Methodologies, Applications and Challenges of Three port DC-DC Converters: A review

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***Abstract*—Electric vehicles (EVs), hybrid electric vehicles (HEVs), and renewable energy integration have increased the demand for converters that can handle multiple sources and bidirectional energy flows. Traditional two-port converters are limited in this regard. Three-port converters (TPCs) provide a single-stage, compact solution by interfacing PV arrays, batteries, and grid/load simultaneously. This paper reviews the literature on TPC topologies and control methods, their applications in EVs, HEVs, and renewable power systems, and identifies research gaps. The review categorizes converters into non-isolated, isolated, hybrid/reconfigurable, and application-specific designs, while also highlighting control strategies such as maximum power point tracking (MPPT), droop control, impedance shaping, predictive methods, and intelligent approaches. Applications including vehicle-to-grid (V2G), grid-to-vehicle (G2V), PV-battery integration, and LVDC microgrids are discussed. The study concludes with identified challenges in scalability, controller complexity, and battery health management, which motivate the need for lightweight and standard-compliant designs.**

***Index Terms*—Three-port DC–DC converters, bidirectional converters, grid-to-vehicle (G2V), vehicle-to-grid (V2G), hybrid electric vehicles, photovoltaic integration.**

I. Introduction

Two-port DC–DC converters are widely used but have inherent limitations when multiple sources need to interact. They only allow energy transfer between one source and one load, which is insufficient in systems requiring PV arrays, batteries, and the grid to exchange power simultaneously [1].

Three-port converters (TPCs) provide a more compact and multifunctional interface, enabling simultaneous power flow between three terminals. Compared to cascaded two-port converters, TPCs reduce conversion stages, improve efficiency, and minimize size and cost [2],[3]. Integrated battery chargers in EVs also demonstrate reduced hardware redundancy when TPCs are adopted [4].

In addition to their use in EVs and HEVs, TPCs also contribute to grid support. Smart infrastructures and big data analytics have been proposed to forecast EV demand and optimize charging schedules, requiring power converters that can handle such dynamic conditions [5]. Meanwhile, LVDC microgrids and multiterminal networks are gaining adoption for renewable integration and EV charging, but they demand robust and scalable converter solutions [6],[7].

This paper reviews the methodologies, applications, and challenges associated with TPCs. It categorizes the literature into topology-based and control-based contributions, discusses application domains, and highlights open research gaps that guide further work.

II. Background and Motivation

Hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) are among the earliest adopters of multi-source power architectures. Several challenges, such as limited driving range, battery degradation, and inefficient energy management, have been reported in literature [2]. These limitations highlight the need for converters capable of managing multiple bidirectional flows.

From the infrastructure perspective, deployment of EV charging and swap stations has significant impacts on distribution systems. Optimal planning requires balancing demand, location, and power flow, which necessitates the use of advanced converters for reliable integration [3]. Integrated on-board chargers (OBCs) that reuse traction inverters further show the importance of compact and multifunctional converter designs.

Review papers on battery charger topologies highlight the evolution from unidirectional to bidirectional architectures, converging on V2G-ready designs [1]. At the same time, big data and smart city approaches to charging demand forecasting require converter hardware that can support dynamic control [5].

In terms of power systems, LVDC distribution is emerging as a promising option for EV charging and renewable integration due to higher efficiency and compatibility with DC-based sources. Voltage-level selection for LVDC grids involves trade-offs between safety, compatibility, and efficiency [6]. Research on multiterminal LVDC networks highlights improved reliability and flexibility for EV integration, though such systems require TPCs for efficient operation [7].

Historically, multiphase bidirectional converters, such as the flyback topology proposed for HEVs [8], demonstrated the feasibility of multiport converters but lacked efficiency for higher power, motivating further advances in TPC designs.

III. METHODOLOGIES FOR THREE PORT CONVERTERS

Research on TPCs can broadly be divided into two categories: topology-oriented and control-oriented methods.

TOPOLOGY-ORIENTED APPROACHES

TPC topologies can be divided into non-isolated, isolated, hybrid/reconfigurable, and application-specific structures.

Non-Isolated Topologies: Zhu et al. [14] presented a non-isolated three-port converter with a three-domain control strategy for PV-battery systems. Zhang et al. [16] extended this idea with variable-structure converters offering wide operation ranges. These are efficient and compact but limited by the absence of galvanic isolation.

Isolated Topologies: Jiang et al. [9] proposed a bidirectional isolated converter for EV-grid applications, enabling V2G and G2V functions. Wu et al. [18] and Zhou et al. [20] introduced families of isolated multiport converters based on DC-link inductors, while Zolfi and Ajami [19] worked on a fuel-cell-based isolated TPC for EVs. These offer safety but increase bulk and reduce efficiency.

Hybrid/Reconfigurable Topologies: Saxena and Kumar [10],[13] proposed high-gain transformerless and reconfigurable boost converters for battery and fuel-cell systems. Moury and Lam [11] designed a soft-switched PV-battery TPC with MPPT, and Al-Soeidat et al. [12] developed a compact three-port design. Cheng et al. [17] proposed a reconfigurable single-inductor topology for renewable applications. These enhance adaptability but introduce control complexity.

Application-Specific Topologies: Bhattacharya et al. [8] developed a multiphase flyback converter for HEVs. Natchimuthu et al. [28] investigated a PV-fed SEPIC for HEVs, while Lai et al. [29] proposed a dual-battery bidirectional converter. Deihimi and Mahmoodieh [15] analyzed battery-integrated converters for renewables. These are tailored but lack general scalability.

Table 1. Comparison of TPC Topologies

Topology Type	Key References	Advantages	Limitations	Applications
Non-Isolated	Zhu [14], Zhang [16]	Compact, efficient	No isolation, limited gain	PV-battery, LVDC
Isolated	Jiang [9], Wu [18], Zolfi [19], Zhou [20]	Safety, high step ratios	Bulky, costly, less efficient	EV-grid, FCEVs
Hybrid/Reconfigurable	Saxena [10],[13], Moury [11], Al-Soeidat [12], Cheng [17]	Flexible, high gain	Control complexity	PV-battery-grid
Application-Specific	Bhattacharya [8], Natchimuthu [28], Lai [29], Deihimi [15]	Tailored to HEVs/renewables	Limited scalability	HEVs, PV-HEVs

CONTROL ORIENTED APPROACHED:

Control strategies focus on managing multiport power exchange efficiently.

MPPT-Based Control: Mastromauro et al. [22] discussed PV MPPT issues under fast irradiance. Chiu et al. [24] and Goudarzian and Khosravi [25] improved MPPT and double-loop methods for battery chargers.

Droop Control: Khorsandi et al. [21] applied droop for LVDC microgrids, enabling decentralized sharing, though with accuracy issues under line mismatches.

Impedance Shaping: Zhang et al. [23] introduced virtual impedance shaping to stabilize cascaded converters.

Predictive/AI Approaches: Saxena and Kumar [10],[13] developed predictive and reconfigurable controls, while Hu et al. [26] applied reinforcement learning for HEV energy management. These approaches are powerful but computationally intensive.

PWM: Kazimierczuk [27] described the fundamentals of PWM-based switching strategies, which remain the basis of all converter control methods but are insufficient alone for advanced multiport objectives.

Table 2. Comparison of Control Strategies

Control Strategy	Key References	Advantages	Limitations	Applications
MPPT (P&O, INC)	Mastromauro [22], Chiu [24], Goudarzian [25]	Extracts max PV power, simple	Oscillations under fast irradiance	PV-fed TPCs
Droop Control	Khorsandi [21]	Decentralized, scalable	Accuracy loss under mismatches	LVDC microgrids
Impedance Shaping	Zhang [23]	Improves stability	Additional design needed	Multi-stage converters
Predictive/AI	Saxena [10],[13], Hu [26]	SOC-aware, adaptive, fast response	Computationally heavy	EVs, renewables
PWM	Kazimierczuk [27]	Simple, widely used	Not sufficient for multi-objective	Base method for all

IV. APPLICATION OF TPCS AND ASSOCIATED CHALLENGES

APPLICATIONS

Three-port converters have been studied in a range of applications, from EV charging to renewable integration and microgrids.

EV Charging and V2G/G2V: Jiang et al. [9] developed a bidirectional isolated converter enabling energy interaction between EVs and the grid, supporting G2V and V2G. These converters reduce the need for multiple conversion stages and improve compactness.

HEVs and Dual-Battery Systems: Bhattacharya et al. [8] proposed a multiphase flyback topology for HEVs, an early demonstration of multiport capability. Natchimuthu et al. [28] experimentally investigated a PV-fed SEPIC converter for HEVs, while Lai et al. [29] developed a bidirectional converter for dual-battery energy storage in HEVs.

PV-Battery Systems and Renewable Applications: Zhu et al. [14] introduced a non-isolated three-port converter for PV-battery integration with a three-domain control method. Deihimi and Mahmoodieh [15] analyzed battery-integrated converters for renewable energy. Moury and Lam [11] presented an integrated PV-battery converter with MPPT, and Zhou et al. [20] proposed a non-isolated TPC for standalone renewable systems.

LVDC Microgrids and Modular Converters: Pei et al. [7] discussed the potential of multiterminal LVDC networks for EV integration. Wu et al. [18] introduced a family of multiport buck–boost converters using DC-link inductors (DLIs), improving modularity and scalability in LVDC systems.

Battery Life Management: Lv et al. [30] examined pulse charging–discharging strategies for lithium-ion batteries, demonstrating improved capacity retention and reduced degradation. Integration of such methods with TPCs could enhance long-term performance.

Table 4. Applications of TPCs

Application Area	Key References	Contribution	Gap/Limitations
EV Charging (G2V/V2G)	Jiang [9]	Demonstrated bidirectional EV-grid power flow	Mainly simulation, limited hardware validation
HEVs (single/dual battery)	Bhattacharya [8], Natchimuthu [28], Lai [29]	Early HEV multiport; PV-fed and dual-battery systems	Limited efficiency or high complexity
PV-Battery Integration	Zhu [14], Deihimi [15], Moury [11], Zhou [20]	Coordinated PV-storage power sharing	Lack of scalability; isolation concerns
LVDC Microgrids	Pei [7], Wu [18]	Multiterminal and modular converters	Higher complexity; limited field demonstrations

Battery Life Management	Lv [30]	Pulse charging extends Li-ion battery life	Not yet integrated with TPC frameworks

CHALLENGES

Despite these applications, several challenges remain for TPCs:

Efficiency vs. Safety: Non-isolated converters provide high efficiency but lack galvanic isolation, while isolated converters add safety but increase cost and bulk [9],[14].

Control and Stability: Conventional MPPT suffers from oscillations under fast changes [22], while droop control loses accuracy under mismatched impedances [21]. Predictive and AI-based controls show promise but are computationally demanding [26].

Scalability: Most prototypes operate at less than 5 kW, limiting their use in high-power EV chargers or microgrid systems [18].

Battery Aging: Although pulse-charging strategies [30] have been proposed, few studies integrate long-term battery health into TPC operation.

Standardization and Communication: Grid-interactive TPCs require compatibility with V2G/G2V protocols, which is rarely addressed in current research [5].

V. Conclusion and Research Gap

This review presented methodologies, applications, and challenges of three-port converters (TPCs). By classifying TPC topologies into non-isolated, isolated, hybrid/reconfigurable, and application-specific types, the study showed how each design offers unique benefits but also limitations. Control approaches, ranging from MPPT and droop to impedance shaping, predictive, and intelligent methods, were also reviewed. Applications across EV charging, HEVs, renewable systems, LVDC microgrids, and battery life management highlight the versatility of TPCs.

Several gaps remain in existing work:

Lightweight embedded control: Predictive and AI-based strategies [10],[13],[26] offer adaptability but are computationally intensive, limiting practical deployment.

Battery-aging-aware integration: Pulse charging methods [30] show potential, but few studies incorporate long-term health into converter control.

Scaling beyond lab prototypes: Most TPC studies remain at sub-5 kW levels [18], whereas EV fast chargers and renewable systems require >10 kW.

Grid standards and communication: V2G/G2V compliance and interoperability protocols are rarely considered in TPC studies [5].

Field validation: Modular and multiterminal LVDC designs [7] show promise but need real-world demonstrations.

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