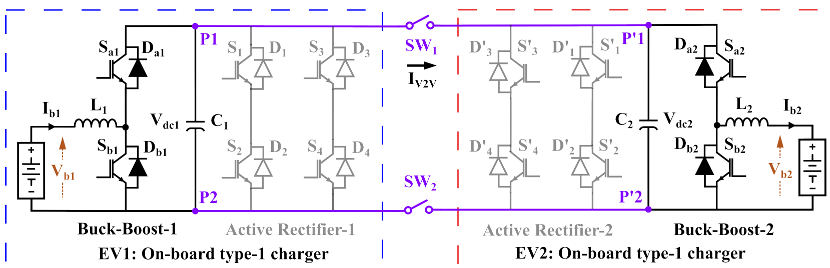

Fig. 8: Topology-3: V2V via direct on-board converters (type: DC power transfer with assumed switches) [107], [108].

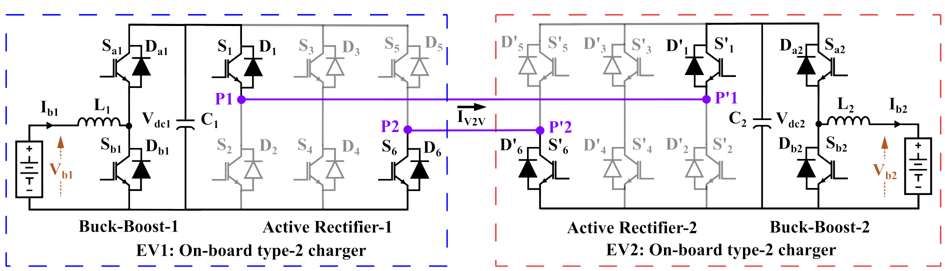

Fig. 9: Topology-4: V2V via direct on-board converters (type: DC power transfer with active rectifiers used as interface) [109].

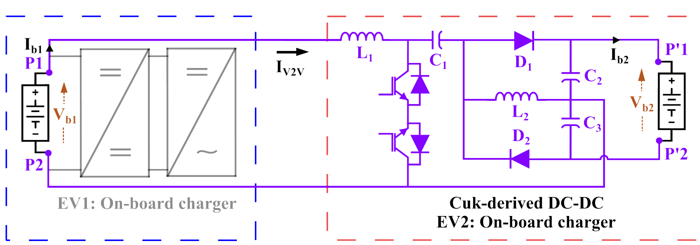

Fig. 10: Topology-5: V2V via direct on-board converters (type: DC power transfer with cuk-derived DC-DC converter) [110], [111].

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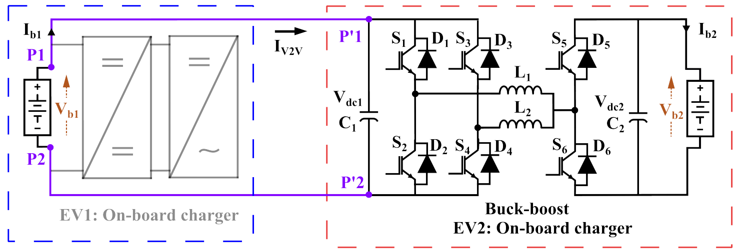

Fig. 11: Topology-6: V2V via direct on-board converters (type: DC power transfer with buck-boost DC-DC converter) [112], [113].

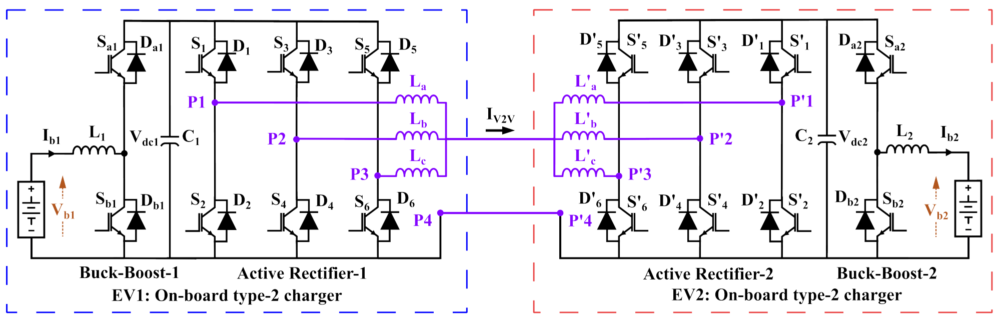

Fig. 12: Topology-7: V2V via on-board drivetrain and motor windings (type: DC power transfer with interleaved DC-DC converter) [114].

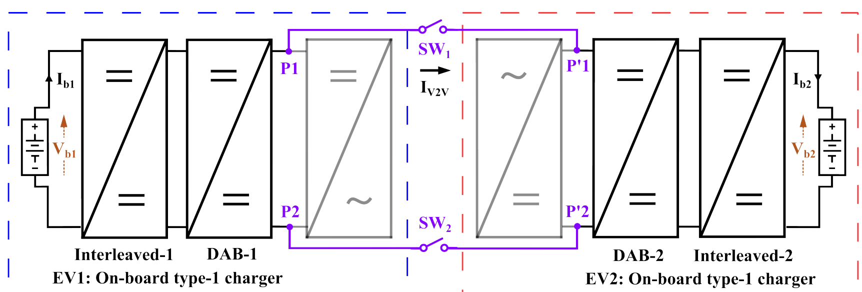

Fig. 13: Topology-8: V2V via on-board converters (type: DC power transfer with single-phase interleaved and DAB converters) [115].

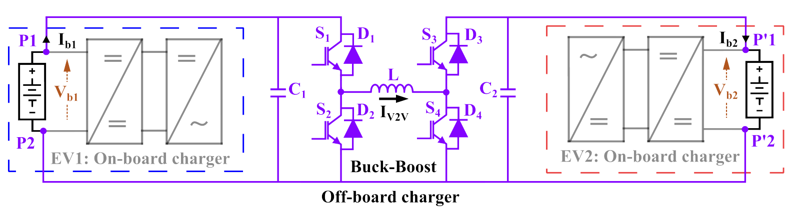

Fig. 14: Topology-9: V2V via off-board interface (type: DC power transfer with Cascaded buck-boost converter) [116].

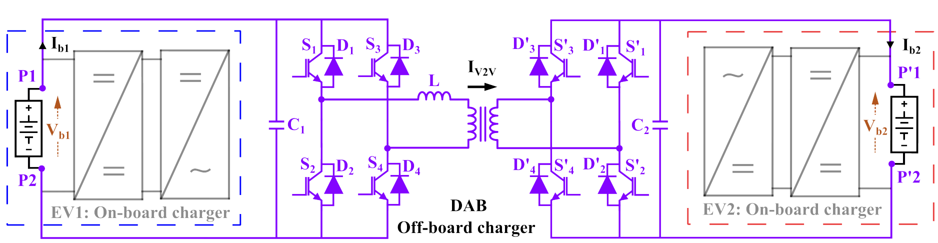

Fig. 15: Topology-10: V2V via off-board interface (type: DC power transfer with phase-shifted DAB converter) [117].

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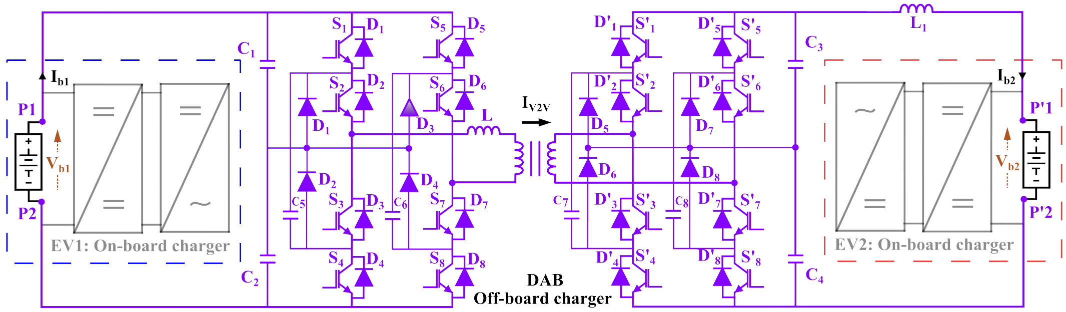

Fig. 16: Topology-11: V2V via off-board interface (type: DC power transfer with phase-shifted DAB converter) [118].

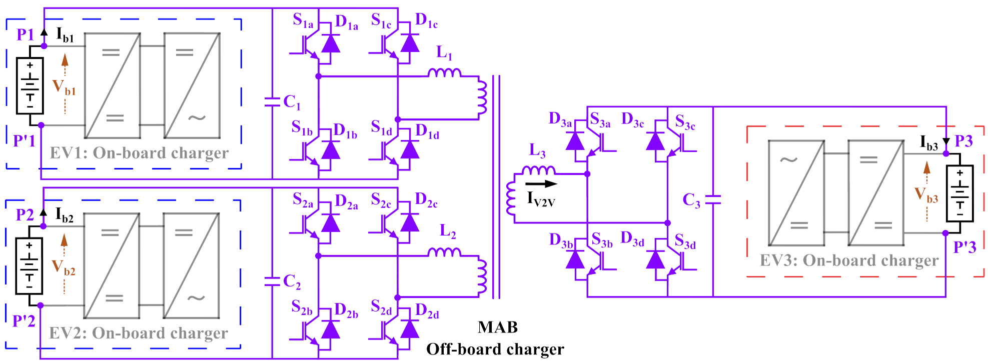

Fig. 17: Topology-12: V2V via off-board interface (type: DC power transfer, with phase-shifted MAB converter) [119].

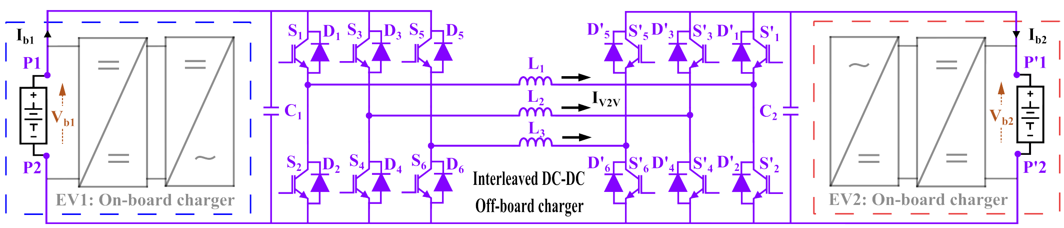

Fig. 18: Topology-13: V2V via off-board interface (type: DC power transfer with interleaved DC-DC converter) [71], [72].

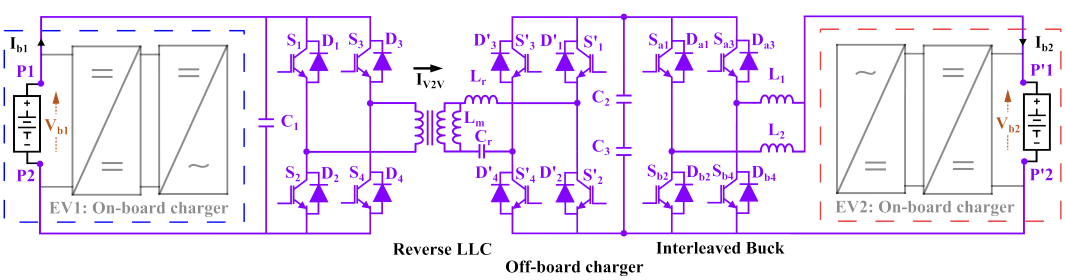

Fig. 19: Topology-14: V2V via off-board interface (type: DC power transfer with single-phase reverse LLC and interleaved DC-DC converters) [73].

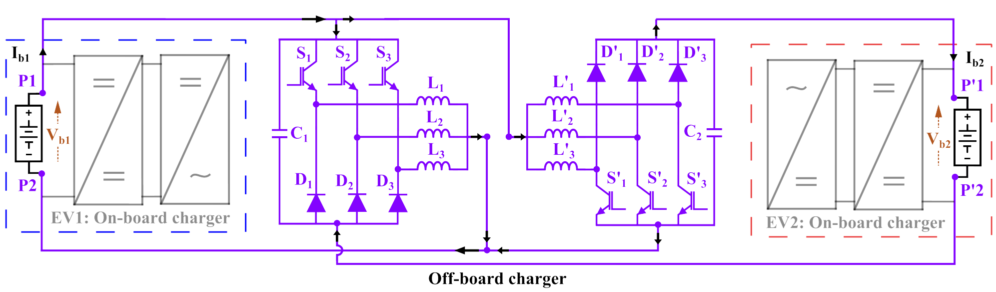

Fig. 20: Topology-15: V2V via off-board interface (type: DC power transfer with interleaved floating dual-boost converter through parallel six channels) [120].

only suitable for charging from high-voltage batteries to low-voltage batteries.

In [120], an off-board, interleaved floating dual-boost converter with six parallel channels has been proposed, as shown in Fig. 20. This converter uses a disturbance observer-based sliding mode control algorithm to achieve its functionality. The control algorithm is used to maintain a constant voltage and power. A proportional-resonant (PR) controller has been implemented to improve current sharing. This is particularly important because the power receiver, referred to as EV2, is susceptible to low-frequency and subsynchronous oscillations. This connection arrangement ensures power flow in scenarios where high power density ($> 20kW$) is required.

3) Wireless chargers: The key features of WPT in EVs have been significantly improved over the years, such as improved coil design [138], [139], reduced coil misalignment [140], improved pad structure [141], higher link efficiency and coupling factor [142], [143]. This has made WPT a promising technology for EV charging as shown by numerous research studies [144]–[148]. The EV WPT charging can be classified into three modes: stationary, dynamic, and quasi-dynamic. Stationary charging occurs when the EV is parked at an MP or CS [149]–[151]. Dynamic charging takes place as the EV moves along a designated charging lane to enhance mobility [152]–[157]. Quasi-dynamic charging involves brief stops, such as at traffic lights [158]–[160].

Another classification criterion is the energy-carrying medium, which can be an electromagnetic field (EMF) or an electric field. EMF is further divided into near and far fields as shown in Fig. 21. Far-EMF is uncommon in EV charging due to inefficiency, the necessity for large antennas, radiation, and safety concerns [161]. Near-EMF includes inductive power transfer (IPT), permanent magnet coupling (PMC), and magnetic resonant coupling (MRC). IPT without resonance leads to efficiency reduction, encompassing both transmitting-side and receiving-side losses, as discussed in [149], [155], [162]. Therefore, MRC achieved by incorporating compensation circuitry, is crucial for maximizing transmission capability and power efficiency. These compensation circuits are also employed for soft switching, as discussed in [163], [164]. Additionally, they play a key role in maintaining a zero phase angle (ZPA) between the input voltage and current, thereby reducing apparent power demand and enhancing power transfer capacity, as demonstrated in [165].

Capacitive compensation topologies differ based on the capacitor connection to coils, categorized into four basic configurations according to the desired characteristics of the load: series-series, series-parallel, series-parallel, and parallel-series [138]. However, enhanced efficiency is attained through compensation networks comprising a greater number of passive elements, as outlined in Table-II. The resonant circuit configuration's effect on different design parameters, including mutual inductance, winding area, inductor and capacitor values, quality factor, and power loss is demonstrated in [166].

While MRC-based WPT [121]–[123], [167]–[179] has been recognized as the most promising solution for EV wireless charging [180], [181], recent research aims to enhance the suitability of capacitive power transfer (CPT), based on an electric field, for EV applications [182]. CPT requires a high operating frequency and has better tolerance to misalignment. Despite its limitations in low power and short-distance applications, CPT has been implemented for EV charging through designing large air-gap systems and integrating matching networks for compensation and voltage (or current) gain [183]–[194]. All the above discussed aspects related to WPT (except dynamic and quasi-dynamic) are equally applicable to WPT-V2V. However, the coil size, shape and its placement for WPT-V2V require further studies.

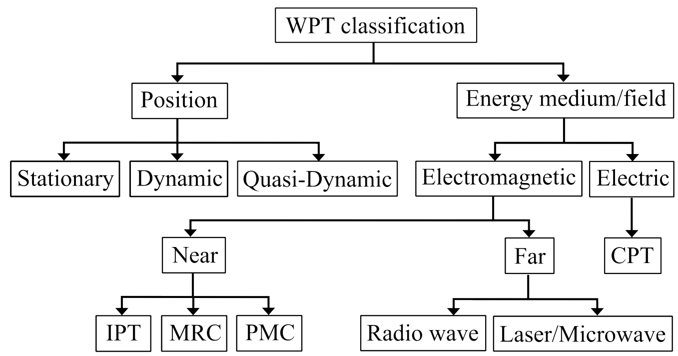

Fig. 21: WPT classification for EV charging [147], [161].

TABLE II: WPT compensation topologies used for EV charging

Compensation network	WPT type	Reference	WPT type	Reference
LC	IPT	[173], [174]	CPT	[185]–[188]
LLC	IPT	[121], [122]	CPT	-
LCC	IPT	[167]–[172]	CPT	-
LCC-S	IPT	[162], [173]	CPT	-
LCL	IPT	[174]–[176]	CPT	[188], [189]
LCL-L	IPT	-	CPT	[190]
LCL-LCCL	IPT	[177]	CPT	-
LCC-S-LCC	IPT	[123]	CPT	-
LCLC	IPT	-	CPT	[188], [191]–[193]
CLLC	IPT	-	CPT	[194]

The recently introduced WPT-V2V system offers several advantages that make it a promising solution for the future of electric mobility. The pictorial representation of WPT-V2V between two EVs via a wireless link is illustrated in Fig. 22, eliminating the need for physical cables and connectors in stationary mode [121], [122], [195] and in dynamic mode [84], [196]–[199]. WPT-V2V can make the charging process more convenient and user-friendly for customers. The absence of physical connections in WPT increases safety, reduces the risk of electric shock [122], and increases reliability because charging ports and cables are less worn with less wear and tear [123].

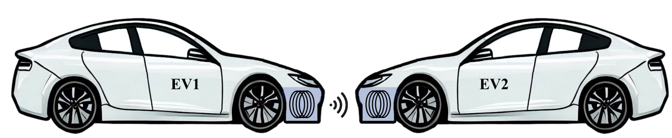

Fig. 22: WPT-V2V power transfer pictorial representation.

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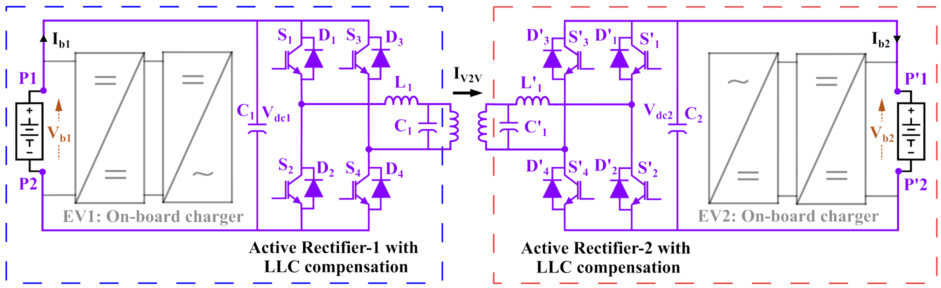

Fig. 23: Topology-16: WPT-V2V (type: AC power transfer with active rectifier plus LLC compensation) [121], [122].

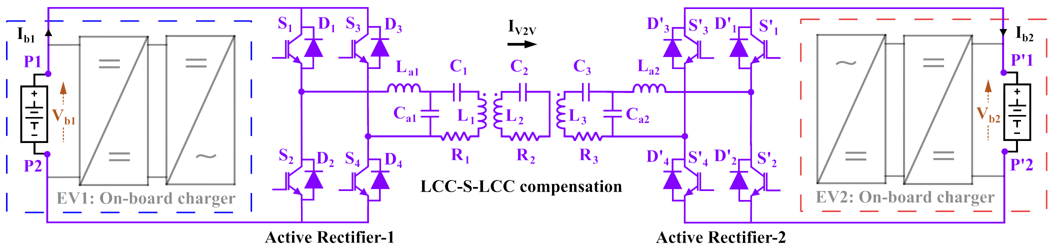

Fig. 24: Topology-17: WPT-V2V (type: AC power transfer with active rectifier plus LCC-S-LCC compensation) [123].

TABLE III: Overview of V2V power transfer connections

No.	Ref.	Connection type	Power transfer type	Converter topology	Charging rate	Isolation	Conversion stages	Switching devices	Reported efficiency
1	[105]	On-board	AC	Boost DC-DC & H-bridge DC-AC	Moderate	✗	4	12	87%
2	[106]	On-board	AC	DAB DC-DC & H-bridge DC-AC	Moderate	✓	4	24	N/A
3	[107]	On-board	DC	Cascaded buck-boost DC-DC	Moderate	✗	2	4	89.5%
	[108]	On-board	DC	Cascaded buck-boost DC-DC	Moderate	✗	2	4	85%
4	[109]	On-board	DC	Cascaded buck-boost DC-DC	Moderate	✗	2	8	97.92%
5	[110]	On-board	DC	Cuk-derived DC-DC	Moderate	✗	1	2	N/A
	[111]	On-board	DC	Cuk-derived DC-DC	Moderate	✗	1	2	98.3%
6	[112]	On-board	DC	Buck-Boost DC-DC	Fast	✗	1	6	88%
	[113]	On-board	DC	Buck-Boost DC-DC	Fast	✗	1	6	N/A
7	[114]	On-board	DC	Interleaved DC-DC	Fast	✗	2	14	91.53%
8	[115]	On-board	DC	Interleaved DC-DC & DAB	Moderate	✓	4	24	N/A
9	[116]	Off-board	DC	Cascaded buck-boost DC-DC	Fast	✗	2	4	N/A
10	[117]	Off-board	DC	DAB DC-DC	Fast	✓	1	8	85-90%
11	[118]	Off-board	DC	DAB DC-DC	Fast	✓	1	16	N/A
12	[119]	Off-board	DC	MAB DC-DC	Fast	✓	1	8	N/A
13	[71]	Off-board	DC	Interleaved DC-DC	Fast	✗	1	4/8/12	N/A
	[72]	Off-board	DC	Interleaved DC-DC	Fast	✗	1	4 (1-ph)	97.85%
	[72]	Off-board	DC	Interleaved DC-DC	Fast	✗	1	8 (2-ph)	97.97%
	[72]	Off-board	DC	Interleaved DC-DC	Fast	✗	1	12 (3-ph)	98.25%
14	[73]	Off-board	DC	Reverse LLC & Interleaved DC-DC	Moderate	✓	2	13	96.1%
15	[120]	Off-board	DC	Interleaved floating dual-boost converter with six parallel channels	Moderate	✗	1	6	N/A
16	[121]	Wireless	AC	H-bridge DC-AC with LLC compensation circuit	Slow	✓	2	8	N/A
	[122]	Wireless	AC	H-bridge DC-AC with LLC compensation circuit	Slow	✓	2	8	N/A
17	[123]	Wireless	AC	H-bridge DC-AC with LCC-S-LCC compensation circuit	Slow	✓	2	8	N/A

The development of the WPT-V2V charging system however faces several technical hurdles that must be overcome to ensure maximum efficiency, including coil design and its angular displacement and compensation circuitry, as described in [200], [201]. In [202], a novel triangular transmitting coil structure with 10 percent higher efficiency than a conventional transmitting coil has been developed to address the angular offset when coupling two EVs for WPT-V2V charging. In [121], [122], a design for on-board chargers has been presented to incorporate single-phase bidirectional DC-AC converters with LCL compensation circuits on both EV sides, as shown in Fig. 23. The capacity and effectiveness of the WPT system are improved by the compensation circuit [171], [203], [204]. The specific load requirements and LCL compensation network are

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considered in the design of the coils, and the use of capacitors helps to minimize the reactive power demand and the overall system performance. To improve the efficiency of WPT-V2V systems, [123] has performed a thorough analysis of both LCC-S-LCC and series-to-series compensation networks, as shown in Fig. 24. Two designs of the intermediate coil were investigated, and the power transfer between two EVs has been governed using the phase angle. From the comprehensive analysis and compensation network structures, the authors have found a more effective solution for WPT-V2V systems. The WPT-V2V charging system can operate more effectively by addressing these technical issues, resulting in faster and more reliable charging for end users. However, human exposure to EMF must be considered in developing WPT-V2V systems [180].

The summary and comparison of conducting and wireless V2V charging methods discussed in the literature are presented in Table-III. The number of conversion stages and switching devices listed in the table are solely for V2V operation and do not include the complete circuit switches. In Table-III, V2V power transfer efficiencies reported by compared papers are also provided. However, these efficiencies cannot be compared among these papers as those are carried out for different power levels and different system parameters. Additionally, the efficiencies differ based on the power level of the receiving EV battery and the disparity in SOC levels between the batteries of the two EVs [108], [109]. N/A in Table-III indicates that the efficiency value is not reported in the paper.

III. V2V Communications

The authors of previous V2V charging techniques assumed convenient access to communication between EVs and that control devices and measurement sensors are available. However, to successfully implement the V2V approaches proposed in the literature for commercial EVs, it is essential to have convenient access to communication between EVs and the controllers and measurement sensors. This access enables effective communication between the two EVs and retrieval of the parameters required for V2V operation.

Vehicle-to-everything (V2X) is a term that refers to communication between a vehicle and ITS components such as roadside infrastructure, vehicles, and pedestrians [205]–[207]. V2X is the base communication technology for vehicle-to-device (V2D), vehicle-to-infrastructure (V2I) [208], [209], vehicle-to-network (V2N) [210], [211], vehicle-to-pedestrian (V2P) [212], vehicle-to-roadside unit (V2R) [213], and V2V [208], [214], [215]. Fig. 25 provides a comprehensive illustration of the manifold applications of V2X, highlighting the seamless integration of different communication links. V2V communications are developed at ITS to enable vehicles to communicate wirelessly with each other. V2V improves traffic efficiency and the user's driving experience, especially in the absence of roadside units (RSUs) through various applications for traffic guidance, location, collision avoidance, intersections, safety alerts, etc. [216], [217]. V2V communication involves establishing a communication channel between EV users before initiating power transfer [218], exchanging data between chargers such as battery voltage, capacity, and SOC, and sending signals to initiate the transfer from one EV to another. In [115], the message queue telemetry transport (MQTT) protocol has been employed for the implementation of V2V communication based on [219]. However, further research and development are needed to enhance the performance and facilitate commercialization.

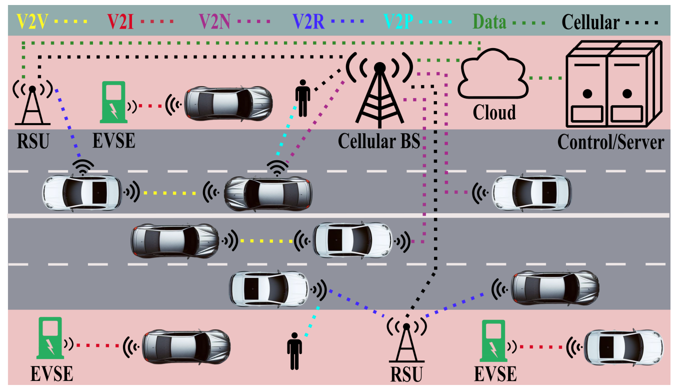

Fig. 25: Explanatory diagram of V2V and related communication links.

A. V2V communication standards and technologies

Within the domain of V2X connectivity, two categories come to the forefront. The initial classification involves direct and short-range communication, made accessible through cellular vehicle-to-everything (C-V2X) and dedicated short range communications (DSRC) technologies. Conversely, the second classification revolves around network-based communication, exclusively facilitated by C-V2X. This mode optimizes public mobile networks to augment the direct communication transpiring over the 5.9 GHz band, utilizing RSUs infrastructure [220], [221]. Communication standards for V2V have been under development for several years, with improvements and new versions being added all the time. Key standards and technologies for V2V communications include DSRC, IEEE 802.11p, LTE-V2V, and fifth-generation millimeter-wave (5G mm-Wave).

DSRC: The typical wireless standard for vehicular communications in vehicular ad hoc networks (VANETs) is the DSRC. It provides a high-quality service with low cost and high bandwidth of 75 MHz divided into seven channels at 5.85-5.925 GHz, as assigned by the federal communications commission (FCC) for V2V communications [223], [224]. DSRC has been mainly developed to exchange and broadcast messages and provide information about vehicles, including their speed, position, and movement, to avoid collisions [222]. The awareness message between vehicles is called a basic safety message (BSM) or cooperative awareness message (CAM) [225]. However, DSRC is also employed for commercial, financial, and entertainment purposes [226] and is utilized in V2V communications due to its lower cost compared to satellite and cellular communications [227]. The reliability of DSRC for V2V communications has been studied in [228]. DSRC depends on RSU, on-board unit (OBU), and the protocol suite for wireless access in vehicular networks (WAVE) to

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TABLE IV: Comparison between V2V communication standards and technologies [205], [207], [214], [222]

Parameter	DSRC / IEEE 802.11p	LTE	5G mm-Wave
Frequency spectrum	5.850 - 5.925 GHz (U.S.) 5.855 - 5.925 GHz (Europe, Singapore, South Korea, and Australia) 5.770 - 5.850 GHz (Japan) 5.905 - 5.925 GHz (China)	0.45 - 4.99 GHz	6 GHz and $\geq$ 24.25 GHz
Data rate	6 - 27 Mbps	1 Gbps	20 Gbps
Bandwidth	75 MHz (U.S.) and 70 MHz (Europe)	$<$ 20 MHz	$>$ 100 MHz
year of release	1999 (DSRC) and 2010 (IEEE 802.11p)	2016	2020
Challenges	Short range and coverage, low data rate, and high infrastructure cost	Resource allocation, physical layer design, security, and privacy	Doppler spread, higher path loss, and short communication range

connect the OBU to the RSU wirelessly. DSRC represents the initial specialized V2X technology created, utilizing the IEEE 802.11p standard, and implemented in the U.S. Comprehensive details on the IEEE and SAE standards employed across various layers of DSRC are discussed in [229], where these standards are based on the SAE J2945/1 standard [230], [231]. A comparison of the DSRC standards and spectrum bands allocated in the U.S., Europe, and Japan is presented in [205].

IEEE 802.11p: IEEE standardized IEEE 802.11p in 2010 for the physical (PHY) and medium access control (MAC) layers of WAVE to support BSMs [232], [233]. It is an extension of IEEE 802.11a and is the core of DSRC with a data rate of 6-27 Mbps. IEEE 802.11bd is an enhanced version of IEEE 802.11p with numerous advantages listed in [234]. The equivalent for IEEE 802.11p is ITS-G5, which has been selected by the European telecommunications standards institute (ETSI) [235]. DSRC and ITS-G5 are essentially identical technologies, with ITS-G5 serving as the designation for the European version. Countries like Australia, China, Korea, and Singapore have designated or are contemplating the designation of the 5.9 GHz band for ITS purposes.

LTE-V2V: Long-term evolution-based V2V (LTE-V2V) is a cellular network technology developed by 3GPP as an extension of the 3GPP Rel-12 device-to-device (D2D) system to take advantage of the broad deployment of LTE technology in vehicular systems [236]. This technology emerged as a viable alternative to IEEE 802.11p, making its debut in late 2016. Since then, it has garnered significant attention in various earlier research studies, as discussed in [206], [221], [237]–[239]. Key benefits include good performance for high-speed vehicles, lower latency, improved reliability, spectrum efficiency compared to IEEE 802.11p, and utilizing the same technology used for cellular communications [220], [222]. The main obstacles for LTE-V2V include resource allocation, PHY layer structure, and synchronization, as discussed in [207]. IEEE 802.11p has been compared with LTE-V2V in terms of latency and packet delivery ratio (PDR) for safety applications in line-of-sight (LOS) and non-line-of-sight (NLOS) scenarios in [240].

5G mm-Wave: With the advent of 5G communications, ITS have seamlessly transitioned into the millimeter-wave spectrum, achieving data rates that surpass 10 Gbps. [241]. The 5G mm-Wave has a wide bandwidth and has been developed to meet the increasing demand for high-speed communications, ultra-reliability, and low latency between vehicles [242]. As a result, the 5G mm-Wave band has been gaining popularity for V2V communications [243]. The licensed bands for 5G mm-Wave are 28 GHz, 37 GHz, and 39 GHz allocated by the FCC in the US, and 63-64 GHz by the electronic communication committee (ECC) in Europe [244], [245]. Since 5G mm-Wave bands differ from country to country, an optimized antenna with a wide bandwidth has been presented to serve multiple global 5G bands in [246]. The disadvantages of mm-Wave spectrum include vulnerability to fog, rain, and snow [247]. Therefore, a compact aperture array (multiple connected antennas) has been presented in [248] to maintain the continuity of the communication link in extreme weather conditions. It can switch and operate in both bands of DSRC (5.9 GHz) and 5G mm-Wave (28 GHz) with high gain and high efficiency for V2V communication. Table-IV shows the comparison between the communication standards and technologies in several countries around the globe [205], [207], [214], [222].

B. Antennas in V2V Communications

Addressing the unique requirements of different applications, the design criteria for antennas are shaped by specific objectives and constraints. In the context of V2V communications, antennas are effectively designed to achieve high gain with compact size and low-cost as highlighted in [249], [250]. The positioning of antennas on a vehicle's body is a subject of active research, exploring optimal configurations for enhanced performance, as discussed in [249], [251]. Furthermore, the strategic installation of multiple antennas on both transmit and receive sides yields numerous advantages over a single antenna, including benefits in diversity, reliability, data rates, and shadowing effects [252]. In [253], four omnidirectional antennas are placed on a vehicle in highway, city, and rural environments to measure the effects of antenna placement on V2V communications. The authors suggest installing multiple antennas at different positions with supplementary characteristics to reduce the effects of shadowing and improve system performance.

The advantages of directional antennas for a vehicular safety alert system in terms of packet collisions and interference are presented in [254]. Multiple directional antennas need to be oriented in different directions to obtain better omnidirectional properties. The influence of vehicle body and antenna placement on omnidirectional coverage characteristics has been minimized in [255] by a hybrid combination technique for directional antennas with low cost. When vehicles have multi-

This article has been accepted for publication in IEEE Transactions on Transportation Electrification. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TTE.2023.3345738

ple antennas, selecting appropriate and optimal antenna combinations for V2V communications is essential for higher performance and maximization of multipath channels [256]. The selection procedure, including the required signaling, has been explained in detail, and its performance has been evaluated for a 5G platooning case in [257]. The main disadvantages of omnidirectional antennas in V2V communications include low interference plus noise ratio (SINR) and higher interference with surrounding wireless connections, and such problems are solved with the beamforming technique described in [246], [258].

C. V2V communication for safety and traffic management

Safety precautions and warnings: Advanced driver assistance systems (ADAS) installed in vehicles reduce human errors that lead to road accidents. It uses in-vehicle sensors such as cameras, radar, and LiDAR to send warnings such as lane change warning (LCW), forward collision warning (FCW), cooperative collision warning (CCW), intersection collision warning (ICW), overtaking vehicle warning, and head on collision warning to avoid collisions between vehicles [214], [259]–[265]. ADAS has also been used to reduce the number of collisions in highways through cooperative collision avoidance (CCA) in [266]. Limitations of ADAS include low performance in severe weather and exclusive use in modern premium vehicles, making it a costly solution for ordinary users [267]. V2V communication can transmit data across surrounding vehicles and cover much greater distances. It also overcomes the visual LOS constraint in ADAS, thus, making it a better solution to reduce collisions [268]. In [269], a simulation-based LCW system based on V2V communication for actual traffic situations has been developed. In [270], an FCW algorithm has been suggested with a hardware prototype for V2V communication for collision avoidance. In [271], the advantages of V2V communication using IEEE 802.11p to transmit data between vehicles for an FCW system are discussed. V2V communication has been recommended in [272] to exchange warnings about possible collisions between vehicles.

Traffic congestions: Traffic jams cost people extra time, energy, and money and increase the probability of car accidents. Thus, one of the objectives for VANETs is data exchange between OBUs, RSUs, traffic lights, etc., to reduce traffic congestion [273], [274]. V2V-based solutions to reduce traffic congestion are presented in [156], [275]–[278]. A protocol with a fuzzy interface has been implemented in [275] for traffic congestion controllers to overcome the unpredictability of traffic congestion. The system considered the speed differential across road lanes using actual data. V2V and V2I communications were used in [276] to exchange traffic data between OBUs and RSUs to find routes with less congestion and minimize travel time on highways. Vehicles merging from local roads to highways cause severe congestion and accidents. Therefore, a control algorithm using V2V communication has been developed in [277] to govern the merge and create enough spaces for vehicles moving towards the highways. The simulation results were shown via the Aimsun micro SDK software for mobility modeling. Wrong timing for lane changes leads to catastrophic collisions; therefore, in [278], a model predictive control (MPC) system has been presented for safe lane changing in multi-lane highway scenarios, which highly depends on V2V communication among the surrounding vehicles. MPC-based systems are discussed in detail in [279]–[283]

Cooperative perception: Perception data about neighboring vehicles and the surrounding environment are fed as input to ADAS, as discussed earlier. The information obtained by sensing devices in a particular vehicle has constraints that limit the perception of that vehicle. To tackle such an issue and enhance the perception coverage, the concept of cooperative perception has been suggested, which uses V2V communication to share the sensor data of a vehicle with other vehicles, in other words, to exchange the perception data between neighboring vehicles [284]. Cooperative perception offers several benefits, such as exceeding the LOS limitation, lane change reliability, and invisible obstacle avoidance, which result in road safety enhancement [285]–[288]. In [289], a perception system for predicting and planning lane change motion in autonomous vehicles (AVs) based on V2V has been studied to further help with avoiding collisions. To boost the feasibility of cooperative perception, [290] has suggested anticipating the value of sensor data before sharing it with other vehicles to minimize the burden of sharing unnecessary information on the V2V network.

Urban intersections: Urban intersections are one of the expected points for serious car accidents; therefore, V2V communication is needed for broadcasting ICWs between drivers to avoid accidents [291]. However, establishing V2V communication links between vehicles encounters obstacles at urban intersections that are blocked due to surrounding blocking objects such as trees, buildings, and other vehicles. In [292], [293], the performance of LOS and NLOS communication links at road intersections were evaluated. In [294], the experimental comparison between DSRC and LTE-V2V for intersections in terms of communication performance and ICW functionality has been presented. In [295], V2V channel characteristics have been evaluated in a dynamic intersection framework at 5.9 GHz. The authors in [296] have tested the reliability of V2V communications at a crowded intersection and presented the benefit of buildings to decrease interference in circumstances with severe network congestion. In [297], control algorithms have been presented with an experimental prototype for collective collision avoidance at traffic intersections and in merging situations. The paper have recommended applying automatic control in case of inevitable collisions using only V2V communication between vehicles. However, the driver should be warned with a warning before automatic control is directly applied to ensure a safer driving experience. In [298], [299], the collision probability of intersection scenarios has been calculated using experimental prototypes. V2V communication is used to calculate the time-to-collision (TTC) based on the two vehicles' displacement, speed, acceleration, etc. In [300], a V2V communication system without the need for RSUs has been developed to behave like an artificial traffic light to reduce the time delay at uncontrolled intersections. In [301], a collision avoidance system has been presented based on V2V communication with a real-time database for complex intersections with non-perpendicular intersecting lanes. Simulation results have been presented using the VEINS framework for vehicular networks. In [302], the effects of four different types of intersections on the channel power delay profile and dispersion losses are studied, depending on the availability of surrounding buildings and the distance between vehicles and the intersection point.

Vehicle shadowing: V2V communications between vehicles can be disrupted by various factors, including surrounding buildings and corners, as described earlier; however, it can also get degraded due to big-size vehicles on the road. The latter issue is commonly referred to as vehicle shadowing as has been discussed in [303]–[307]. In [303], several properties of V2V links (at 5.8 GHz) during vehicle shadowing scenarios are analyzed, such as LOS and NLOS path loss, shadow fading, cross correlation, and delay spread using a school bus as an obstacle or obstruction. In [304], geometric and stochastic analysis has been performed to measure the shadowing region and the effects of shadowing on DSRC links between vehicles. Windshield cameras, as presented in [305], [307], reduce vehicle shadowing by providing real-time footage of the road ahead and sharing them with the rear vehicle through V2V communication based on DSRC, enhancing drivers' visibility and improving road safety.

Platooning: platooning refers to a coordinated group of vehicles that use V2V communications to move together and has been widely used in connected autonomous vehicles (CAV) as discussed in [308]–[310]. A platoon of vehicles communicates with each other to maintain a safe distance and match the pace of the lead vehicle to improve safety by reducing the risk of accidents, as discussed in [311]. Platooning has been considered a means to improve traffic flow, reduce congestion, and increase the effectiveness of freight transport and can be applied to a wide range of vehicle types [312]. In [313], automated platooning of multiple trucks with the associated control system has been presented to reduce labor costs, energy consumption, and CO_2 emissions and increase road capacity for other vehicles. String stability in vehicle platooning, described in [314], means maintaining a stable formation and limiting disturbances to ensure safe and effective operation and is used as a performance standard for vehicle platooning systems [315]. In [316], a nonlinear control algorithm based on the Lyapunov technique has been developed for a platoon of multiple CVs with V2X communication. Stability analysis has been performed, and the performance of the system is tested under several scenarios of vehicle platooning, merging, and diverging. Fast and continuous V2V communication with low time delays is critical in platooning. Therefore, in [317], [318], the importance of time delays in V2V communication has been presented along with vehicle dynamics to ensure safe emergency braking on time. [317] presented the maximum tolerable communication delays between platooning vehicles without compromising safety.

D. V2V communication security:

Vehicle cybersecurity is a top priority for transportation agencies such as the national highway traffic safety administration (NHTSA), an agency of the U.S. federal government [319]. Major challenges in V2V communications include protecting driver privacy and ensuring the information transmitted is accurate, secure, and protected from hacking or other malicious activity. Developing a system that guarantees the authenticity of the transmission source and prevents any tampering is of paramount [320]. Several strategies and proposals have been presented to reduce deceptive messages in V2V communications as discussed in [209], [215], [321]–[326]. In [215], a new efficient system called message-linkable group signature (MLGS) has been suggested to provide high security against V2V communication and vehicle privacy threats with low latency and without drastically degrading safety and performance. [321] has demonstrated a simple and secure approach for V2V communication in internet-of-vehicles (IoV) networks. The suggested encoding technique is effective and has low time complexity, and it advocates the use of link fingerprints created from channel characteristics and blockchain-based data exchange for real-time authentication. [209] has investigated the tools necessary for secure and private ITS and emphasized that using the suggested cloudlets in V2V communication can provide the required security.

IV. Challenges, Commerce, and Future Developments

Implementing V2V technology has the potential to greatly improve the sustainability of EVs. However, despite the promising outlook, there are significant challenges that are impeding its widespread adoption. These challenges include issues with EV user interfaces, safety concerns related to high charging rates, security, power limits, cost, payment mechanisms, user trust, compatibility, and standardization [327]. It is critical to overcome these barriers to seamlessly integrate V2V technology into everyday life. On the business side, the lack of standards for V2V power transfer is a major hurdle affecting interoperability. To solve this problem, new standards for power transmission, connectors and communication protocols need to be defined. This will ensure smooth and efficient power exchange among EV owners, and promote the widespread use of EVs in the transportation sector. The following sections delve into these challenges, propose solutions, explore current commercial developments, and provide insights into the future advancements of V2V technology.

A. Challenges

V2V is a promising technology that has the potential to enhance EV adaption and reduce range anxiety. However, there are numerous obstacles to overcome before the widespread adoption can occur. The main challenges associated with V2V technology are as follows:

i. EV user interface: accessing the EV user interface for V2V communication remains a critical hurdle. Currently, there is no direct approach to establish direct communication between two EVs for V2V power transfer.

ii. Communication platform: in order for an EV user to place V2V power transfer request while on the road, and at the same time, other EV users who may be willing to provide the energy at some financial charge, there should be a robust marketplace platform (for example, based on crowdsourcing). The platform would be the backbone of V2V power transfer ecosystem.

iii. Safety concerns: when charging EVs from each other at high charging rates, commonly employed approaches include DC fast charging V2V techniques. However, this method can lead to a significant current flow, which presents a substantial safety risk. In regards to WPT-V2V techniques, concerns regarding safety arise due to thermal effects and electromagnetic interference issues. To address these issues, researchers must carefully consider a number of factors, such as protection measures, isolation techniques, and strategies for managing potential fault scenarios.

iv. Security: ensuring the security of V2V communication is vital, as it entails constructing robust systems that not only verify the source's authenticity but also prevent unauthorized alterations while avoiding interference with other wireless devices.

v. Power limit and charging rate: as discussed previously in Section-II, on-board chargers are typically constrained by their maximum power outputs (between 1.9 kW to 19.2 kW). To achieve faster charging rates and thus reduce V2V power transfer time, innovative solutions and/or high-power topologies should be developed.

vi. Cost: there should a well defined mechanism to agree upon the cost of energy transfer prior to the actual V2V operation.

vii. Payment mechanism: efficient, seamless, and secure money transfer between two parties, potentially utilizing a user-friendly mobile application, should be available/developed.

viii. User trust and acceptance: encouraging EV owners to embrace V2V energy transfer technology can be challenging. Potential users worry about whether V2V charging systems are reliable and convenient, which may slow down the adoption. Consequently, there is a need for more portable, user-friendly, and comfortable solutions to integrate V2V technology into EVs.

ix. Compatibility: given the variations in capacity, voltage levels, life cycles, and charger specifications among EV manufacturers, it is important that new V2V charging solutions cover a wide range of power levels and battery voltages. This will ensure smooth V2V for wider types of EVs and their varying charging requirements.

x. Standardization: in order to enable seamless compatibility between different EV models from different manufacturers, there is a critical imperative to develop unified V2V charging standards and protocols.

B. Commercial Developments

The increasing popularity of EVs highlights the necessity for a standardized V2V power transfer system among them. This parallels the existing EV charging standards such as the society of automotive engineers (SAE), the international electrotechnical commission (IEC), GB/T, and Chademo, which vary by country. In Table-V, an overview of current standards is provided, encompassing various aspects of EV charging, connectivity, and wireless technologies, as per [328]–[330]. This table includes the latest version dates, indicating revisions across many standards, with newer versions introducing additional improvements.

Several papers have delved into standards concerning voltage and current levels for EV charging, as outlined in [39], [40], [42], [332]. Furthermore, standards related to EV charging at CSs are discussed in [101], [103], while standards for EV charging through WPT are covered in [147]. Without established standards for V2V power transfer, managing and sustaining V2V charging between diverse EV models is a complex task [137]. Addressing these challenges requires the development of new standards encompassing power transmission, connectors, and communication protocols. This is essential for efficiently overseeing power flow, whether through aggregators or wirelessly, ensuring a seamless and effective power transfer experience for EV owners. Ultimately, this initiative will contribute to the widespread adoption of EVs and their seamless integration into the transportation sector.

Bidirectional chargers installed in some EVs such as the Nissan Leaf, Ford F-150 Lightning, Volkswagen ID.4, and Kia EV6 enable G2V and V2G operations [333]. More recently, there have been some commercial products for wired V2V charging, such as Andromeda Power's ORCA Inceptive, which provides a portable, off-board, 50-kW DC station, but it incurs additional costs for the EV owner and must be carried in the trunk, taking up extra space [334]. Hyundai has introduced another V2V charging option for their EVs in the Indian market, available on the Hyundai Kona model [335]. However, Kona owners will have to resort to a pre-charged EV to charge their own EV, which Hyundai will deliver to a specified location. It should be noted that Hyundai has not yet demonstrated a direct V2V charging capability between EV users. As for wireless charging, it has been gaining popularity in the global market through various companies such as WiTricity, Hevo, Wave, and InductEV [336]–[339] are now offering commercial products for EV wireless charging; however, WPT-V2V has not yet been implemented into a commercial product.

C. Future Developments

The future of V2V technology is expected to have significant advancements across multiple fronts. Key areas of development include improvements in WPT systems, standardization initiatives to ensure interoperability among various manufacturers, enhancements in V2V communication, and the implementation of advanced technologies and commercial solutions. These efforts aim to improve efficiency, charging rate, and power levels to facilitate more efficient energy transfer between EVs, which could lead to faster charging times. To address range anxiety, EV manufacturers are taking proactive measures by incorporating V2V charging capabilities. Additionally, there is a notable movement towards standardizing V2V technology to enable seamless communication

This article has been accepted for publication in IEEE Transactions on Transportation Electrification. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TTE.2023.3345738

TABLE V: Key standards shaping the future of EV charging infrastructure [328]–[331]

Objective	Standard	Latest release date	Related description and applications
Interoperability	SAE J3105 SAE J1772	05-2023 10-2017	Defines the criteria for the conductive charging of EVs in North America, covering physical, electrical, and functional requirements
	SAE J3068	07-2022	Conductive charging requirements of EVs for a three-phase coupler
	CHAdeMO (3.0)	04-2021	Charging protocol enables charging at over $500kW$ power ($< 900kW$), facilitating smooth communication between the EV and the charger
	IEC 61851	07-2023	EV conductive charging system
	IEC 62196	10-2022	Dimensional compatibility requirements for accessories such as EV plugs, socket-outlets, connectors, and inlets designed for conductive charging of EVs
Safety	SAE J2344	10-2020	Safety guidelines for high-voltage vehicles, including EVs, during charging and regular operation
Power Quality	SAE J2894/1 GB/T 29316	01-2019 2012	Guidelines and requirements for EV chargers, facilitating design decisions on power quality
WPT	SAE J2954 IEC 61980	08-2022 05-2023	Sets industry standards for stationary WPT of EVs, covering interoperability, electromagnetic compatibility, safety, and testing, aligning with SAE J1772 charge levels
	SAE J1773	06-2014	Outlines the compatibility criteria for inductively coupled WPT for EVs in North America at frequencies much higher than power line frequencies
EVSE	SAE J2953/1	05-2023	Requirements for interoperability of EVs with EVSE
	SAE J2293/1	02-2014	Functional requirements for interoperability of EVs with EVSE
	SAE J2293/2	02-2014	Communication requirements for interoperability of EVs with EVSE
	GB/T 40428	2021	EMC requirements and test methods of conductive charging for EVs
	GB/T 18487.2	2017	EMC requirements for EVSE
Grid interconnection	SAE J3072	03-2021	Outlines interconnection requirements for onboard, grid support inverter systems and defines communication protocols between EV and EVSE
Communication	SAE J2945/1	04-2020	Requirements for on-board V2V safety communication system through DSRC links
	SAE J2847/6	09-2020	For EVs and CSs to communicate during WPT and ensure successful alignment of coils
	SAE J2847/3	03-2021	For EVs with on-board inverter to communicate via IEEE 2030.5-2018 (supports SAE J2836/3)
	SAE J2847/2	09-2023	For EVs and off-board DC chargers to communicate through SAE J1772 coupler
	SAE J2847/1	08-2019	For EVs smart charging through the utilization of smart energy profile 2.0
	SAE J2836/2	08-2023	Use cases for EVs communication with DC off-board charger
	SAE J2836/3	01-2017	Use cases for EVs communication as a DER
	SAE J2931/1	09-2023	Requirements for PLC digital communication between EVs and EVSE
	SAE J2931/4 SAE J2931/6	05-2023 08-2022	Communication requirements for data-link and PHY layers using broadband PLC between EVs and EVSE
	SAE J2931/7	02-2018	Security requirements for digital communication among EVs, EVSE, utility, etc
	GB/T 41578	2022	Technical requirements and tests for information security of EV charging system
Development	SAE J1938	11-2022	A basis for developing vehicle electronic systems and a product development checklist
	SAE J3083	03-2017	Offers valuable guidance for predicting the reliability of automotive electronic components
Charging cables	IEC 62752 GB/T 41589	02-2019 2022	Control and protection devices within the cable designed for mode 2 charging of EVs
	GB/T 33594	2017	Charging cables for EVs

and energy sharing among EVs. Establishing global standards governing V2V power transfer and communication protocol are anticipated, creating a standardized framework [340]. The emergence of mobile applications facilitating financial transactions in the context of V2V charging, coupled with robust business models, is also noteworthy. Although the current costs are relatively high, especially for DC off-board and WPT based systems, there is an expectation that costs will decrease as the technology matures and becomes more commercialized. Despite being in its early stages, V2V power transfer has garnered increasing interest from the automakers and government agencies, and the outlook is optimistic. Widespread adoption of V2V power transfer is anticipated in the near future.

V. Conclusion

This paper presents a comprehensive review of V2V technology, with a specific emphasis on its power transfer and communication aspects between vehicles. The authors explore various optimization techniques and thoroughly analyze circuit topologies from the literature relevant to power transfer. While V2V power exchange has been shown to be a viable solution for emergency scenarios, ongoing research is being conducted on novel topologies and reliable systems to enhance its efficacy. Nonetheless, to ensure the affordability and commercial feasibility of V2V power transmission technology, it is crucial to address safety, reliability, sizing, power loss, charging speed, and cost challenges through further research and development. Furthermore, the communication aspect of V2V technology is comprehensively analyzed, encompassing an explanation of standards, protocols, and their practical applications for enhancing traffic safety and management. In this context, the challenges that must be overcome to achieve widespread implementation of V2V technology are also discussed. It also highlights the imperative of setting standards for V2V power transfer and communication. Lastly, the paper emphasizes on the critical needs for further development to ensure the long-term sustainability and viability of V2V technology. This review aims to function as a valuable reference guide for researchers engaged in the field of V2V power transfer.

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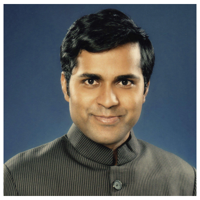
Azizulrahman Shafiqurrahman (Member, IEEE) received the B.Sc. degree in Electrical and Electronics Engineering from the University of Sharjah, Sharjah, UAE, in 2020 and the M.Sc. degree in Electrical and Computer Engineering from Khalifa University, Abu Dhabi, UAE, in 2022. From August 2020 to July 2022, he was a Research and Teaching Assistant at Khalifa University. Since November 2022, he has been a Research Engineer with the Department of Electrical Engineering and Computer Science, Khalifa University. His current research interests include applications of power electronics in electric vehicles and power quality enhancement.

Vinod Khadkikar (Fellow, IEEE) received the M.Tech. degree in power electronics, electrical machines and drives from the Indian Institute of Technology, New Delhi, India, in 2002, and the Ph.D. degree in electrical engineering from the Ecole de Technologie Superieure, Montreal, QC, Canada, in 2008.

From 2008 to 2010, he was a Postdoctoral Fellow with the University of Western Ontario, London, ON, Canada. In 2010, he was a Visiting Professor with the Massachusetts Institute of Technology, Cambridge, MA, USA. He is currently a Professor with the Department of Electrical Engineering and Computer Science, Khalifa University, Abu Dhabi, United Arab Emirates. His research interests include applications of power electronics in distribution systems and renewable energy resources, grid interconnection issues, power quality enhancement, active power filters, and electric vehicles.

Dr. Khadkikar is a distinguished Lecturer of IEEE Industry Applications Society. He is currently Co-EiC of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS and an Associate Editor for IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS and IET Power Electronics.



Akshay Kumar Rathore (Fellow, IEEE) is an IEEE Fellow and expert in power electronics and control of electrical motor drives. He is a full professor and program leader of the BEng. degree programme in electrical power engineering at Singapore Institute of Technology (SIT), Singapore. He received the Gold Medal for securing the highest academic standing in M.Tech. degree (2003) among all electrical engineering specializations at the Indian Institute of Technology (BHU) Varanasi, India. He received his PhD degree in Power Electronics from the University of Victoria, British Columbia, Canada in 2008. He had two subsequent post-doctoral research appointments with the University of Wuppertal, Germany, and the University of Illinois at Chicago, USA. From November 2010 to February 2016, he served as an Assistant Professor at the Department of Electrical and Computer Engineering, National University of Singapore. From March 2016-Dec 2021, he served as an Associate Professor at the Department of Electrical and Computer Engineering, Concordia University, Montreal, Canada where he was listed in the Provost Circle of Distinction in 2021. He served as Graduate Program Director and Chair of Graduate Awards during 2020-21.

Owing to his exemplary research contributions, Dr. Rathore received 2013 IEEE IAS Andrew W. Smith Outstanding Young Member Achievement Award, 2014 Isao Takahashi Power Electronics Award, 2017 IEEE IES David Irwin Early Career Award, 2019 IES Publications Service Recognition Award, 2020 IEEE IAS Outstanding Area Chair Award, 2020 IEEE Bimal Bose Award for Industrial Electronics Applications in Energy Systems and 2021 Nagamori Award. He published above 300 research papers in international journals and conferences, including 110 Journals that include 98 IEEE TRANSACTIONS. He supervised 11 PhD theses, 13 Masterâs theses and trained 5 research engineers and four postdoctoral fellows. His research is mainly focused on the current-fed dc/dc converters, circuit topologies, soft-switching techniques, novel modulation schemes, multilevel inverters, and control of electrical motor drives. He contributed to 3 book chapters in 3 different books and recently edited one book âAdvanced Concepts and Technologies for Electric Vehiclesâ published by CRC press (Taylor and Francis). He has a European patent licensed to WEG, Brazil.

Dr. Rathore is currently serving as the co-Editor-in-Chief of IEEE Transactions on Industrial Electronics, IAS Awards Department Chair, IEEE Nikola Tesla Award Committee member, IES AdCom Member-at-Large, IEEE IES Fellow Evaluation Committee member, and as the Chair of IEEE IAS Renewable and Sustainable Energy Conversion Systems Committee. He led and chaired the IEEE IAS Industrial Automation and Control Committee (2018-19) and IEEE IAS Technical Committee on Transportation Electrification (2016-17). He served as an IEEE IAS Distinguished Lecturer from 2017-2021.

Dr. Rathore served as the Paper Review Chair (eq. to co-Editor-in-Chief) of IEEE Transactions on Industry Applications (2016-17 and 2020-21), Editorin-Chief of IEEE IES Technology News (ITeN) (2016-18), Associate Editor of various journals, i.e., IEEE Transactions on Industrial Electronics (2014-19), IEEE Transactions on Industry Applications (2013-21), IEEE Transactions on Transportation Electrification (2014-19), IEEE Journal of Emerging Selected Topic in Power Electronics (2013-19), IEEE Transactions on Vehicular Technology (2016-19), IEEE Transactions on Sustainable Energy (2014-2021) and IET Power Electronics (2015-19).