VOL. 23, NO. 2, 2024, 163-179
elektrika.utm.my
ISSN 0128-4428

ELEKTRIKA
Journal of Electrical Engineering

State of-The-Art Multi-Input DC-DC Converter Topologies and their Control Techniques: A Review

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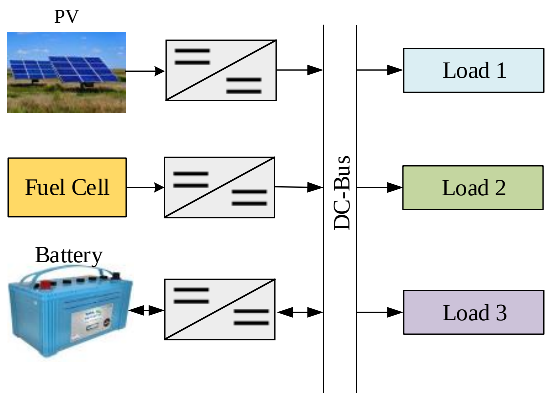
Abstract: Environmental awareness and technological advancement have made renewable energy sources such as fuel cell, solar photovoltaic (PV), wind energy an emerging research area. Power electronics converters are used as interface between the renewable energy sources and the load unit, aimed at matching these sources with the load demand and improving the steady-state and dynamic characteristics. Traditional method of using multiple single-input single-output dc-dc converter to integrate several renewable energy sources, comes with challenges in controller design, poor efficiency, low power density and increase in cost. To address these limitations, the use of an integrated multi-port converter is a preferable solution. Recently, several multi-port dc-dc converter topologies have been reported each having its peculiarity in terms of number of component count, relationships between input and output, voltage conversion ratio, control algorithm and efficiency. This article reviewed multi-port dc-dc converters presented by different research groups from the point of view of topology, input and output relation and structure. Furthermore, control algorithms proposed to solve various control problems are also reviewed.

Keywords: Control techniques, dc-dc converter, multi-input, multi-output converters

Article History: received 3 January 2024; accepted 19 July 2024; published 29 August 2024

1. INTRODUCTION

The increasing participation of renewable energy (RE) such as photovoltaic (PV), fuel cell (FC), wind turbine (WT), in dc-microgrid has demonstrated to be the best alternative for decarbonization, decentralizing and modernization of conventional (fossil fuel based) power grids [1]–[3]. Although, low output voltage and the intermitted nature of renewable energy source (RES) and large variation in power demand due to variable loads remains a major challenge particularly from control point of view. In such a system, there is a strong need for boosting the output voltage of the RES to match the load voltage. This demands the use of high voltage gain converters, which have become more prevalent in recent years and as a result, the technology for manufacturing such converters has developed as well. Although, conventional converters are limited to connecting a single source of distributed generation, however, to enhance a better system stability and reliability it has therefore, become essential to simultaneously use these energy sources to generate the desired regulated output voltage for the load. This has led to the evolution of multi-port converter (MPC) topologies. There are several multi-input converters topologies with the common goal of effectively integrating several power sources and loads. However, each topology has its own peculiar benefits and drawbacks. MPC converter can be obtained by using an independent single-input single-output converter for each port [4]–[6], or using a single multi structured converter [7] as illustrated in Figure 1. The former comes with an increase in size, cost and complex power management scheme, while the later has low component count compact size and simple control algorithm [8]. An integrated multi-port converter can be used in place of numerous separate dc-dc converters with dedicated input sources. Utilizing a multi-input converter is superior to utilizing a series of independent converters in terms of efficiency, component count, size, cost, simple structure and performance [8].



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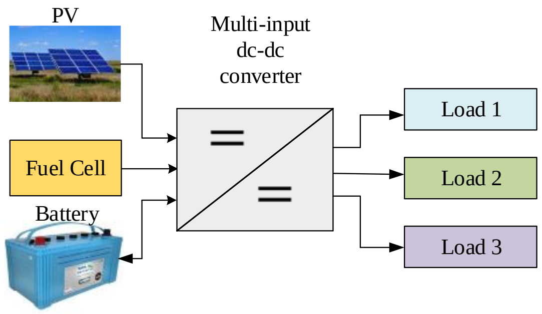

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Figure 1. Multi-input multi-output converter structure (a) independent SISO converter (b) single multi structured converter.

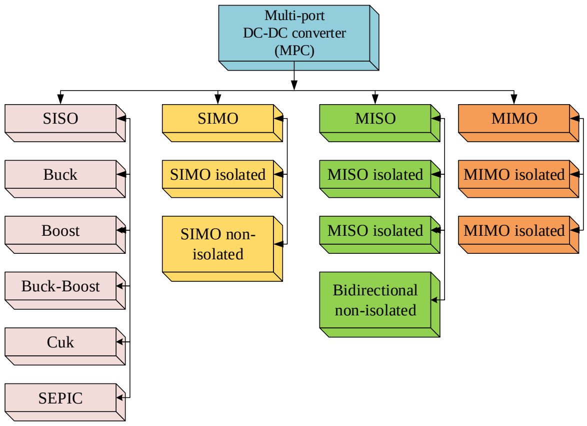

Figure 2. Classification of MPC

The evolution of MPC topologies, has contributed to the integration of electronic power system, since they are capable of simultaneously connecting multiple sources with different terminal voltage characteristics and simultaneously transferring power to the output [9]–[11]. These converters are becoming more popular in sustainable energy applications due to their great potential in providing cost-effective and compact power electronics solution to various application with improve reliability, availability, increase in power density and reduce overall system cost [10], [12]–[14]. The primary feature of these converters is their ability to handle energy from a variety of sources, resulting in power transfer to the output from a variety of sources with varying magnitudes, which is only achievable with a robust control system. The quantity of power supplied to the load can be efficiently managed by altering the duty cycle of the control switches. This control can also be used to maintain a constant output voltage, output current, or power [15]. So, this paper presents a review of various multi-input dc-dc converter with their control techniques. The paper is structured as follows: section 2 describes the classification of multi-port converters with respect to their input, output relationship and structure, section 3 discussed various control techniques for multi-port converters, while section 4 concludes this article.

2. CLASSIFICATION OF MULTI-PORT CONVERTERS

Multi-port converters (MPC) are classified based on the inputs and outputs relationship, which constitutes the following configurations: single-input single-output (SISO) converters, multiple-input single-output (MISO) converters, single-input multiple-output (SIMO) converters and multiple-input multiple-output (MIMO) converters respectively. Furthermore, the classification can be sub-divided into isolated and non-isolated as illustrated in Figure 2.

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An isolated type MPC provide electrical isolated by means of a high frequency transformer (HFT) providing safety and voltage scaling. However, isolated converters increase the cost and size of a converter while also reducing efficiency due to associated losses. On the contrary, non-isolated converters are the most appropriate for application where smaller footprint is a basic requirement due to their compact structure, improve efficiency and light weight. In addition, non-isolated multi-port converters have simple design when compared to their isolated counterparts, however, for high gain application non-isolated MPC require improvement in voltage boosting.

2.1 Single-Input Multiple-Output Converter

Single-input multiple-output (SIMO) converters are designed to produce multiple output voltage of different magnitude from a single-input source. This is aimed at satisfying the different voltage requirement of a particular load. This converter can have isolated [30] structure or non-isolated structure depending on the intended application. A SIMO isolated converter for electric vehicle charging application is reported in [31], [32]. The converter reported in [31] provides high voltage conversion ratio and galvanic isolation between medium voltage to low voltage of electric vehicle (EV) battery using an intermediate transformer as illustrated in Figure 3.

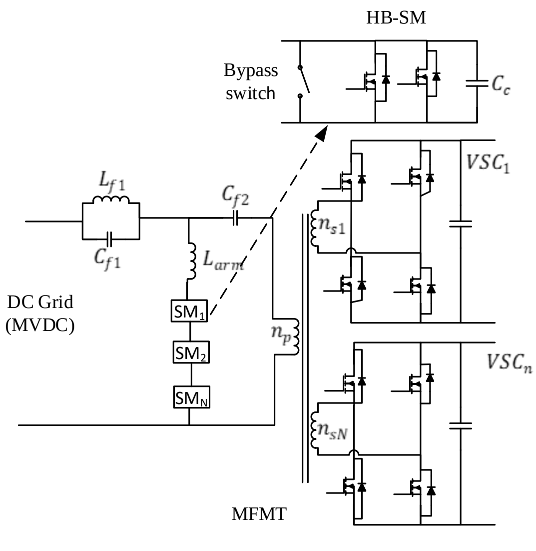
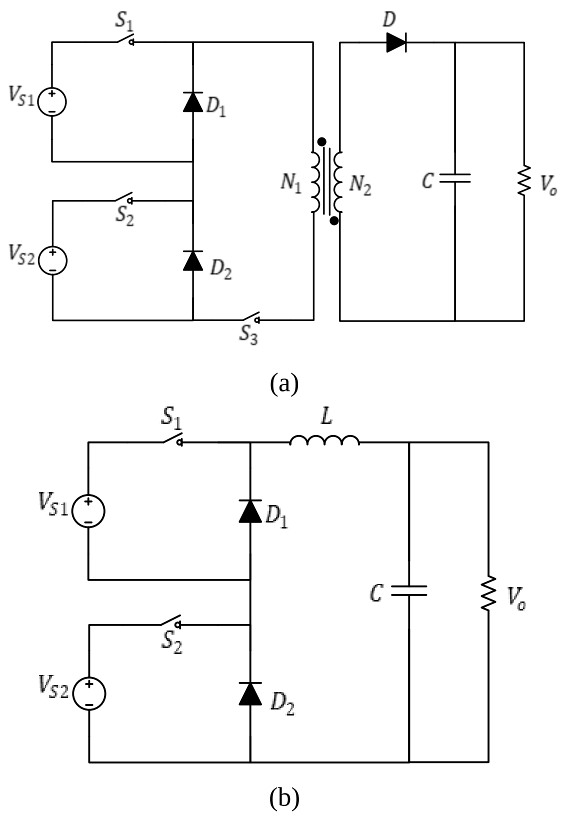


Figure 3. Single-input multi-output converter for EV charging [31]

However, the multi winding isolation transformer reduces the power density and increase the converter weight and volume. In order to achieve better dynamic response, high efficiency and low ripple single-input multi-output converter based on interleave structure is proposed [11]. The combined converters are connected in parallel, distributing their losses across components thereby facilitating thermal management. On the contrary, this topology is affected by cross regulation issues. Furthermore, interleaved structure increases the component count and system cost.

2.2 Multi-Input Single-Output Converter

Multi- input single-output (MISO) dc-dc converters are capable of delivering controlled output voltage from multiple source with different voltage levels and/or power capacity to a common load output for diversified application [33]–[35]. This converter can be classified as (a) isolated [36] and (b) non-isolated [37], [38] as shown in Figure 4. Isolated converters employ a high frequency transformer to provide isolation between the low voltage and high voltage side to avoid risk of electric shock and achieve voltage boosting. However, the downsides of isolated converters are low power density, bulky structure and increase in cost due transformer core. On the other hand, non-isolated converter does not require galvanic isolation and can match the impedance of the source with that of the load [2]. Additionally, non-isolated converters have simple structure, however, they are limited by low voltage gain.



(b)

Figure 4. MISO dc-dc converters (a) Isolated (b) non-isolated

2.2.1 Isolated Multi-Input Single-Output Converter

One of the promising methods of achieving high voltage conversion ratio is by using a galvanic isolation. This concept provide an extra degree of freedom by adjusting the turns ratio of the isolation transformer to satisfy a wide range of load requirement and regulation [39]. Isolated MISO converter are reported in [12], [40], [41]. The converter reported in [12] integrates two-low voltage dc source to control the transfer of energy from input to output using a pulse-width modulation (PWM) technique as shown in Figure 5. Consequently, due to discontinuous conduction mode operation and the secondary side modulation, the primary side switches are operated with soft switching. Furthermore, the dc component of the current through the transformer magnetizing inductance is reduced due to discontinuous conduction mode (DCM) operation mode of the primary inductor. The grid-connected application three-phase multi-input topology converter reported in [40] utilizes a three-phase isolation transformer supplied by N-level neutral point clamped inverter (NPC). Although, the independent power management is performed by N-level inverter, eliminating the possibility of additional dc-dc converter, this topology exhibits a complex magnetic structure and high number of control switches due to multi-level structure.

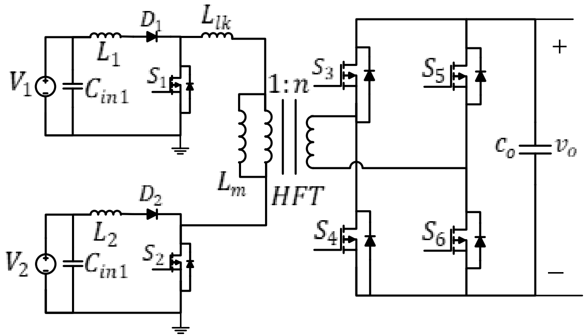


Figure 5. Dual-input single-output converter for renewable energy application [12]

These features reduce the power density, increase the cost and increase complexity of controller design. In addition, the topology support only a unidirectional power flow. A bidirectional isolated MISO dc-dc converter with continuous input current is reported in [41]. The continues input current nature of this converter make a suitable candidate for fuel cell application. perhaps, the presence of HFT complicate the converter design in addition to high number of controlled switches which complicates the controller design. A modified isolated half-bridge converter topology utilizing three operation modes is reported in [42]. The tri-modal configuration consists of a freewheeling branch consisting of diode and a switch as shown in Figure 6. The converter provides dual independent control variables for the three basic operating modes at constant switching frequency cycle. The switching sequence always provide a clamping path for the leakage inductance energy of the isolating transformer. Furthermore, the leakage inductance energy is used to provides soft-switching operation of all the primary switches under a wide range of source and load condition.

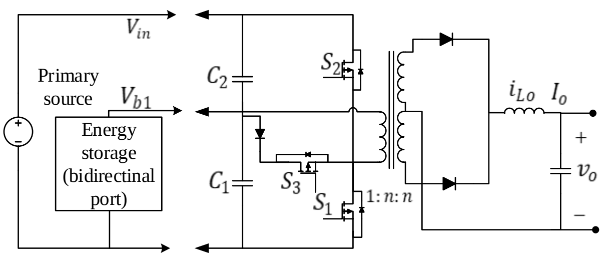


Figure 6. Tri-modal three-port converter [42]

2.2.2 Non-Isolated Multiple-Input Single-Output Converter

For application requiring high power density, non-isolated converters are the ideal candidate this is due to absence of high frequency transformer. The absence of transformer reduces the converter volume, weight and cost. In [43], a dual-input hybrid converter based on switch inductor techniques is presented. However, this converter does not support bidirectional power flow, furthermore the power switches are tuned-on with hard-switching. To increase the efficiency, a converter with soft-switching ability for renewable energy application is reported by [44]. The converter has high efficiency due to low switching losses as a result of zero-voltage switching (ZVS) during turn-off and zero-current switching (ZCS) at turn-on of the power switches. The converter reported in [45] produces high voltage gain using a time sharing concept with parallel-charged and series-charged inductors as shown in Figure 7. However, due to lack of common ground between the input and output makes the controller design challenging.

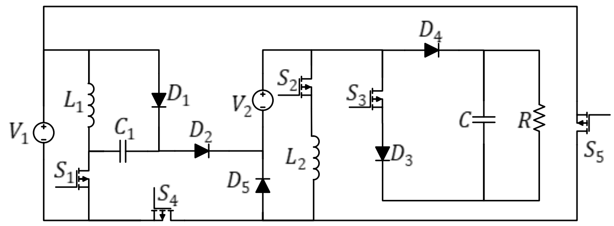


Figure 7. Dual input single output dc-dc converter [45]

Dual-input single-output dc-dc converters are reported in [30]–[32]. The converter reported in [47] consists of several distributed generation made up of fuel cell (FC), battery and photovoltaic (PV) as input sources. The converter supply both active and reactive power to the grid based on time-sharing scheme which produce five different duty cycle. Consequently, different duty cycles are required to be adjusted under different load conditions and this aspect complicates the controller design. An independent voltage and power control MISO converter for RES is reported in [48] and depicted in Figure 8. The converter adopts a switching algorithm that allows independent control of output voltage and power absorbed from each source. Furthermore, independent current sharing among the various sources is achieved. This feature simplifies the controller design. Despite the attractive features, this converter has high magnetic losses due to utilizing extra couple-inductor.

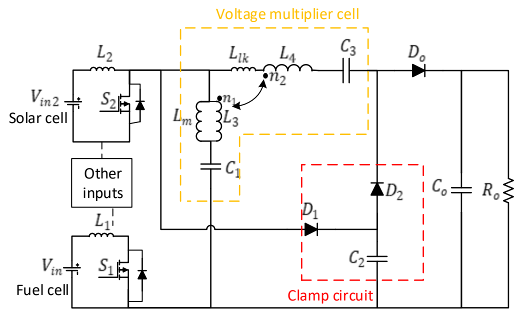


Figure 8. Multiple-input single-output converter reported in [48]

The author in [49] proposes a high voltage gain single input inductor multi-input converter for PV application shown in Figure 9. The proposed multi-input converter (MIC) has high voltage gain and possess low output voltage ripples by deploying a diode-capacitor cell. Unfortunately, in this topology, the voltage gain is increased at the expense of increasing the number of diode-capacitor cells. This, however, reduce the converter power density, cost, size and weight. In addition, the switches are operated under hard switching condition. Furthermore, due to series connection of the sources, the inputs currents are equal from both sides, but the output voltage is different due to different power production. This aspect complicates the voltage regulation.

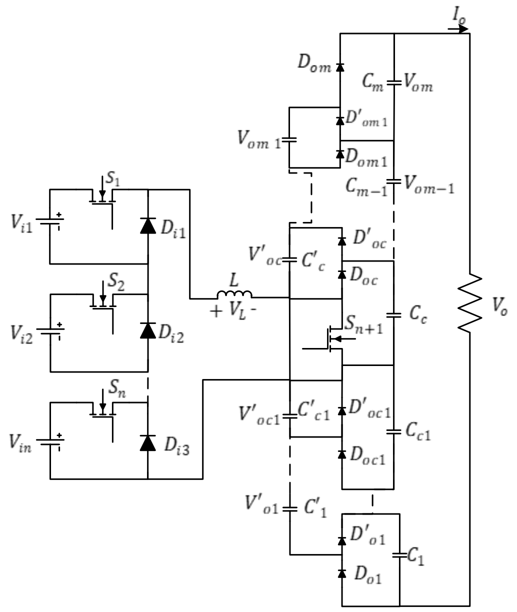


Figure 9. Single-inductor MISO [49]

In [50], [51], non-isolated multi-input single-output converters are proposed, these converters demonstrates high efficiency due to soft-switching operation. However, the high efficiency obtained is achieved by increasing the turns ratio of the coupled inductor which reduces the power density of the converter.

2.2.3 Bidirectional Non-Isolated Multi-Input Single-Output

Bidirectional power converters are widely used as interface in an uninterrupted power supply unit (UPS), hybrid electric vehicle (HEV) smart grids application and

RE application such as FC, PV and wind turbines due to their flexibility. Depending on application, bidirectional converter can also be isolated type or non-isolated type. With a significance difference of high conversion ratio in the case of isolated and high-power density in the case of non-isolated structure. To improve the power density, non-isolated bidirectional multisource converter for EV application have been investigated [52], [53]. Although, the converter in [52] achieves high voltage gain, the individual control of battery charging and discharging process complicate the control algorithm. This converter is shown in Figure 10.

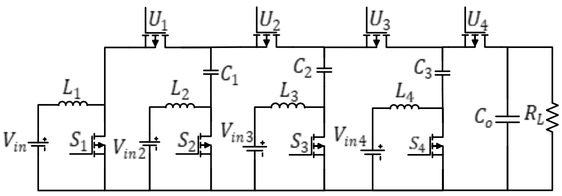


Figure 10. MISO converter proposed in [52]

Figure 11 shows a MISO converter based on single-ended primary inductor converter (SEPIC) proposed in [39]. The proposed SEPIC converter has a bidirectional input-port ability and positive regulated output voltage which is suitable for charging and discharging an energy storage system (ESS) in a hybrid renewable energy system. In addition, the load power can be easily divided between the input sources. However, this converter is not suitable for high gain application.

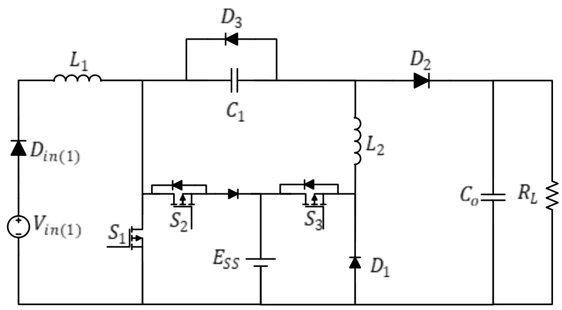


Figure 11. SEPIC-based MISO DC-DC converter [39]

Table 1 provide a comparison of some selected multiple-input single-output converters in terms of number of power switches, diodes, inductor, capacitors, topology and characteristics.

2.3 Multi-Input Multi-Output Converter

The advancement in semiconductor technology has made it possible to develop converter capable of dispatching power from multiple-input sources to multiple-output load. This topology finds application in vast area which include electric power supply units, automotive industry (electric vehicle), data center, microprocessor cores, telecom interface, dc microgrids, hybrid renewable energy system and many more [7]. Multiple output dc-dc converter are studied by several authors and reported in various literature [54]–[56]. The general architecture of MIMO converters is shown in Figure 12. MIMO converters can also be grouped as isolated and non-isolated type as discussed in the following section.

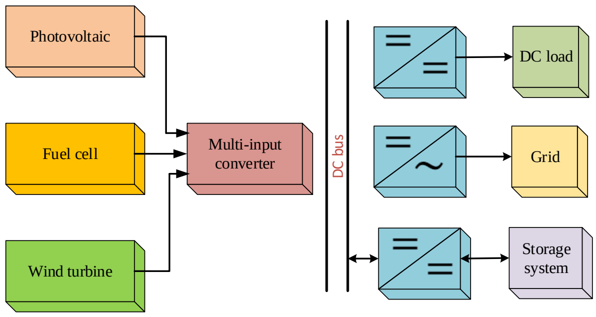
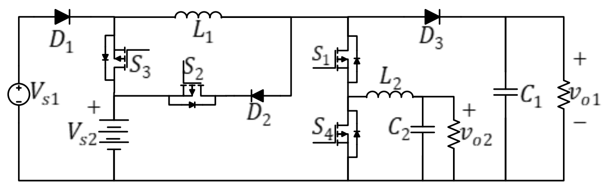


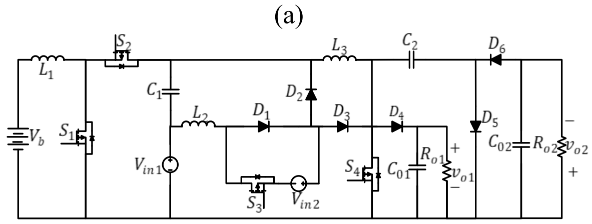
Figure 12. General architecture of MIMO converters

2.3.1 Non-Isolated Multi-Input Multi-Output Converters

High voltage gain non-isolated multiport converter for renewable energy application are proposed [57]. The non-isolated converter proposed in [57] achieved soft switching operation for all the semiconductors by utilizing the leakage inductance of the couple inductor. Furthermore, high voltage gain is obtained with the help of a coupled inductor. However, use of coupled inductor reduces the power density of the converter. A dual-input dual-output converter for electric vehicle application is reported in [58], [59] and shown in Figure 13 (a) and (b) respectively. The dual output is required to supply the electric motor and the auxiliary load while the input is obtained from a battery and a renewable energy source. This converter requires a control scheme that regulates the battery charging and discharging process as well as the output voltage control which complicate the controller design. In addition, the dual input inductor as shown in Figure 13 (b) increase the converter size and cost. Furthermore, under heavy load conditions, the peak inductor current increase, which further escalate the current stress and the conduction loss [60]. Moreover, the magnetic component accounts for sizable proportion of the overall weight and volume imposing a limitation on the power density. A multi-input dc-dc converter for hybrid renewable energy reported in [61]–[63] operates in continuous input current which makes them suitable for RE application. Furthermore, the converters are design to extract maximum power from the RES. However, the converter reported in [62], [63] has high number of active switches which lower their power density.



(a)



(b)

Figure 13. Dual-input dual-output converter for electric vehicle application (a) converter reported in [58], (b) converter reported in [59]

To mitigate this issue and increase the power density of multi-input converters, single-input inductor-based converter remains a good candidate [60]. This is due to their relatively low voltage stress as a result of voltage sharing among system elements. Single input-inductor converters have high power capability, high power density, low cost and simple control strategy compared to multiple input inductor-based converters [45], [64]. A single-input inductor buck converter with ten independent output is reported in [19]. The converter features a digital PWM controller and a comparator-based output switch controller for low feedback to provide an on-chip system power requirement. However, due to common inductor for different power transfer ports, a severe cross-regulation issues is encountered [45], [64]. To mitigate the cross-regulation issues, an improved control scheme is required which increase the cost and controller complexity [66]. In [67] a current source mode single-inductor MIMO converter naturally mitigate cross-regulation by virtue of the constant inductor current. A high power density single inductor multiple-input multiple-output converter based on switching capacitors for imbedded application is reported in [68]. This converter has fast response and low cross-regulation; however, it is affected by cross-coupling issue.

Table 1. Comparison of some selected multiple-input single-output converters

Ref	S	D	L	C	TC	Topology	Isolation	Merit	Drawback	Application
[12]	6	2	3	2	14	Boost	Yes	Achieve soft switching	Low power density due to HFT	Renewable energy
[41]	6	-	4	4	15	Bidirectional boost	Yes	Achieve soft witching	Require auxiliary commutation circuit	Medium power application involving fuel cell.
[43]	3	5	2	1	11	Boost	No	Compact structure	High switching loss due to hard-turn-on	Low power hybrid energy integration
[44]	4	6	3	5	18	Buck-boost	No	Wider range of soft switching	Requires edge resonant module to achieve soft switching.	DC micro grid
[45]	5	4	2	2	13	Boost, buck-boost	No	Improve gain without additional voltage multiplier circuit	Not suitable for high voltage gain application	Fuel cell electric vehicle
[47]	4	2	2	-	8	Boost	No	Simultaneous MPPT of the DG sources	Complex control scheme	Hybrid distributed generation (DG) system
[49]	*n+1	n+1	1	1		Boost	No	Possible transfer of power from each input to the output	Increasing the gain requires an increase in the number of voltage multiplier cell (VMC) this increase the volume, cost of the converter	Low power PV application
[50]	2	2	3	3	10	Bidirectional buck-boost	No	High voltage gain and low component count	Use of three winding coupled inductor reduce the power density	Interface for hybrid system consisting of PV, battery and load
S = switch, D = diodes, L = inductor, C = capacitor, TC = total components, *n= is the number of inputs										

MIMO topologies requires a comprehensive power management algorithm to ensure optimal operation of all inputs sources, improved efficiency and reliability [47].

2.3.2 Isolated Multi-Input Multi-Output Converters

Isolated multi-input are proposed and reported in [10], [12], [21], [69]. These converters provide the required electrical isolation. Moreover, high voltage gain can be achieved by adjusting the transformer turns ratio. However, MIC based on HFT are affected by magnetic inductance saturation due to different magnitude of the input voltage on the same winding of the HFT. Although, this can be mitigated by connecting a capacitor in series with the HFT which receives the voltage difference between the two input and thereby blocking the flow of dc current as reported [12] Figure 14.

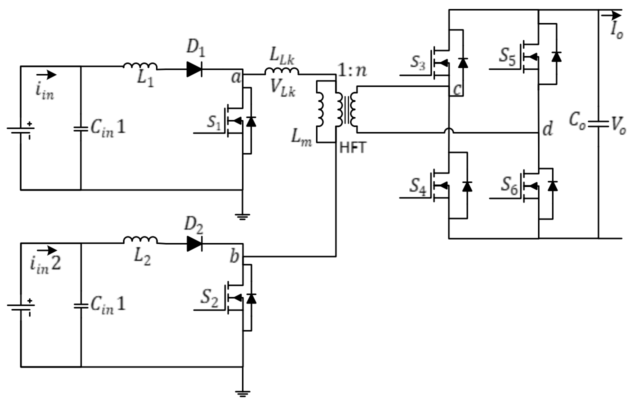


Figure 14. Dual input single output converter [12]

Additionally, power balancing (or voltage balancing) of multiple input can be achieved by regulating the phase shift between adjacent half bridge network on the grid side as reported in [70]. However, this topology has low power density due the high component count. Similarly, saturation of transformer magnetic inductance can be restrained by actively controlling the winding of the transformer and limiting the dc component of the current. This requires sensors and complicated control scheme. Pasan *et al;* [12] adopted a DCM of the primary inductor in all operation to minimize the dc component of the current through the transformer magnetizing inductor.

Another issue of concern in HFT is the device voltage overshoot which is caused by current mismatch due to connection between the input inductor and the leakage inductance of the HFT, although this can be mitigated by using a snubber circuit [71]. On the contrary, the additional circuit reduce the power density and increase weight and footprint of the converter. The converter reported in [10] achieve ZCS and ZVS for the primary and secondary switches respectively, the resonance effect between the transformer leakage inductance and the parasitic capacitance of the power switches impose a voltage stress across the switches. An isolated buck-boost converter with reduced magnetic structure is reported in [21]. The converter uses a single primary winding couple inductor for various inputs which results into reduced size and volume as compared to conventional converter. However, this converter requires a voltage clamp circuit to mitigate the voltage stress. Thus, this increases the circuit component count. Table 2 presents the features, merits and drawback of different multi-port converters, while Table 3 presents a summary of classical features of isolated and non-isolated converters structure.

Table 2. Features, merits and drawback of different MPC structure.

Topology	**Features**	**Merit**	**Demerits**
SIMO	Interfacing multiple voltage level from a single source	• Ability to supply multiple load	• Limited to single input source. • Low reliability due to single power input. • Cross-regulation issues.
MISO	Interfacing multiple voltage source to supply single load.	• Suitable for application with diverse source. • Simple control due to common ground. • Ability to integrate multiple input. • High input flexibility	• Limited to single output. • Increase in input source increase the number of active switches. • Sources with different V-I characteristics are difficult to interface.
MIMO	Operation is based on time-sharing scheme.	• Ability to integrate various sources and load. • Reduced count of components [54]. • Enhance reliability. • Better flexibility.	• Restricted duty cycle due to time sharing scheme. • Limited utilization of energy sources • Suffer from cross-regulation issues. • Require complex control scheme to mitigate cross-regulation [53].

Table 3. A summary of basic features of isolated and non-isolated multi-input converter structures

Topology	Type	Benefits	Drawbacks	Application	Ref
Isolated	Three-port converter based on multi winding transformer	• Attain high voltage conversion ratio. • Leakage inductance can be recycled. • Possibility of soft switching operation. • Provide galvanic isolation	• High number of passive and active components, • Low power density. • Reduced efficiency. • Large volume and weight • Voltage overshoot during turn-off due to current mismatch between the leakage inductance and boost inductor. • Require a snubber circuit to alleviate overshoot.	Renewable energy application	[12]
Isolated bidirectional converter	Dual input bidirectional current-fed DC-DC converter	• Suitable for PV and FC sources. • Low input current ripple • High voltage gain • Bidirectional power flow ability.	• Non-isolated structure • Limited output voltage gain • Not suitable for RE sources due to intermitted nature of the RES • Soft-switching ability.	Battery/ultracapacitor based PV application	[10], [72]
Isolated Multi-port converter	Multiport modular DC-DC converter	• Power balancing ability with low components count. • Provide isolation. • Adjustable voltage gain. • Independent MPPT control. • Soft-switching ability	• Voltage overshoot at turn-off instant of power switches due to current mismatch between the input inductor and the transformer leakage inductance. • Require a snubber circuit to mitigate the voltage overshoot.	Medium voltage DC interface for distributed PV application.	[70]
Multi-input high gain non-isolated DC-DC converter.	Multiport multi-operating DC-DC converter.	• Low component count. • High power density • Support bidirectional power operation. • Allow easy integration of additional input. • Reduced voltage stress across power switches.	• Difficulty in component design for bidirectional operation when the voltage gain increases.	Suitable for PV and FC applications due to continuous input current.	[13], [60]

3. CONTROL METHODS

DC to dc power converter is gaining more and more attention in application such as industry, aerospace, microgrid, unmanned aerial vehicle (UAV), academia where excellent dynamic performance is envisaged. Some of the key performance index in converter design are efficiency, power density, transient response [73]. These converters are designed to achieve optimal dynamic performance. The control algorithm has a great influence on the dynamic performance of the converter system [74][75]. However, selection of suitable controller depends on the topology and real application control problem such as efficiency, response time, robustness [75][76]. The controller design for multiple-port converter unlike SISO system is not straightforward. MIMO-based controller design involves solution of sets of non-linear equation, which is a complex task. Basically, control methods of dc-dc converter can be based on parameter of interest namely voltage mode control (VMC) and current mode control (CMC) [77]. Furthermore, the control methods can be categorized as linear control and non-linear control methods as described in Figure 15.

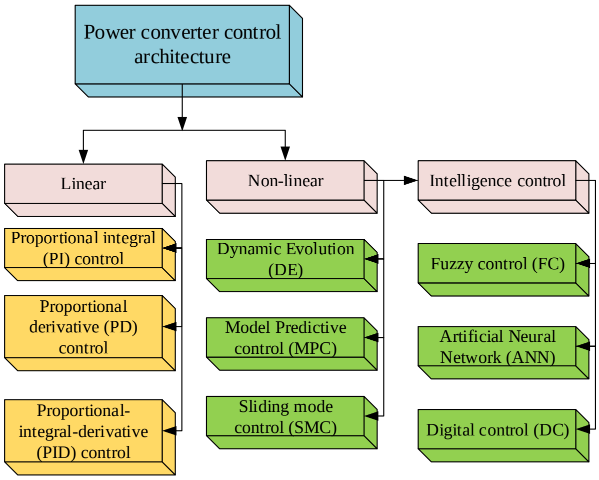


Figure 15. Power converter control architecture

3.1 Linear Control

A linear controls approach is based on analogue models where the power converters are designed based on linear models. This control method is capable of achieving stabilize regulation of output voltage however, achieving optimal dynamic performance with this control method remains a challenge. This is because, the design of linear controllers purely based on frequency domain analysis where optimal response for time domain is not considered [74]. Although these controllers are easy to design, it is difficult to design a control algorithm with high performance with linear controllers.

3.1.1 PI and PD control

A proportional plus integral (PI) controller is suitable for eliminating a steady-state error [78]. The author in [79] proposed a PI based active power flow controller to reduce conduction loss for multi active bridge converters. The proposed control scheme is based on perturb and observe (P & O) tracking of minimum current point of the multi active bridge converter current characteristics. Although the proposed controller does not require the complex modelling associated with non-linear converters, but at light loads the optimal duty cycle increase with boundaries of perturb components and this ramp up the rms current minimization which cause succession steady-state oscillation. Design of PI or proportional derivative (PD) controller for a multivariable process is presented in [80], where an iterative linear matrix approach is adopted for turning the MIMO. The solution of Lyapunov equation with bounded real lemma with no initial points requirement are used to optimize the gain of the PI/PD. Although, this is applicable to first-order controller design, however, existence of controller is not guaranteed. In [81] the authors designed a PI controller for a dual input bidirectional converter to provide output voltage regulation in a dc microgrid. The controller demonstrates a good performance for both charging and discharging of the hybrid energy storage system.

3.1.2 PID Control

Proportional integral derivative (PID) control is a widely used control method due to its simple functionality, wide range of operating condition and robust response. PID controls are used in dc-dc converter to control the converter gain by changing the input switching duty cycle. This is achieved through comparing the input signal with the output signal with the help of a feedback. Furthermore, PID control can be hybridized with other control techniques to improve control method. In [82] a double-loop voltage mode controller for output voltage regulation is reported. The proposed controller based, exhibits good tracking and robust performance. The general structure of a PID controller is shown in Figure 16.

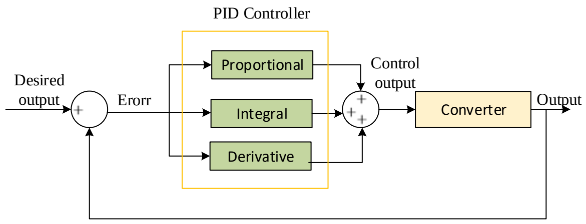


Figure 16. General structure of a PID controller

3.2 Non-Linear Control

Several converter topologies exhibit a non-linear characteristic in their dynamic equations, which necessitates the need to linearize the system around point of equilibrium, for the design of control strategy. Consequently, this approach requires certain estimation which does not represent the exact system model due to neglecting the disturbance and perturbation in linear model. Therefore, to achieve a reliable result and effectively control the system taking into consideration the presence of disturbance and perturbation, non-linear control strategies provide the best solution.

3.2.1 Dynamic Evolution

Dynamic evolution (DE) is a non-linear control method that reduces the dynamic state error through forcing it to follow the path of evolution irrespective of the existing disturbance. In this control method, the dynamic characteristics of system that operates on the target equation by time is ensured [76]. Furthermore, the precise knowledge of the model parameters is not required in this method. The author's in [83] examined the performance of power factor correction boost converter using a DE path theory. The controller performance under heavy and light load conditions were examined. The control algorithm verifies the robustness of the controller.

3.2.2 Model Predictive Control

A model predictive control (MPC) method is based on feedback loop that makes the system variable follow the reference value by using a predefined cost function. This controller has the ability to handle MIMO system making it a multi variable controller. Some of the attractive features of this controller are low economic load dispatch, reduced operating cost and cost function as well as optimized management of power flow. A combination of MPC maximum power point tracking (MPPT) algorithm are adopted to improve the control performance of a boost converter as presented in [84]. Sliding mode control (SMC) when compared to conventional controller (PI, PD, PID) is more robust and possess better ability to remove the steady-state error [85]. However, SMC technique is affected by sampling rate and difficulty in finding suitable sliding surface. Furthermore, it is affected by chattering phenomenon. Figure 17 illustrates the implementation of MPC for a dc-dc converter.

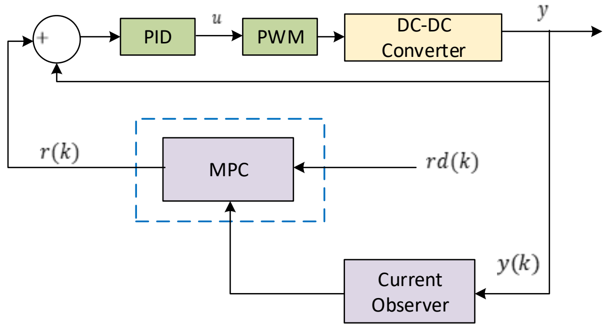


Figure 17. MPC for a DC-DC converter.

3.2.3 Sliding mode control (SMC)

Sliding mode control (SMC) is a non-linear control method used to control a variable structured system by ensuring that the output value is close/equal to the values assigned on the sliding surface. This controller has fast dynamic performance, high stability, easy to implement and strong feature against uncertainties [86][87]. SMC control method when compared to other non-linear control method such as fuzzy control, has low computational time. This control method consists of reaching mode and sliding mode. These attractive features have led to the development of hybrid control scheme based on switching methods. In [88] a double integral sliding mode control for single-input-multiple-output buck converter was proposed. The control scheme demonstrates a better dynamic performance in comparison with linear control. The load and components are protected against excessive overshoot, undershoot and long settling time.

In multi output converter topology independent control of the individual output voltages and change in load currents of this outputs results into cross-coupling and cross-regulation issues making it difficult to independently control the individual output. Furthermore, this issues negatively affect the steady-state and transient performance of the converter. To improve the performance of multi-output converter (MOC) an adaptive control strategy is required to improve stability and efficiency. The author in [89] proposed an adaptive estimator based sliding mode control to address the cross-coupling and cross-regulation issues. The design of the adaptive law for estimating the system disturbance is aided by the adaptive estimator and the input of the SMC is designed to generates the switching signals based on the estimated parameters. In [90] MIMO based SMC for single-phase quasi-Z-source inverter is reported. The proposed control system simultaneously controls both the ac and dc sides of the system. The structure of SMC is depicted in Figure 18.

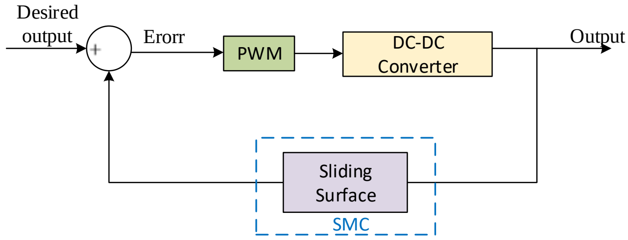


Figure 18. Structure of SMC

3.2.4 Fuzzy Logic Control

Fuzzy logic control (FLC) is a non-linear intelligent control technique that mimic human thought process. The control method requires a set of pre-defined rules known as membership functions. FLC does not require an exact mathematical model of the system making is much simpler [91]. However, the controller design is based on system performance awareness knowledge and skills of the designer. The system response is based on input in which conclusions are drawn on the basis of set of assign rules. FLC are capable of handling non-linearities. Figure 19 illustrates the block diagram of fuzzy control algorithm.

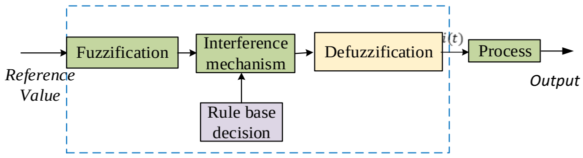


Figure 19. Block diagram of fuzzy control architecture

3.2.5 Artificial Neural Network

Artificial neural network (ANN) is a controller based on human thinking consisting of several artificial neurons that mimic a biological human brain. A sets of suitable scaling factors used as inputs to ANN generates the reference tracking error signals used for generating the switching signals to control a power converter. ANN can be used in either online or offline mode and have high fault tolerance level due to its ability to estimate the function mapping [85].

3.3 Digital Control

A dual-loop consisting of output load voltage regulation and current control of the low voltage source decoupled digital control strategy for two-input integrated SEPIC-buck converter is reported in [92]. The relative gain array theory (RGA) of MIMO based on the discrete-time model of the proposed converter is applied to establish the possible combination of input and output parameters for realizing the optimal load allocation to input sources. A summary of feature benefits and drawbacks of some selected control methods is presented in Table 5.

Table 4. Summary of control architecture for MIC

Control scheme	Features	Merit	Demerits	Ref
PID	Suitable for low complexity linear control	• Simple structure. • Nominal efficiency is many applications. • Low control complexity. • Can easily be hybridize with other control methods	• Not suitable in application requiring high performance. • Require advance turning method for high performance application. • High overshoot, steady-state error and settling time. • Difficult for MIMO system.	[93][94][95] [96]
SMC	Is a non-linear control with high dynamic performance	• Low computation time • High dynamic performance • Fast and finite time response • Applicable to linear and non-linear systems. • Robust against disturbance and perturbation and substantial model uncertainties. • High stability. • Easy to implement.	• Complicated due to requirement of accurate parameters and state information. • Affected by chattering phenomenon. • Output voltage is affected by steady-state error due to variable switching frequency. • Require multiple control methods to overcome chattering effect.	[88][76][97]
DE	Reduce dynamic state error	• Precise knowledge of the model parameter is not required. • Capable of compensating input and output variation. • Ability to respond to fast changing in load.	• Expensive for practical application.	[83]
MPC	Non-linear control with simple online iteration	• Fast dynamic response. • Reference tracking ability • Simple implementation • Can be applied to linear and non-linear. • Minimized operating cost, cost function and economic load dispatch. • Effective for MIMO system	• Require an accurate system discrete-time model. • Need to design the prediction & optimization block. • High computational time. • Can be affected by circuit parameters.	[90]
FLC	Robust and non-linear control with wide range of stability.	• Robust response. • Fast dynamic response. • Simple implementation • Require no prior knowledge of the system parameters. • Less measurement is required in designing the controller. • Suitable for MIMO systems	• High settling time. • Require membership function to operate. • Complex computation. • Less sensitivity to parameters variation. • Strong assumption and experience are required in fuzzification process.	[98][99][100] [101]
ANN		• Ability to handle complex system. • Suitable for non-linear control. • Does not require detailed information of the system.	• Require knowledge of the control law. • Doe does not require converter model for its operation.	[85]

4. CONCLUSION

In this article, a review of multi-structured dc-dc converter is presented. The multi-port converter reviewed in this article, are classified based on the relationships between their input and output. The input output relationships are considered based on number of input and output and structure as isolated or non-isolated as well as power flow direction. The different classifications are discussed with their associated benefits, drawbacks and respective area of applications. In addition, comparison between some selected multi-structured converter in terms of number of component count, topology and application is presented. Furthermore, some control methods for multi-port converter are discussed. Finally, a summary of the control methods highlighting their feature, merits and demerits are presented.

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