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Multi-Port Converters for Interfacing Renewable Energy Sources: State-of-the-Art

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ABSTRACT

Several power electronic converters are merged to fulfill different requirements such as interfacing Renewable Energy Sources (RESs) to energy storage systems (ESS), grid, and loads. Some applications would require several converters that reduce the efficiency, increase component counts and complicating the control strategies. The interfacing of separate energy sources utilized in electrical vehicles (EV) and grid-connected applications has drawn attention to Multiport Converters (MPC).

Additionally, MPCs have a smaller component count and compact design compared to multiple independent DC-DC converters. This led to an increase in the power density and a decrease in complexity and cost of the converter. This article Introduce a comprehensive review for numerous numbers of publications regarding MPCs, advising a simple classification for MPCs. The classification introduced in the article is based on the applications. This classification would be a beneficial tool for researchers in the field while highlighting different control and modulation strategies used in MPCs and Discussing the limitations and boundaries of MPCs.

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المحولات متعددة المنافذ لربط مصادر الطاقة المتجددة: أحدث التقنيات

علاء محمود، محمود أيمن أحمد، أحمد حافظ.

ملخص: يتم دمج العديد من محولات الطاقة الإلكترونية لتلبية متطلبات مختلفة مثل ربط مصادر الطاقة المتجددة بأنظمة تخزين الطاقة والشبكة والأحمال، وتتطلب بعض التطبيقات العديد من المحولات مما يقلل من الكفاءة ويزيد من عدد المكونات ويعقد استراتيجيات التحكم. لقد لفت ربط مصادر الطاقة المنفصلة المستخدمة في المركبات الكهربائية والتطبيقات المتصلة بالشبكة الانتباه إلى المحولات متعددة المنافذ. بالإضافة إلى ذلك، فإنها تحتوي على عدد مكونات أقل وتصميم مضغوط مقارنة بعدد من المحولات المستقلة. أدى هذا إلى زيادة كثافة الطاقة وانخفاض في تعقيد وتكلفة المحول. تقدم هذه المقالة مراجعة شاملة لعدد كبير من المنشورات المتعلقة بالمحولات متعددة المنافذ، وتنصح بتصنيف بسيط لها، سيكون هذا التصنيف أداة مفيدة للباحثين في هذا المجال مع تسليط الضوء على استراتيجيات التحكم المختلفة المستخدمة فيها ومناقشة حدود وقيود استخدامها.

الكلمات المفتاحية – السيارة الكهربية، الأنظمة الهجينة، الشبكات الصغيرة، المحولات متعددة المنافذ، مصادر الطاقة المتجددة.

1. INTRODUCTION

RES are widely dispersed globally in the last decades due the deficiencies of fossil fuel sources, climate change phenomena and global warming [1]. Traditionally, DC-DC converters drive RES systems at their maximum power limit, regulate the voltage/current at a fixed level and connect energy storage devices. However, the conventional DC-DC converters are one-to-one; one input connected to one output. Thus, for renewable energy sources with uncertainty or limited period of generation, several converters must be deployed. This reduces efficiency and increases the cost and complexity.

The drawbacks of traditional DC-DC converters are numerous, including variable switching frequency, complicated control mechanisms, high voltage stress, significant ripple, low efficiency, and substantial resonant current for semiconductor devices, as well as high VA ratings for resonant components [2], [3]. Leakage inductance in the transformer contributes to low efficiency and high switch stress. Traditional converters also experience voltage stress on the secondary side and circulation loss on the primary side of the transformer [4]. Additionally, the large output inductor on the secondary side causes core loss [5]. To address these issues, several methods have been proposed, such as soft-switching forward-flyback converters, non-resonant mode converters, and three-level (TL) converters. These approaches aim to achieve zero-voltage switching, reduce voltage stress, improve efficiency, and simplify circuit designs.

Interleaved DC-DC converters have been widely used in household appliances, industrial equipment, and national defense construction, among others [6], [7]. Interleaved DC-DC converters are effective in lowering the amplitude of the total current ripple, increasing the ripple frequency of the output current, and enhancing the control capability for high currents.[8]–[12]. Interleaved topologies also eliminate output voltage ripples [13].

Capacitor clamped h-bridge, Multi-leg/multi-phase interleaved [14], and tristate boost converter topologies [15] are used to reduce output voltage ripple and enhance the voltage conversion ratio,. However, the related topologies have a limited gain and more active switching devices. In [16] the coupled inductor topologies provide high voltage gain, however large current ripples deteriorate the connected port in RES or battery unit. Using the switched-capacitor approach in conventional non-isolated converters is one way to solve this issue and produce high voltage gain while effectively integrating various energy sources [17]–[22].

When connecting the multiple energy sources used in EVs and grid-connected applications, multiport converters come into focus. Moreover, MPCs used a smaller structure and require fewer components than multiple independent converters. This results in an increase in power density and the converter's complexity and cost decrease. Consequently, MPCs are a wise option for RESs, EV applications, and grid-connected systems. [23].

This article claims to have the following contributions:

• Introducing a comprehensive review for numerous numbers of publications regarding MPCs.

• Advising a simple classification for different types of MPCs. This classification would be a useful tool for researchers in this field.

• Proposing effective comparisons between different MPCs in EV, PV, and Hybrid Systems. These comparisons identify the most promising topologies in these fields.

• Discussing the limitations and boundaries of MPCs This would direct the research efforts to solve these limitations.

The rest of the article is structured as follows, Background and Classification of MPCs explained in section 2. Comparative analysis of MPCs along with classification are discussed in section 3. Control Methodology for MPC is given in section 4. Limitations of MPCs provided in section 5. Lastly, the conclusions are presented in section 6.

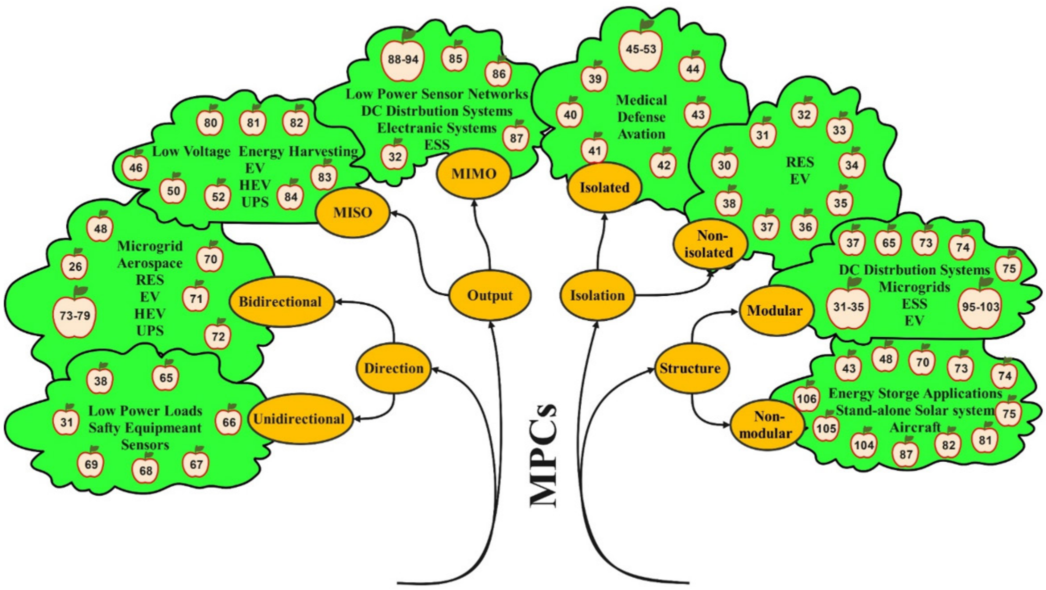


Figure 1. The general classification of MPCs based on Applications.

2. BACKGROUND AND CLASSIFICATION OF MPCS

The idea of generating electricity from dispersed RES has gained popularity in recent years. Multiple RES, for example solar and wind, with varying capabilities needs integration to the power grid or a load to be used in various applications [5], [24]–[30] . One effective method for coordinating various power sources and smoothly integrating them into the grid has been suggested: multiport DC-DC converters [28], [29], [31]–[33].

Different sources or storage units are typically connected to a common dc bus via separate dc–dc converters. As a result, power transfer between sources and storage becomes a two-stage operation, which reduces system efficiency. On the other hand, a multiport converter (MPC) simplifies this by providing a single dc–dc converter as a unified interface for several energy sources or storage units [31], [34]. This results in a more compact form and increases system efficiency by removing unnecessary power conversion stages.

The overall MPC classification according to Applications is displayed in Fig. 1, and the explanation of each category's representation is provided in the subsections that follow.

2.1. Isolation Requirement

2.1.1. Non-isolated

In this category the loads and the sources are not isolated. These converters are mostly employed in the applications of EVs and renewable energy. Design and control complexity of this converter is straightforward. Fig. 2 (a) and Fig. 3 (a) [35]–[43] depict the overall architecture of these kinds of converters. Because there is no transformer involved, it has the advantages of being lighter and less expensive.

2.1.2. Isolated

The converters in question have electrical isolation. Electrical isolation is a crucial component needed for a variety of applications, including grid-connected, effective, reduced electromagnetic interference and noise-free power transfer. In applications related to medicine, defense, and aviation where electrical isolation is crucial, these are used, depending on the sensitivity of the load and a top priority in terms of safety.

The converters shown in Figures 3 (b) and 2 (b) These converters fall into two categories: transformers with individual windings for each port. [44]–[53], with each port linked to a single winding on the primary side. [54]–[58]. where all inputs are used on the common ground. The transformer windings' turns ratio can be used to simply manage the voltage levels while providing protection from high voltages and currents. The lack of windings makes single winding converters the favored option. Because transformers are necessary, the converter is heavier, more expensive, and more difficult to operate. Furthermore, the circuit structures have a very high control complexity.

Integrated isolated multiport converters fall into two categories. One type of converter makes use of a transformer where each port has its own winding. As a result, every port has electrical isolation [49]–[51], [59]–[61]. The second type of converters is connected to a single transformer primary side through several ports [62]–[69]. Because it requires less winding in the transformer, the second topology is preferred.

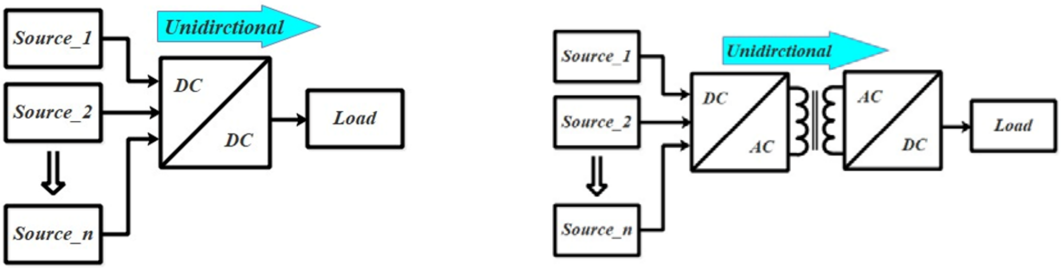
2.2. Operating Direction

2.2.1. Unidirectional

Since these MPCs only have one direction of power flow, they are frequently employed in renewable energy applications where energy storage devices like solar, wind, etc. are not available. Regarding the low-power utility including onboard loads such as safety equipment and sensors [36], [43], [70]–[74]. The typical designs of the unidirectional converters, ether non-isolated or isolated are displayed in Fig. 2(a).

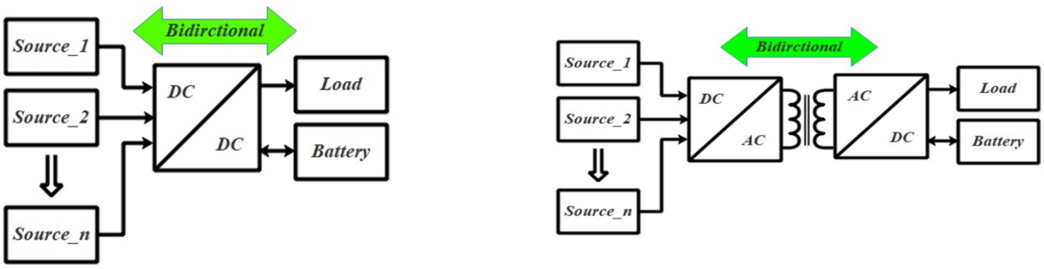
2.2.2. Bidirectional

The power flow in this kind of converter can be either way, and they primarily utilized in the following areas: microgrids, renewable energy, batteries, super-capacitors, elevators and escalators, electric or hybrid propulsion systems such as trains and automobiles, and aerospace applications. When used in conjunction with different input sources and loads, these converters offer the benefit of bidirectional energy transfer for HESS systems [31], [53], [75]–[84] as illustrated in Fig. 3 (a). The number of components was decreased by using bidirectional converters.



(a) (b)

Figure 2. (a) Unidirectional non-isolated MPC & (b) unidirectional isolated MPC.



(a) (b)

Figure 3. (a) Bidirectional non-isolated MPC & (b) Bidirectional isolated MPC.

2.3. Outputs

2.3.1. Multiple inputs single output

(MIMO) converters are those that have two or more outputs. MPCs are referred to as multiple input single-output (MISO) converters if they only have one output. The main applications for MISO converters include RES, hybrid and EVs propulsion, low voltage energy harvesting, and UPS systems. The typical construction of MISO converters illustrated in Fig. 4(a). Energy storage and renewable energy applications uses these in [51], [55], [57], [85]–[89].

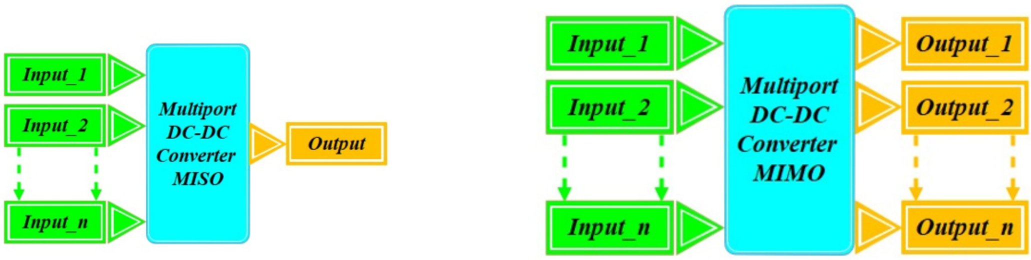
2.3.2. Multiple outputs

These converters integrate numerous input sources and supply a range of voltages in low power sensor networks, modern electronic systems, dc microgrids, and energy storage units, [37], [90]–[99]. The multiple output converter's general architecture shown in Fig. 4(b). Complexity of control in load regulation is relatively great.

2.4. Structure

2.4.1. Modular

As seen in Fig. 5(a), adding or removing a new source is made reasonably easy with fewer components, using these MPCs. enhance the system's dependability, which is crucial for energy storage devices, EVs, and microgrids [36]–[40], [42], [70], [78]–[80], [100]–[108]. DC home distribution systems make extensive use of the easily extensible modularity in both the load and source ends.

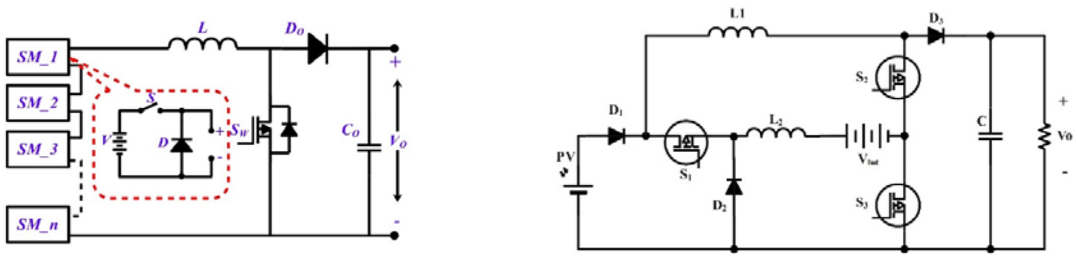


(a) (b)

Figure 4. (a) Basic structure of MISO and (b) MIMO converter.

2.4.2. Non-modular

Appending fundamental structure in series, as illustrated in Fig. 5(b), extends these converters topology. A limited topological extension from a basic structure is imposed by energy storage devices in a subset of converters. These MPCs find wide application in energy storage applications. According to needs, the energy elements are charged in parallel and can transfer energy to a load. They provide two-way power flow for energy storage systems [48], [53], [75], [78]–[80], [86], [87], [92], [109]–[111].



(a) (b)

Figure 4. (a) Basic structure of MISO and (b) MIMO converter.

3. COMPARATIVE ANALYSIS OF MPCS

The MPCs and the evolution of their applications are covered in detail in the following section.

3.1. MPC for PV

A converter with three ports presented in [112] with boost and buck operation modes. A SEPIC-based design replaces the traditional buck-boost or Cuk topology. The TPC operates in four modes. By distributing the duty cycle for each switch using a time-sharing control approach, the power flow management algorithm uses a mode-specific voltage regulation strategy. With the series capacitor providing intrinsic protection against output short circuits, the SEPIC-based construction helps to minimize input current ripple.

A brand-new multi-port multi-directional converter (MPMDC) is introduced in [113]. With just one inductor and one transformer, the MPMDC has galvanic isolation and achieves high voltage conversion ratio. The MPMDC's advantage of multi-directional power flow regulation allows it to be used to renewable energy, battery energy, and bus energy. This allows an energy storage system to flawlessly function its power conditioning feature. A 200W model was constructed and measured. The converter has a maximum efficiency of 94%.

A innovative multi-function isolated three-port bidirectional converter presented in [114] as a design for a standalone photovoltaic (PV) system, as depicted in Fig. 6. The topology that was described consisted of a unidirectional step-up converter and a bidirectional step-up/step-down converter. To increase the converter's practicability, numerous operating stages were employed, and every operation mode could be controlled with just one pair of complimentary PWM signals. Moreover, the topology served to increase conversion efficiency by recovering energy leakage through inductance.

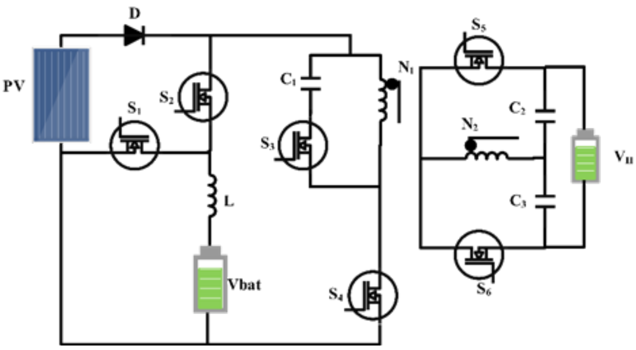


Figure 6. Circuit diagram of three-port bidirectional converter in [114].

A special kind of MPC that is partially isolated, is described in [115]. The converter known as the HOMPMLC, can produce DC and AC outputs from DC sources. A new multilevel inverter (MLI) topology is used in the HOMPMLC to create a high-quality AC output. This new topology uses five switches to create a seven-level improved quality AC output, and a forward power converter is used to create the DC output port.

A non-isolated three-port converter was presented by Elmakawi et al. in [116] with a 5H inverter, to supply a home load that ranged in power from 50 Watts to 3500 Watts, as seen in Fig. 7. The converter that is being described can run both on standalone and grid-tied electricity. An eight-mode operation innovative demand-side management method is described. The battery charging and discharging, PV maximum power point, 400 V DC bus voltage, load voltage in standalone mode, and grid-connected injection current are all regulated by the presented control system. The presented solution is feasible for building-integrated PV systems, according to the simulation results.

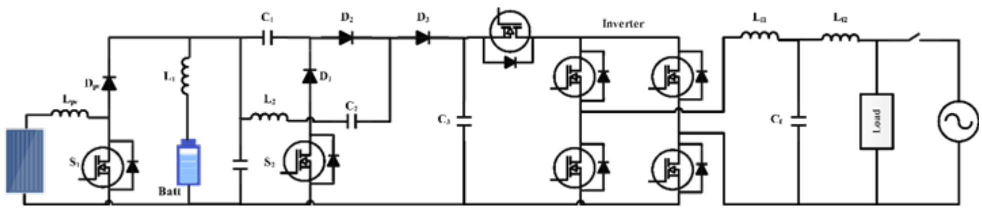


Figure 7. The Presented TPC topology in [116].

A converter for standalone applications presented in [117]. In this system, the secondary port is split to integrate a solar energy system and the battery unit. Thus, the secondary port is used for both storage and acts as the input energy source. The system also incorporates the Adaptive Neuro-Fuzzy Interference (ANFIS) based MPPT controller with improved voltage boost ratio and power efficiency.

A three-port Cuk converter (TPCC) that is non-isolated is shown in [118] for use in renewable RES. To solve the effect of cross- coupling in multiport converters caused by several interacting control loops, the control scheme is made consisting of a decoupling network. By managing the

solar system and ESS in accordance with availability, the converter controls the output voltage. The ESS port has the ability to charge and drain the storage battery in both directions. Reducing switching losses, the converter control algorithm operates with one or two switches.
described in [119] a modified power flow management control combining boost TPC with time sharing control to be used in a standalone solar PV system. In that study, a non-isolated TPC is introduced. when the TPC changes its operational parameters. There is an anti-battery overcharge feature in the control algorithm.
A non-isolated three-port converter (SCI-TPC) presented in [120] by combining switching capacitor converter, a series resonant converter, and a bidirectional buck-boost converter, to accomplish direct power conversion in a single-stage among three ports. PWM used in order to accomplish flexible power regulation and power balance between the ports, and in order to reduce the impact of cross-regulation PFM were implemented.

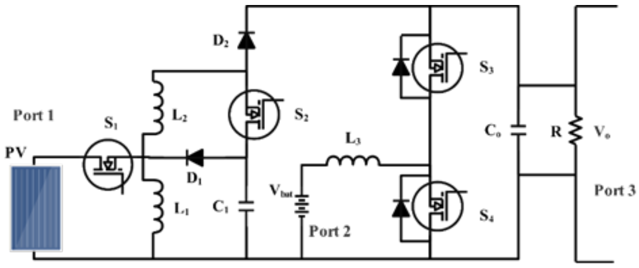


Figure 8. Circuit diagram of three-port bidirectional converter in [121].

A triple port buck-boost converter was introduced by B. Chandrasekar et al. in [121]. For utilizing solar energy and charging the battery seen in Figure 8, it contains two unidirectional ports and a bidirectional one. In Comparison to a traditional buck-boost converter, voltage conversion ratio is larger, and the output voltage's polarity is maintained positive. In order to store energy using the bi-directional boost converter, a battery is placed at the bi-directional port. Table 1 presents a comparison of different MPCs utilized in PV applications.
Performance comparison of multiport converters used with PV applications is summarized as shown in Table 1. In this comparison, the following elements are considered: components count, control method, topology, and conversion efficiency.

Table 1. Comparison of various MPCs used in PV Applications.

Ref.	D	S	L	C	Total	Control	Topology	Eff.
[118]	0	3	3	3	9	PI/MPPT	Non-Isolated	94%
[117]	5	3	5	6	19	ANFIS/MPPT	Non-Isolated	95%
[113]	5	5	2	3	15	PI/MPPT	Isolated	94%
[119]	3	3	1	2	9	Time sharing / PI/MPPT	Non-Isolated	NR
[114]	0	6	2	5	13	MPPT/Not Reported	Isolated	94.5%
[116]	4	2	3	4	11	PI/MPPT	Non-Isolated	87%
[112]	4	4	2	3	13	Time sharing / PI/MPPT	Non-Isolated	NR
[120]	5	6	3	10	24	PI/MPPT	Non-Isolated	94%
[115]	2	6	1	1	10	PI/ OVPT	Isolated	99.5%
[121]	4	4	3	2	13	Multi Objective Controller	Non-Isolated	93.6%

From the comparison, [115] presented a multi-port converter powered by solar energy and uses PI/optimal voltage power tracker (OVPT) to control the operation of the circuit, which is classified as isolated, and its efficiency reaches 99.5%. also [117] presented a multi-port converter powered by solar energy and uses ANFIS/MPPT to control the operation of the circuit, which is classified as non-Isolated, and its efficiency reaches 95%.

3.2. MPC for EV

Introduced a multi-port converter for combination construction in [122]. The presented converter design can transfer energy between many sources, including solar PV and energy storage devices like batteries, as well as acting as a SIMO converter. The converter's modular design has two benefits are the integration of numerous input sources with different voltage-current characteristics and the use of fewer components. MLI outputs can be connected to several voltage levels. EVs motor drives use multilevel inverters to reduce torque ripples and harmonic distortion.

As seen in Fig. 9, a bidirectional multi-port converter is presented in [123] for energy storage in EVs. It works in both buck and bidirectional boost modes. The suggested construction has three ports, the converter only uses two power switches, making it simple to move power between the sources. This causes the system's overall cost to decrease. A prototype power rate of 150 W at 50 kHz switching frequency, with input voltages of 20 V and 12 V, is built.

A multiple output high gain converter with three simultaneous outputs is presented in Reference [124]. It works by using two switches that are each controlled by a single PWM drive signal. This converter uses a big inductor, capacitors, and switched-capacitor and switched-inductor techniques. While the other two output voltages only reach half of the primary output voltage's gain, the primary output voltage achieves a much higher gain. Applications for this converter include solar energy and electric vehicles (EVs) in switched mode power supply (SMPS) and renewable energy systems.

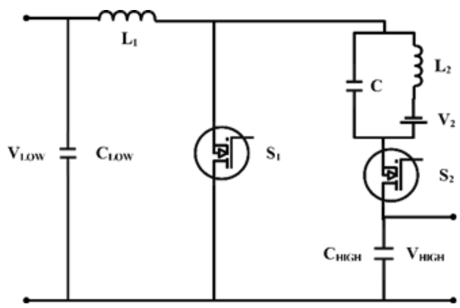


Figure 9. Circuit diagram of the Presented MPC in [123].

A converter design introduced in [125] with one battery and two solar cells for extra storage. The converter's dependability is increased when each input unit fails thanks to individual control over the input sources. For the battery port, the MPPT technique is used for control and regulation; for the input ports, the MPPT approach is used; and for the load port, a modified PI regulator is employed. A 500W, 72V prototype is created in order to validate the model.

As seen in Fig. 10, Reference [126] presents a dual input, dual output (DIDO) converter intended to include several power sources into electric vehicles. In comparison to other topologies, this modular converter has a more straightforward construction and fewer components. It can handle several inputs with different current and voltage capacities and generate boost, buck, and buck-boost outputs without the need for a separate transformer. The switches' duty cycles are managed by use of a rudimentary PI controller.

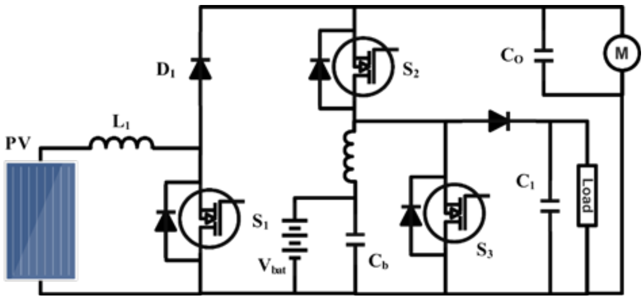


Figure 10. Circuit diagram of the Presented Converter in [126].

An isolated multi-port converter was presented by M.M. Savrun in [127] for the integration of multiple EVs with households in DC microgrids that uses loads of energy. The converter may perform the functions of a T-type inverter, a high-frequency transformer (HFT), and two bidirectional buck/boost converters in an interleaved design. The converter interface monitors the best possible energy flow between EVs and customer residences by integrating the energy of two distinct EVs. Utilizing a BEV and an FCEV as energy units, the vehicle-to-home (V2H) concept's energy needs are met.

SIMO converter in Presented in [128], it can be used for auxiliary power requirements in EVs to supply various auxiliaries as well as the onboard electric motor. By avoiding the problems with cross-regulation, it generates two independent output voltages. A prototype was used to confirm the converter's validity, and it may be extended to numerous outputs.

An interleaved converter with high gain and decreased voltage stress was presented in [129] using coupled-inductor and switched-capacitor circuits. This is appropriate for connecting low-voltage energy sources, like those seen in electric car applications. Reverse-recovery problem with diodes is mitigated by increasing the voltage gain by the use of a voltage multiplier step.

A bidirectional multiport converter and a control approach comprising presented by the authors in [130]. With a simplified switch converter architecture, the system that is being described incorporates four ports. The converter that is being described offers a large voltage gain at low battery/supercapacitor voltages and a reduced duty cycle. Furthermore, it makes it possible to design a transformer with a low turn ratio, increasing HFT's efficiency. Consequently, the voltage spikes brought on by HFT's leakage inductance were diminished. With the flexibility to transfer power in both directions, the architecture can sustainably power the EV's electric motor and recover braking energy.

A MPC for electric vehicle applications is introduced in reference [131], which makes it easier to integrate a battery and supercapacitor into the drivetrain. In order to achieve isolation, bidirectional power capability, and soft switching all of which are very desirable characteristics for EVs dual active bridge converters are used. To control its charge and guard against power surges, the battery runs in current control mode. Additionally, there is no requirement for an inbuilt DC/DC converter because the MPC can charge the battery from any DC input. Table 2 presents a comparison of different MPCs utilized in EV applications.

Table 2. Comparison of various MPCs used in EV Applications.

Ref.	D	S	L	C	Total	Control	Topology	Eff.
[122]	4	4	1	2	11	ANN /MPPT	Non-Isolated	NR
[126]	3	3	2	3	10	PI/MPPT	Non-Isolated	NR
[124]	6	2	1	5	14	NR	Non-Isolated	85%
[128]	2	2	2	2	8	PID	Non-Isolated	NR
[125]	7	3	4	5	19	PI/MPPT	Isolated	NR

[123]	0	2	2	3	7	NR	Non-Isolated	94%
[127]	0	10	2	3	15	PI	Isolated	96%
[130]	2	6	3	4	15	PI/MPPT	Isolated	96%
[131]	0	10	3	2	15	PI	Isolated	NR
[129]	4	4	1	5	14	NR	Isolated	97%

Performance comparison of multiport converter used with EV applications is summarized as shown in Table 2. In this comparison, the following elements are considered: components count, control method, topology, and conversion efficiency.

From the comparison, [123] presented a multiport converter that uses only 7 components in the circuit and considered the lowest number among the designs presented in Table 2, which is classified as non-isolated, the efficiency reached 94%. [129] presented a multiport converter used in EV charging. No details of the control unit were shown, and the converter can be classified as isolated, with an efficiency of 97%. while using 14 components in the circuit.

3.3. MPC for Hybrid Systems

The solar photovoltaic panels, wind generator, battery, and DC microgrid depicted in Figure 11 are connected using a power electronic interface presented by Walied Alharbi et al. in [132] that has four ports. In order to connect the DC microgrid's 380 V to the other three ports, which have lower nominal voltages, the presented converter uses a two-winding transformer. The transformer's possible power losses are minimized, though, because power is sent directly to the battery port from the solar and wind ports. The multiport converter controller designed to optimize power extraction from renewable resources and regulate the battery's charging current.

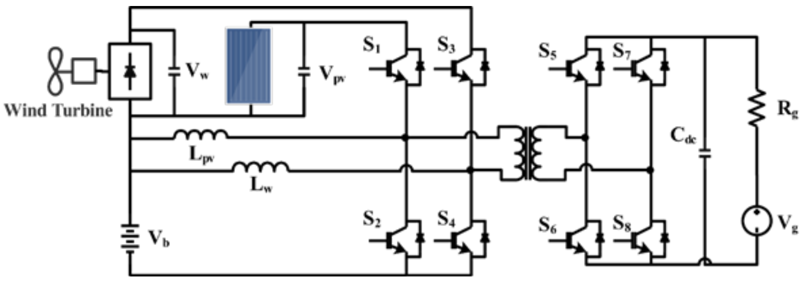


Figure 11. Circuit diagram of the Presented MPC in [132].

A unique filter-based technique for managing and regulating the state of charge (SoC) of batteries and supercapacitors in a hybrid energy storage system (HESS) in a microgrid is shown in reference [133]. Using the energy capabilities of each storage component and its corresponding SoC, a gain technique is devised to control the battery cycles of charging and discharging. The control technique makes use of the HESS's normalized battery capacity and has a straightforward structure.

For battery ESS integrated PV systems, a MPC introduced in [134], with a differential power process feature. Only the differential power, or partial power, needs to be handled by the dc-dc converter because the MPC can control the majority of the active power generated by the ac grid, battery, and PV. For the MPC, the voltage fluctuation of the battery and PV addressed using a modified space vector PWM. Applications like micro-grids, hybrid energy systems, battery ESS in PV systems, etc. are good fits for the converter.

A novel multi-source hybrid energy storage converter intended for DC microgrid applications is presented in Reference [135] . This system connects with a hybrid energy storage system (HES) that uses batteries and supercapacitors to manage power variations from photovoltaic sources,

wind, and unexpected load disruptions. This method decreases the size of the storage unit and increases the battery's lifespan.
A hybrid model predictive control (MPC) with bidirectional buck-boost port and high voltage gain is presented in reference [136] for the integration of batteries with a single-phase AC microgrid. Three ports are available on the converter: a DC output port for general usage, a bidirectional DC port for the battery, and a bidirectional AC port for the grid. One benefit of the MPC is that it reduces power losses by allowing bidirectional power flow in a single power conversion step between a low voltage battery and the utility grid.
A high gain multiport presented in [137] based on low voltage batteries and supercapacitors. The topology has these advantages, bidirectional power flow between any two ports, wide zero voltage switching range, and galvanic separation from the dc bus for the battery using a current-fed dual active bridge structure. Additionally, because the suggested topology only uses one transformer for a three-port interface, there are fewer control variables involved, which lowers the complexity of the control. A 1-kW laboratory prototype was constructed to confirm the efficacy of the suggested converter and control strategy.
A multi- port for ESS in DC microgrids was presented by Binxin Zhu et al. in [138]. With its low voltage stress and high voltage gain, the design has the ability to connect simultaneously several energy storage batteries and the DC bus. A detailed analysis of the converter's operation and performance characteristics was conducted, and an experimental prototype with two input ports and 200 W of power was constructed.
A three port converter presented in [104]. Consists of one bidirectional battery port and two unidirectional power source ports. The converter that is being presented uses four power switches in addition to four diodes. The structure is intended for applications involving hybrid generation since it has unidirectional and bidirectional inputs. The load can be powered by the input power sources. The converter had an efficiency of roughly 86%.
Described in [103] the presentation of two switched-diode-capacitor voltage accumulator structures, two distinct double-input step-up converters were introduced. The two converters were operated at a switching frequency of 30 kHz. High conversion efficiency and low component stresses were attained by the converters.
[54] created a separate MPC to control the power of several RES at once. Every port that a source is attached to has only one switch used by the converter. The converter was deployed for hybrid generation systems consists of two PV panels and one wind turbine, MPPT controller used to manage the system. Table 3 presents a comparison of different MPCs utilized in applications related to Hybrid Systems.

Table 3. Comparison of various MPCs used in Hybrid Applications.

Ref.	D	S	L	C	Total	Control	Topology	Eff.
[132]	0	8	2	3	13	PI/MPPT	Isolated	NR
[136]	0	9	4	4	17	PI	Non-Isolated	97.3%
[135]	1	4	3	4	12	PI/MPPT	Non-Isolated	NR
[138]	0	4	2	2	8	Interleaved control	Non-Isolated	90%
[137]	0	10	4	4	18	PI	Isolated	96%
[104]	4	4	2	1	11	MPPT/ NR	Non-Isolated	86%
[54]	7	3	4	5	19	MPPT/ NR	Isolated	NR

Performance comparison of multiport converter used with hybrid systems application is summarized as shown in Table 3. In this comparison, the following elements are considered: components count, control method, topology, and conversion efficiency.

From the comparison, [136] presented for a multiport converter that uses 17 components in the circuit, which is classified as non-isolated, the efficiency reached 97.3%. [137] presented a multiport converter classified as an isolated with an efficiency of 96%, using 18 components in the circuit. Both converters use a PI-controller to control the operation of the circuits.

3.4. Application-focused classification using MPC selection criteria

Several topologies are seen to have evolved throughout time for various uses. Each topology has unique characteristics. As a result, choosing a specific MPC converter becomes difficult. For this reason, this section concentrates on the process of choosing an MPC converter for the intended application.

The voltage and power ratings are estimated, and the sources are chosen carefully in the MPC selection process. A modular topology is recommended when projecting future source additions or integrations. Every application has certain requirements that must be met. To this end, the application diagram presented in Fig. 12 provides a thorough analysis of the selection criteria.

For instance, if a certain task is chosen for a combination of sources, for example PV panels, battery, and fuel cell, for the EVS application, the modular structure is first chosen because the source integration is already there. The charging and discharging processes require two-way power flow. Any MPC can be chosen in this manner with ease using the application diagram and design guidelines.

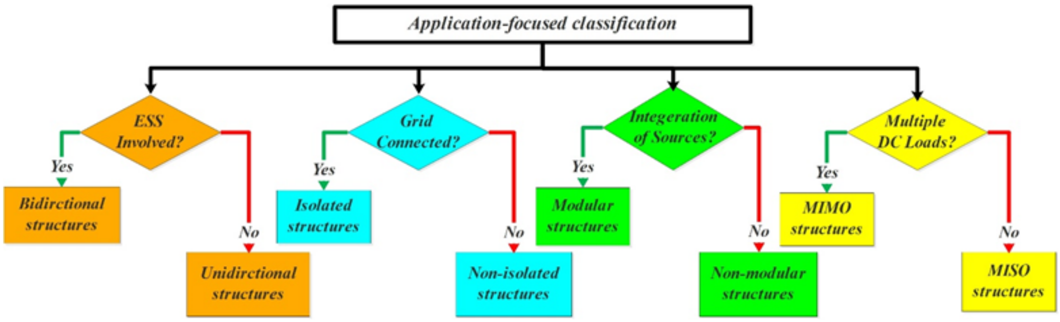


Figure 12. Application-focused classification of MPCs.

4. CONTROL METHODOLOGY FOR MPCS

To achieve the maximum efficiency of multiport converters, control techniques have vital role as it can optimize the overall performance and operations of these converters. Control parameters for MPCs are the input voltage, duty cycle ratio, reference voltage, and output voltage. However, these parameters cannot be optimized simultaneously, trade-offs are essential for a few parameters, that are chosen as per the application requirements. The power source or applications used can influence the choice of the control system. If the source is PV/Wind, the MPC can achieve a maximum power point (MPP) to track and control the charging current of the battery according to the requirements of its charge controller. This helps to increase the energy production of the solar PV modules and wind turbines and increase the system's overall efficiency [139]–[143].

Control techniques for multiport converters have been explored in several papers. One approach is the use of feedback linearization techniques to ensure linearity in dynamic behaviour and decoupling, with a PI controller for stability and robustness to load unpredictability [144]. Another strategy involves the implementation of current peak control with a 180° phase difference between the currents of the inductors, allowing for tracking of current references in a closed loop. A balancing control method has been proposed for load imbalance in one arm of a multiport converter, achieving balanced three-phase current and limited to voltage error of DC link.

Control techniques for multiport converters are essential for optimizing performance across various applications, these techniques include Nonlinear control techniques, particularly feedback linearization. This approach ensures decoupling and stability, effectively managing load uncertainties while maintaining performance through linear approximations [145], Space vector modulation (SVM) techniques enhance power stabilization, peak shaving, and voltage sag compensation, thereby reducing grid stress during peak charging times [146], and Bi-directional multiport converters facilitate seamless power transmission within specified voltage ranges, making them suitable for renewable energy applications [147]. These control techniques significantly enhance the functionality and efficiency of multiport converters, challenges remain in scalability and real-time adaptability. Further research is needed to address these limitations and improve the robustness of control strategies.

5. LIMITATIONS OF MPCS

Although multiport converters have certain limits, they can all be used effectively in certain situations. Because of its efficiency qualities and price, non-isolated multiport converters might be considered the best choice for low power applications. While isolated MPCs more appropriate in applications where high-power is a requirement, this type of multiport converter is particularly useful for low-power applications. Consequently, choosing a specific topology for a particular application, it is crucial to take trade-off variables into consideration. Among these restrictions are:

• The need for a transformer in conventional MPCs, which adds complexity to the circuit [148].
• Low effective duty cycle operation is also a concern in conventional multi-port converters [149].
• Lack of common ground can be an issue in multi-port converters [150].

These limitations highlight the need for further research and development to overcome These difficulties and improve the performance and efficiency of multi-port converters.

6. CONCLUSIONS

This paper presents a state-of-the-art review on MPCs, the paper Introduced:

• A comprehensive review for numerous numbers of publications regarding MPCs.
• A simple classification for different types of MPCs. Researchers, designers, and engineers could learn more about the technical features, principles of operation and selection standards for MPCs with the help of this classification.
• Classification based on applications such as EV, PV and Hybrid systems.
• Finally Discussed the limitations and boundaries of MPCs which will direct the research efforts to solve these limitations.

Multiport converters play a critical role in the fields of RES, EVs, ESS, and micro-grids, all of which are covered in this paper and the future work would be:

• Introduce a Modular MPC design for renewable energy applications.
• Compare the recent control techniques used in MPCs for renewable energy applications.

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