IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 2 May 2024, accepted 7 June 2024, date of publication 12 June 2024, date of current version 2 July 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3413354

TOPICAL REVIEW

Multi-Port Non-Isolated DC–DC Converters and Their Control Techniques for the Applications of Renewable Energy

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This work was supported by the Deanship of Research and Graduate Studies at King Khalid University through the Large Group Research Project under Grant RGP 2/57/45.

ABSTRACT In recent times, the increasing demand for energy consumption on a global scale and the prevalent use of power electronics DC-DC converters in various applications, such as hybrid energy systems, hybrid vehicles, aerospace, satellites, and portable electronic devices. To increase the converters' dependability, effectiveness, adaptability, and cost-effectiveness, they have undergone substantial research and development. Diverse input levels can be merged for diverse output levels using new converter topologies, which increase their possibilities from single input-single output setups to multi-input-multiple configurations. The goal of ongoing research is to lower costs and component counts while raising efficiency and dependability. This review paper focuses on the analysis of non-isolated converters, especially for SI-MIMO topologies produced from different converter types. The research work, also includes control techniques and methods like proportional integral derivative, sliding mode control, model predictive control, state-space modelling, fuzzy logic control, and maximum power point tracking, which are all integrated with non-isolated DC-DC converters while considering things like settling concerns, response time, and complexity.

INDEX TERMS DC-DC converter, multiport converter, voltage gain boost, reduction of switch voltage stress, bidirectional converter, unidirectional converter, ZVS, ZCS, soft-switching, control systems.

ABBREVIATION

AC	Alternate Current.
ACO	Ant Colony Optimization.
ALC	Actively Switched Inductor-Capacitor.
ANN	Artificial Neural Network.
ASPWM	Augmented Sinusoidal Pulse Width Modulation.
CCM	Continuous Conduction Mode.
CCS-MPC	Continuous Control Set Model Predictive Control.
CSM	Current-Source-Mode.
D	Derivative.
DC	Direct Current.
DCM	Discontinuons Conduction Mode.
DDTM	Double-Duty-Triple-Mode.
DE	Differential Evolution.
DF	Dynamic Freewheeling.
DIDO	Dual Input Dual Output.
DISO	Dual Input Single Output.
DMPPT	Distributed Maximum Power Point Tracking.
EGUs	Energy Generation Units.
EMI	Electromagnetic Interference.

The associate editor coordinating the review of this manuscript and approving it for publication was Zhixiang Zou.

EMS	Energy Management Strategy.
ESUs	Energy Storage Units.
EV	Electric Vehicles.
FC	Fuel Cells.
FCS-MPC	Finite Control-States Set Model Predictive Control.
FLC	Fuzzy Logic Control.
FOVs	Field-Of-Views.
GA	Genetic Algorithm.
HC	Hysteretic control.
HCM	Hybrid Conduction Mode.
HIIA	Hankel Interaction Index Array.
I	Integral.
ICR	Incremental Resistance.
IGBTs	Insulated-Gate Bipolar Transistor.
LED	Light-Emitting Diode.
LMI	Linear Matrix Inequality.
MIMO	Multi Input Multi Output.
MISO	Multi Input Single Output.
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor.
MPC	Model Predictive Control.
MPP	Maximum Power Point.
MPPT	Maximum Power Point Tracking.
MR-MIMO	Multicell Reconfigurable Multi Input Multi Output.
NVS	Normalised Voltage Stress.
OFC	Output Filter Components.
OVACC	Output-Voltage-Aware Charge Control.
P	Proportional.
P&O	Perturb and Observe.
PEM	Proton Exchange Membrane.
PI	Proportional-Integral.
PID	Proportional Integral Derivative.
PM	Participation Matric.
PSCs	Power Semiconductor Components.
PSO	Particle Swarm Optimization.
PSO-PID	Particle Swarm Optimization Proportional Integral Derivative.
PV	Photovoltaic.
PWM	Pulse Width Modulation.
PZT	Piezoelectric Transducer.
RES	Renewable Energy Sources.
RGA	Relative Gain Array.
SC	Soft Computing.
SEPIC	Single-Ended Primary-Inductor Converter.
SIDO	Single Input Dual Output.
SI-DIDO	Single Inductor Dual Input Dual Output.
SI-DISO	Single Inductor Dual Input Single Output.
SI-SIDO	Single Inductor Single Input Dual Output.
SIMO	Single Input Multi Output.
SI-MIMO	Single Inductor Multi Input Multi Output.
SISO	Single-Input Single-Output.
SSOs	Sub Synchronous Oscillations.
SMC	Sliding Mode Control.
SSM	State Space Modeling.
TLC	Three-Level Converter.
TSS-HB	Three-State Switching Hybrid Boost.
UPS	Uninterruptible Power Supply.
V	Voltage.
VMC	Voltage Multiplier Circuit.
VR	Voltage-Ripple.
VSI	Voltage Source Inverter.
VSM	Voltage-Source-Mode.
ZQR	Z- Quasi Resonant.

I. INTRODUCTION

The growing demand for clean energy has prompted the use of renewable energy sources (RES) as a viable method for energy generation [1]. Advancements in renewable energy-based power systems, hybrid vehicles, aerospace systems, smart grids utilizing renewable energy, and portable devices have posed challenges in designing new DC-DC power conversion systems. Multiple ports with changing voltage levels are required in a wide range of industrial applications, including photovoltaics, electric cars, data centres, and personal computers. Multiple independent single-input single-output (SISO) converters are commonly used to ensure voltage regulation and power control across these ports. However, this approach results in a significant number of components, leading to high overall costs and a large system volume. To tackle this issue, two types of integrated multiport DC-DC converters have been introduced in [2], the multiplexed semiconductor devices and integrating N-port converters based on typical buck [3], boost [4], and buck-boost [5], [6] converters were proposed. These integrated converters effectively reduce the quantity of semiconductor devices and inductors, thereby improving both cost efficiency and power density. In the past years, oil-based power plants have been utilized [8]. The massive consumption of oil became scarce and eventually developed generation of hybrid power systems could be operated along with oil. However, the efficiency of power plants was observed due to the contribution of scarcity of natural gas and crude oil. Besides that, the burning of fossil fuels led to serious negative impacts on the environment, highly abundant and this method became costly [7], [8], [9], [10], [11]. RES has emerged as a new generation method, with multiple converter topologies and control strategies, [12], [13], [14], [15], [16], [17] additionally it has less maintenance and moderate efficiency.

Fig. 1 depicts the power converter family, categorizing both isolated and non-isolated converters and demonstrating standard converter topologies. The operation of a closed-loop DC-DC converter system is shown in Fig 2 Power converter operation is demonstrated in conjunction with a control technique aimed at stabilizing both the load and the source simultaneously. Furthermore, this control technique employs a feedback control loop from the load side to compare it with a desired reference value, aiming to achieve the optimal operation of the DC-DC converter.

The upcoming systems will consist of multiple input energy sources integrated through multi-input power

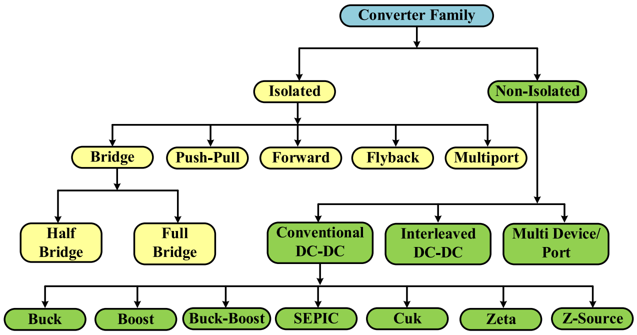


FIGURE 1. Flowchart of converter family [18].

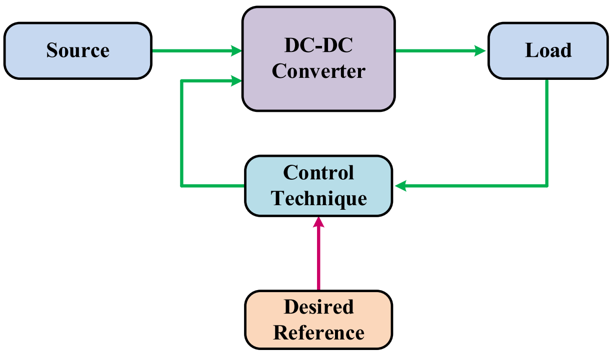


FIGURE 2. Closed loop DC-DC converter system.

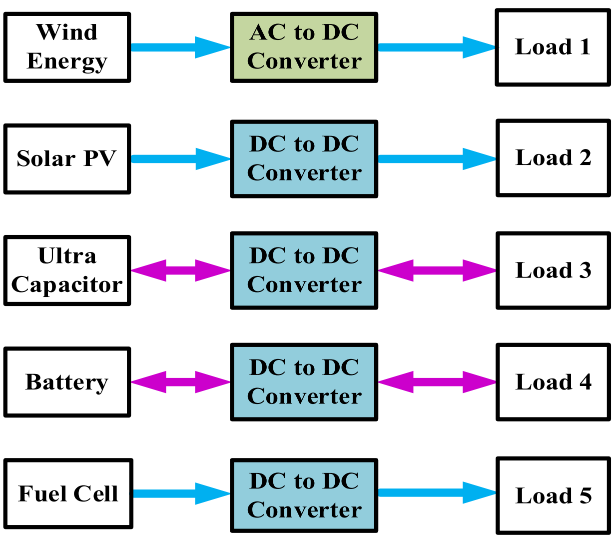


FIGURE 3. Conventional single – Port DC – DC converter structure.

electronics converters are demonstrated in [19], [20], and [21]. These converters can accommodate various input sources and leverage their advantages to provide controlled output for diverse applications.

In the literature, two structures for DC-DC conversion have been documented. The conventional structure illustrated in Fig. 3 involves combining multiple sources at a distinct load and utilizing separate DC-DC conversion stages for

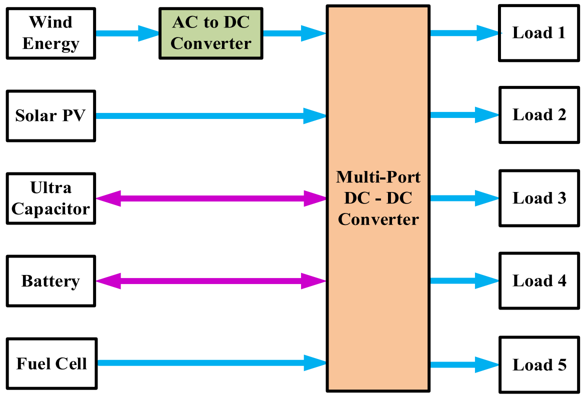


FIGURE 4. Multiport DC – DC converter structure [21].

each source, allowing for independent control of the converters. This particular structure is commonly employed in grid-connected systems and standalone hybrid energy systems [19]. However, the multiple stages of power conversion and the need for communication devices in this system result in higher converter costs. Moreover, the independent control of multiple converters adds complexity to the system. To overcome these drawbacks, a multiport structure is adopted, as illustrated in Fig. 4. The entire structure is treated as a single power converter in this system, combining several sources, and the power regulation is handled by controllers. These multiport power electronics converters were created for a variety of purposes, including hybrid energy systems, hybrid cars, satellite/aerospace applications, and uninterrupted power supply. They offer advantages such as a simple structure, conversion stages that have a minimal number, and fewer devices. The low terminal voltage of supercapacitors and their wide range of voltage variations during charging and discharging operations present a significant difficulty. Therefore, a bidirectional DC-DC converter with a high voltage conversion ratio is needed to connect the lower supercapacitor voltage to the greater DC-link voltage [22]. Such applications are fundamentally dependent on the steep voltage conversion ratio provided by continuous gain-based bidirectional DC-DC converters.

This article examines recent developments in trends within the field of MIMO DC-DC converter topologies applied to renewable energy system applications. The study explores the operation of power converters, incorporating control techniques to concurrently stabilize both the load and source. Additionally, it delves into the advantages, disadvantages, and applications of MIMO DC-DC converters.

This comprehensive investigation undertakes the following scholarly endeavours:

- A meticulous study of parameters, comparing non-isolated DC-DC converter topologies with exacting precision.
- An exhaustive comparative analysis delving into the intricacies of design considerations relevant to a

spectrum of multiport converters tailored for renewable energy applications.
- A comprehensive assessment discerning the strengths and limitations of various multiport converter configurations, thereby offering nuanced insights.
- A rigorous comparative examination elucidating the efficacy of diverse control techniques deployed within multiport converter systems, contributing to a deeper understanding of their operational efficacy.

The remaining sections of the paper are organized as follows: Section II introduces single input single output DC-DC converters. Section III presents multi-input non-isolated DC-DC converters. Section IV introduces multi-output non-isolated DC-DC converters. Section V discusses various control techniques. Section VI addresses challenges and future trends. Finally, Section VII provides the conclusion.

II. SINGLE INPUT SINGLE OUTPUT DC-DC CONVERTER

Currently, there is a significant rise in non-isolated converter topologies due to the increasing demands of modern applications. However, conventional non-isolated converter topologies have some drawbacks that can negatively impact their efficiency and reduce the lifespan of the equipment they are integrated with. As a result, there is a growing trend towards hybridizing converter topologies as a means of addressing these challenges. Hybridizing converter topologies involves combining different converter topologies based on their unique features and limitations. In the case of non-isolated converter topologies, some limitations affect the performance. For example, features large input and output ripples, discontinuous input and output current, higher switching stress, and a higher duty cycle ratio. However, there have been recent advancements in the development of hybrid non-isolated DC-DC converter topologies, as illustrated in Fig. 5.

Fig. 5 (a) shows a transformer-less double-duty-triple mode DC-DC converter topology with high gain [23]. This topology offers several advantages over traditional non-isolated converter topologies, including a reduced component count and enhanced efficiency. Operating on two distinct duty cycles mitigates the challenges associated with a high duty cycle ratio. The converter operates in three different modes, leveraging power electronics components efficiently to achieve higher voltage gain and a stable output. Consequently, it eliminates the need for complex circuit structures such as voltage lift techniques, voltage multiplier circuits, and coupled transformers. Experimental testing has confirmed its suitability for DC-Microgrid applications, making it a viable integration option within renewable energy systems. The various topologies of Single Input Single Output converters are compared, and various applications are discussed in Table 1.

Its implementation facilitates smooth operation and enhances the lifespan of renewable energy extraction equipment, such as photovoltaic (PV) cells. A different converter configuration called the high gain three-state switching hybrid boost converter is introduced in [24], as depicted

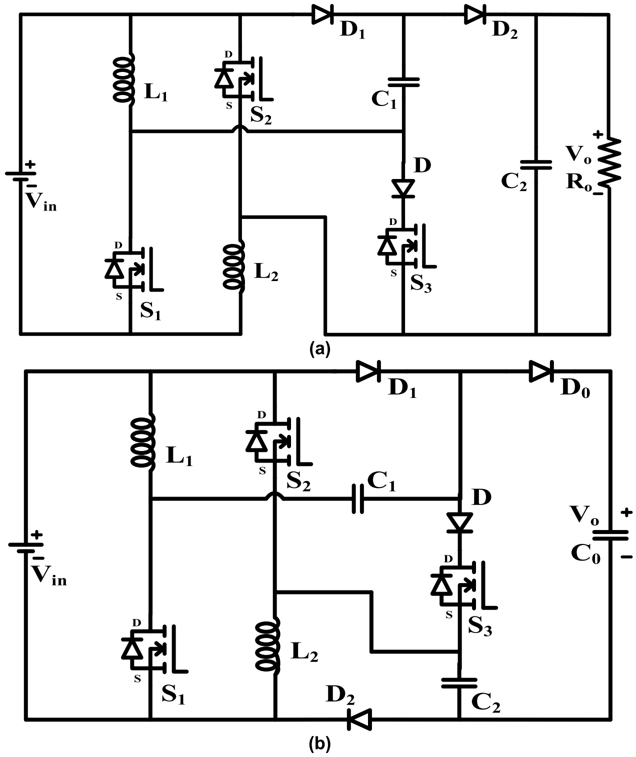


FIGURE 5. (a) High gain transformer-less double-duty-triple-mode DC/DC converter. (b) High gain three-state switching hybrid boost converter.

in Fig. 5 (b). This converter belongs to the category of non-isolated topologies and shares similarities with the abovementioned hybrid converters. However, it incorporates an additional voltage lift circuit to achieve high voltage gain. count, enhanced output voltage gain, and optimal switching duty cycle ratios. By employing two distinct duty cycle ratios and operating in three different modes, it achieves excellent characteristics of voltage boosting. This topology is particularly suitable for voltage-boosting applications generated through renewable energy, such as fuel cells and, photovoltaic (PV) ensuring optimal efficiency. The control of single-input, single-output systems is covered in [25]. Switched Inductor Boost Converter has the following key features: high voltage conversion along with voltage-stress reduction across power electronic switch [26]. The inductor and capacitor in LC2D configuration are used to improve the current and voltage, respectively, while the diode protects the reverse flow of current [27]. A specific equation provides the closed-loop system's transfer function. Routh-Hurwitz's criterion is now less important from the standpoint of assessing the overall stability. A closed-loop system's transient response is determined by its closed-loop poles. A plot of the system poles when this gain varies from zero to infinity is called a root locus. A physical system experiences a transient after being abruptly activated by a sinusoidal waveform before reaching a steady state, also known as the sinusoidal steady state. The chapter uses both Nyquist and Bode charts to assess how close a system is to instability. A novel high-gain boost

TABLE 1. Comparison of various topologies based on single input single output converters.

Reference	Year	Type	No. of Component	Applications
[23]	2019	DC-DC	11	➢ Double-duty-triple-mode (DDTM) converter for dc-microgrid. ➢ Utilized for low input power
[24]	2019	DC-DC, DC-AC	11	➢ High gain three state switching hybrid boost (TSS-HB) converter for dc-microgrid. ➢ Single duty pulse confines the gain of voltage.
[28]	2018	DC-AC	13	➢ An ideal dc-dc converter for distributed generation has a high step-up and two coupled inductors. ➢ Elimination of turn off voltage spike. ➢ Transformerless grid connected PV systems
[29]	2016	DC-DC	13	➢ Stand-alone and grid-connected systems for renewable energy sources. ➢ Achieving high voltage levels without the need for magnetic components.
[30]	2021	DC-DC	12	➢ Anti-interference capability, high voltage gain, low component stress. ➢ Converter is appropriate for fuel cell vehicles.
[31]	2023	DC-DC	11	➢ Converter achieves significantly higher gain voltage factor. ➢ Single duty ratio perseveres with implication of converter. ➢ Suitable for high power applications

converter with a tri-switching state, which is non-isolated, has been proposed in [32]. Furthermore, it offers the advantages of reduced component The various optimization goals and constraints of battery energy storage systems are examined, with a specific emphasis on factors such as cost, capacity, lifespan, and emissions are discussed in [33].

III. MULTI INPUT NON – ISOLATED DC-DC CONVERTER

A development of multiport converters topologies can be stated. The converters have multiple input ports which have multiple power supplies. Furthermore, the multiport structures extended the opportunity of making the entire system simpler and more compact. This multi-input converter is further classified into DISO, DIDO & MISO.

A. DUAL INPUT SINGLE OUTPUT DC-DC CONVERTERS

A dual-input, single-output DC-DC converter is a versatile power electronics device designed to accept power from two different sources, offering flexibility and redundancy in power supply arrangements. These converters automatically or manually switch between inputs and are frequently employed in energy harvesting applications, which combine conventional power sources with gathered energy from sources like solar panels. High efficiency, small size, and dependability are the converters' main selling points, which make them ideal for a range of uses including IoT systems, renewable energy sets, and portable devices. A soft-switched DISO converter topology that can assimilate two low-voltage energy sources into a DC bus. Coupled inductor and voltage multiplier circuit (VMC) techniques have both been used to increase the voltage gain, as was presented in [34]. Electromagnetic interference (EMI) is significantly reduced due to the input and output ports sharing a common ground. Power can be transferred to the load from two separate input voltage sources. However, [36] Z- Quasi-Resonant (ZQR) converters are the most prominent features with individual energy glide manipulates among the sources along with easy design, implementation process and higher gain at a low duty cycle [34], [35], [36], [37], [38], [39], [40], [41], [42], [43]. The primary benefits of the converter listed in Table 2 include the need for fewer components, the possibility to use a variety of sources with various voltage and current characteristics, and the capacity to obtain high voltage gain without using high-frequency switching.

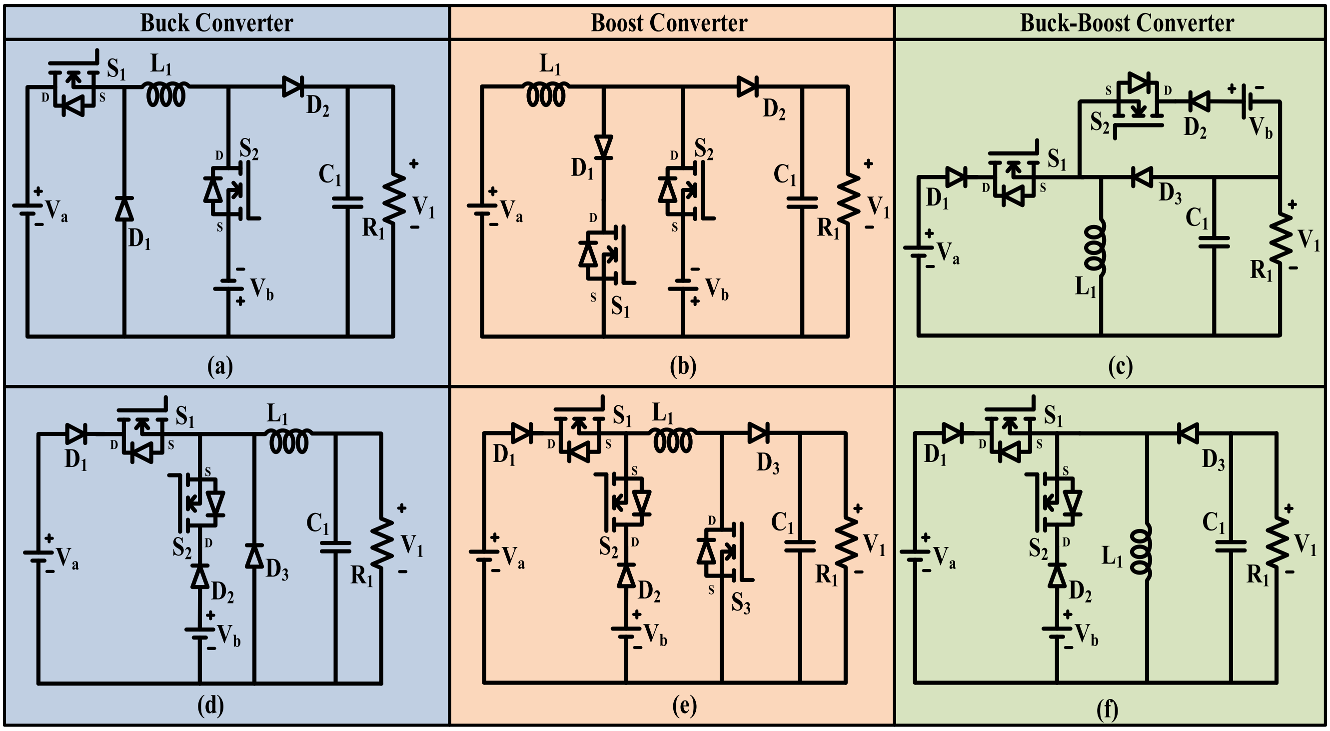
In the literature, several multi-input single-output DC-DC topologies have been published [38], [39], [40], [41]. The majority, however, use a buck or buck-boost gain relations for the output voltage. Recently, other topologies of the boost type that have a dual input and a single output have also been proposed. However, they have the following serious flaws, which restrict their uses for PV. The DISO DC-DC converter [41] offers several significant advantages, including the ability to achieve a high output voltage with a relatively low working duty ratio, continuous source current at both inputs, a shared ground, and reduced switch voltage stresses, among others.

DISO is given to the battery and used to charge the EV. The reliability of the drive is increased along with a reduction in the dependency on a single source when many sources are integrated to meet the needs of the load. Instead of a cascaded topology or a parallel topology, the direct integration of sources contributes [44], with a single inductor to reduce the cost and volume. The comparison of various dual input single output converter topologies is discussed in Table 3.

B. DUAL INPUT DUAL OUTPUT DC-DC CONVERTERS

Two input sources and two loads are integrated by the converter's four IGBTs, two inductors, two filter capacitors, and

TABLE 2. SI-DISO converters is derived from Buck, Boost, Buck-Boost.



three diodes. Even when one of the input sources is unavailable, the converter topology allows for the powering of both loads. The proposed topology has fewer component counts and fewer voltage stresses than the standard topologies, which increases converter efficiency [49]. It can be used in step-up and step-down modes. In [50], the converter can be used in UPS applications since it is designed to be used in conjunction with H-bridge cells rather than other types of DIDO converters that are already in use. The capacity to serialize several voltage sources as the input helps the circuit's output voltages reach higher levels while also ensuring redundancy. However, in this design, adding more input voltage sources is simpler and requires fewer parts. Consequently, it is simpler to implement this topology.

The H-bridge cell2 in the DIDO buck-zeta topology is changed to a voltage source to increase the circuit efficiency. [51] introduces a straightforward converter capable of generating two distinct voltage levels from two different energy sources at the input side. It is crucial to optimize the size and cost of power electronic converters to guarantee the effective and dependable operation of electric vehicles (EVs) and drives. At least two separate DC voltage levels are required for EVs and some drive applications, one for the electric motor and the other for auxiliary loads. It can supply power to EV loads as well as perform on-board battery charging as explained in [52]. The number of input and output terminals can be selected as per the vehicle requirement.

A single-stage non-isolated bidirectional four-port buck-boost converter with a smaller number of switches with integration of diversified sources in [53]. As illustrated in Fig. 6 (a), the SI-DIDO DC-DC converter is utilized to regulate the input voltage V_{PH} to the MPP voltage V_{PH}, and MPP and to produce a steady output voltage V_O to power the load. The converter will also manage and schedule the energy supplied by the two inputs piezoelectric transducer (PZT), and solar photovoltaic (PV) cells and the energy spent by the two outputs in [54]. A cutting-edge single-inductor dual-input dual-output (SI-DIDO) DC-DC converter for solar energy harvesting applications that lowers system costs and boosts overall power transfer effectiveness.

The single inductor is scheduled for the energy transfer among the dual inputs and dual outputs in each clock cycle rather than being shared in a multicycle-prescheduled time-slot way. As a result, each clock cycle regulates V_{PH} and V_O, and voltage ripples are minimal. This allows a significant reduction in the size of a capacitor connected to V_{PH} and V_O [55]. The battery provides one of the inputs, and its voltage is nearly constant. The lighting environment has an impact on the other PV cell input.

The converter VO-regulated output voltage ought to remain rather stable when the lighting changes. Once more, in this section, we solely consider line regulation that doesn't result in switching mode. Change the loading current and evaluate the converter's performance to address the line regulation that results in mode switching. The system is running with a lighting condition of 33700 LUX and a switching load current between 4 and 7.5 mA. The signal mode is changed to 1 by the mode detection circuit when it notices the change. The

TABLE 3. Comparison of various topologies based on dual input single output converters.

Reference	Year	Type			Component Counts	Output Power/ Voltage	Efficiency (%)	Voltage Gain	Advantages
		Input		Output					
		1	2	1					
[35]	2022	DC	DC	DC	16	200 W	95.87	High	➢ Low voltage stress. ➢ High efficiency.
[36]	2022	PV	Grid	Battery	10	300 W	91.5	9.54	➢ Easy to design, Manipulation, and implementation process. ➢ Low switch voltage stress. ➢ Comparatively low cost.
[37]	2023	Battery	Supercapacitor	DC Link	13	5 kW	91.8	High	➢ Any port can transfer power. ➢ power flow is independently controlled. ➢ Size and cost are low.
[40]	2019	DC	DC	DC	16	293 V	85	High	➢ Continuous input current with bidirectional energy flow. ➢ Lower current stress and losses
[41]	2022	DC	DC	DC	8	500 W	-	High	➢ Continuous current for both inputs. ➢ Simple structure. ➢ High voltage gain.
[42]	2022	PV	Battery	DC	9	116mV	-	-	➢ Low cost and volume, portability of converter. ➢ Direct integration of sources is done, instead of cascaded topology. ➢ Complexity is less.
[43]	2021	DC	DC	DC	12	48 V	-	4	➢ Load current ripple is low. ➢ Isolates input sources. ➢ Gain boosting.
[45]	2020	PV	Battery	DC	13	200 W	93.6	2	➢ PWM Switching methods used. ➢ Control strategy is simple.
[46]	2021	DC	Battery	DC	14	100V	97.22	2-2.5	➢ Simple circuit. ➢ Low Volume, High efficiency. ➢ All switches operate under soft switching
[47]	2022	PV	Battery	AC	14	300~700 W	-	-	➢ Only differential power needs to be handled by dc – dc converter. ➢ High efficiency and integration, and lower cost can be achieved.
[48]	2022	DC	Battery	DC	17	535 W	94.88	High	➢ Soft switching performance is achieved. ➢ Voltage stress across the switches and diodes are low.

voltages of V_{PH}, $_{OP}$, and V_O experience re-regulation in the updated mode, indicating that the converter has switched to the heavy load mode of operation. The comparison of various dual input dual output converter topologies is discussed in Table 4.

C. MULTI INPUT SINGLE OUTPUT DC-DC CONVERTERS

The necessity and importance of a non-isolated converter don't have any galvanic isolation between the source and load sides, therefore the variations on the source side directly affect the load side of the converter. In contrast, isolated converters have a separate ground, which means that the input does not impact the output side of the converter. This enables them to operate effectively with a wide range of inputs and deliver a stable output. One common reason for using isolated converters is to ensure safety. By isolating the input and output ports, these converters enhance consumer safety on the load side and prevent short-circuit currents from flowing back to the source side. Isolated converters incorporate transformers into their design to achieve this isolation. Fig. 6 (b-c) shows the basic structures of the MISO converter. Fig. 6 (d) indicates the modular high voltage structure of a multi-input non-isolated converter. The comparison of various MISO converter topologies is discussed in Table 5.

A single-input single-output converter typically requires one transformer, while a MIMO converter may require multiple transformers [58]. However, this results in larger volumes, higher costs, lower power density, and reduced efficiency compared to non-isolated converters, which do not require such transformers. Another consideration is that isolated converters often require expensive measuring equipment, such as isolated probes, to measure currents. In the case of an isolated MIMO converter, multiple isolated probes are necessary, significantly raising the overall cost. Consequently, if consumer safety is not a concern, non-isolated converters prove to be a suitable choice for multi-input converters. Isolated converters also encounter various significant challenges, such as leakage inductance, core saturation, thermal effects, high voltage spikes across switches, and larger sizes, leading to higher costs compared to non-isolated converters. This study

TABLE 4. Comparison of various topologies based on dual input dual output converters.

Reference	Year	Type				Component Counts	Output Power/ Voltage	Efficiency (%)	Advantages
		Input		Output					
		1	2	1	2				
[49]	2018	DC	DC	DC	DC	11	80V & 60V	-	➢ Less number of components. ➢ Independent control of output voltage.
[50]	2021	DC	DC	DC	DC	13	40V & 5V	-	➢ Achieve higher level output voltages ➢ Implementation of circuit and increase the number of output voltage is easier. ➢ Less number of components.
[53]	2021	PV	Battery	Motor	DC	11	42.67V & 42.81V	98.2	➢ Less Component Count. ➢ Control strategy is simple and more reliable. ➢ Cost effective.
[54]	2019	PV	PZT	Battery	DC	15	180 mW	88.1	➢ Extra energy back to battery. ➢ Lower static power consumption
[56]	2021	DC	DC	DC	DC	11	90V & 75V	92.3	➢ Improved dynamic behavior and utilize maximum energy
[57]	2019	PV	Battery	Battery	DC	13	120 W & 20 W	-	➢ Cross regulation will be reduced by improving transient response.

TABLE 5. Comparison of various topologies based on multi input single output converters.

Reference	Year	Type		Component Counts	Output Power/ Voltage	Efficiency (%)	f_s (kHz)	Voltage Gain	Advantages
		Input	Output						
		DC/ AC	DC/ AC						
[58]	2021	DC	DC	10N	450 W	93.5	30	15.66	➢ By increasing the number of inputs or the turns ratio of connected inductors, voltage gain can be enhanced. ➢ Voltage stress is low.
[59]	2023	DC	DC	8N+1	300 W	93.3	40	-	➢ Current stress on each input is low. ➢ Size of the converter is reduced.
[63]	2021	DC	DC	16	4 kW	96.1	20	-	➢ Input sources can be used individually or combine to enlarge total power. ➢ Total cost of energy is reduced. ➢ Prolonging of battery lifetime.
[64]	2021	DC	DC	7N	1.1 kW	91	15	-	➢ Cost effective. ➢ High power and low power application.
[65]	2020	DC	DC	9	400 W	96.37	100	-	➢ Simple structure. ➢ Component count of power conversion is reduced. ➢ High flexibility design.
[77]	2019	DC	DC	4N+6	200 W	98	120	8	➢ Less number of active switches. ➢ Light weight and less expensive.
[79]	2023	DC	DC	13	600 W	96.77	20	5	➢ Low voltage stress. ➢ Interface to allow any number of input sources.
[80]	2017	DC	DC	16	80 W	85	30	4	➢ In the absence of one or two resources, the converter can supply the required power to the load.

*N- Number of Modules

introduces a multi-input DC-DC converter designed for integrated PV applications, where the isolation of input and output terminals is not required.

The key attributes of the proposed converter in this paper are its high-power density, compact size, high efficiency, and affordability. In this scenario, a non-isolated topology is the optimal choice. Despite certain drawbacks like a high duty cycle ratio, low voltage gain, and additional circuitry in non-isolated DC-DC converter topologies, it is widely acknowledged in the literature that non-isolated topologies

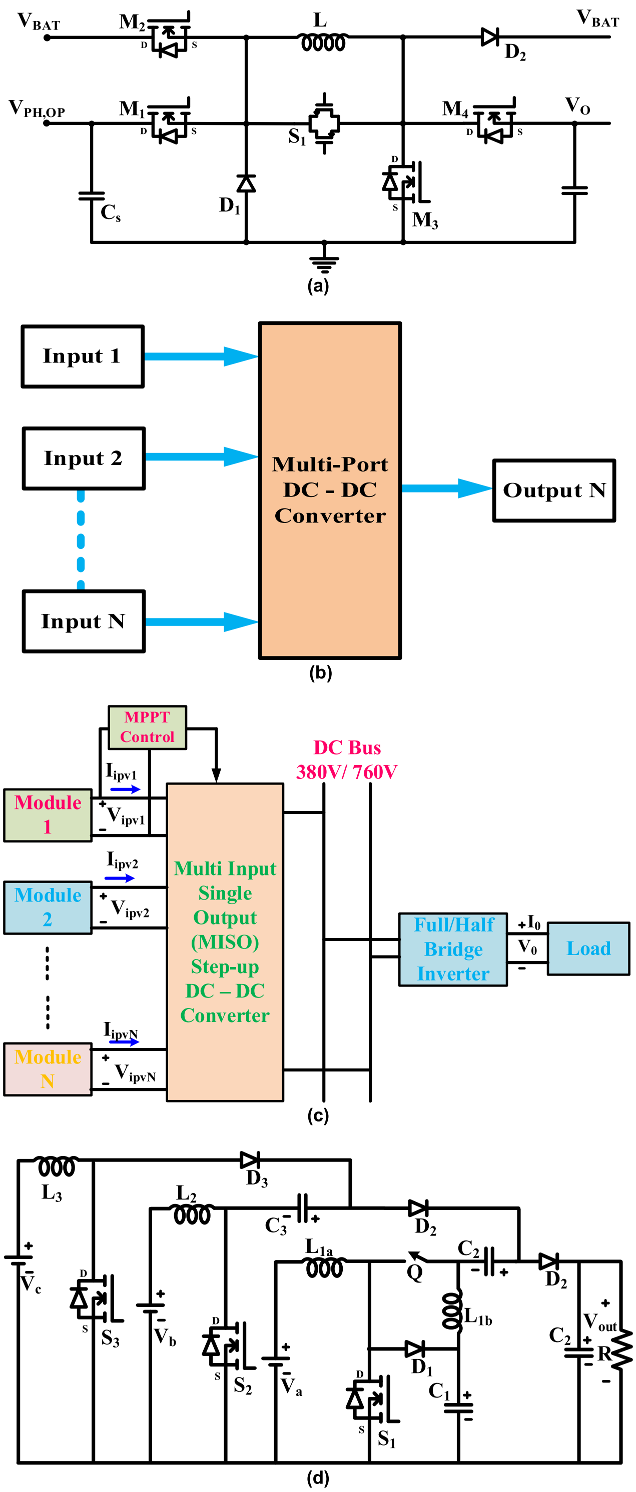


FIGURE 6. (a) SI-DIDO DC – DC Converter. (b) Basic Structure of MISO Converter. (c) MISO DC – DC Converter. (d) Modular high voltage multi input converter [66].

are more advantageous and feasible for renewable energy applications compared to isolated converter topologies. The objective of this research is to address existing technical challenges and enhance the performance of non-isolated DC-DC converters in renewable energy applications. The MISO converter utilizes a single control system to achieve maximum power point tracking (MPPT) for PV sources, eliminating the need for multiple MPPT controllers as in a typical PV system. There are different converters available in the literature that take multiple inputs [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78].

Due to the practical constraints of a normal boost converter's voltage gain and its high-power loss at severe duty cycles, significant research has been undertaken on high step-up DC-DC converters. During boost mode operation the input current flows through the inductor and to achieve a high voltage conversion ratio for diode-capacitor voltage multiplier cells (VMC) [59], The converter [60] combines three-port boost and buck topologies to transmit power from and to energy storage units (ESUs) with continuous current, increasing the battery life as a single ESU. Additionally, switching capacitor technology and the primary boost switch are used in operating modes that provide power from energy storage units (ESUs) and energy generation units (EGUs) to the output along with increased voltage gain and continuous input current. A solar PV system with a fly-back converter and multiple ports. Because it includes many input sources and multiple output loads, the multiport system can typically transfer energy in both directions and improves the amount of possible energy utilization.

The fly-back converter [61] may convert between AC/DC and DC/DC, operating in both cases, and it appears to be flexible for any situation. The objective of PWM control approaches is to regulate the DC-bus voltage and achieve load-sharing control in alignment with the energy management strategy (EMS) [62]. However, the complex nature of these multi-input single-output converters presents challenges concerning reliability, efficiency, power density, control systems, cost, and device size [63]. The step-up n -n-stage DC-DC converters report Continuous current and almost high-voltage gain and can be expandable are the advantages of the converter proposed in [66] and [67], but it requires multiple input sources and many switches with the introduction of each stage making it unfit for various applications. Despite the high voltage gain of [68] and [70], it has considerably low normalised voltage stress (NVS) on its switches/diodes. Another important advantage of the proposed topology is that, as the number of input units increases, the voltage gain increases too, but the NVS on switches/diodes decreases. Less component count can reduce the size, mass and cost of the converter. Simultaneous or independent power transfer capability has been provided for input sources in [69]. Further, the bidirectional power flow capability has also been provided through the usage of a battery without any additional switches. A distinguishing characteristic of the DC-DC converter [71], [72], [73], [74], [75], [76], [77], [78], [79] is the utilization of an actively switched inductor-capacitor (ALC) network, a feature not commonly found in other multiport converters. However, multi-input DC-DC converters have been extensively employed in various research areas concerning hybrid electric vehicles and fast charging of electric vehicles. These converters offer several advantages compared to conventional converters, including the reduction of power devices, the minimization of power conversion stages, and the centralization of control. A power electronics system is given for converting the electrical energy of a PV panel to a suitable form. A DC-to-DC converter architecture based on the integration of SEPIC and CUK converters has been presented, increasing the overall power output of renewable energy sources. If one of the input sources fails to operate, an effective energy management approach is applied to provide energy to the load. The converter has various advantages, including limited operation modes, no switching duty cycle limitations, and smaller component sizes. As an alternative to the centralized PV converter topology, the concept of PV distributed maximum power point tracking (DMPPT) has emerged to address power losses caused by irradiance mismatch and shading scenarios. In DMPPT technology, each module in a PV system is equipped with its converter and controller. This enables each module to independently perform maximum power point tracking (MPPT), maximizing the harvested power from the entire PV system. Parallel MICs with a single MPPT controller and current estimation have a greater component count, resulting in a bigger footprint, cost, and loss. The multi-input convert has the benefit of low part numbers and continuous input current, making it appropriate for renewable energy applications [76], nevertheless, it lacks bidirectional power flow.

The converter design presented in [78] is a multi-input single-output converter that addresses partial shading's drawbacks and enables the PV system to function at MPPT without the need for an extra energy buffer, such as a battery and it has a combination of series and parallel ones.

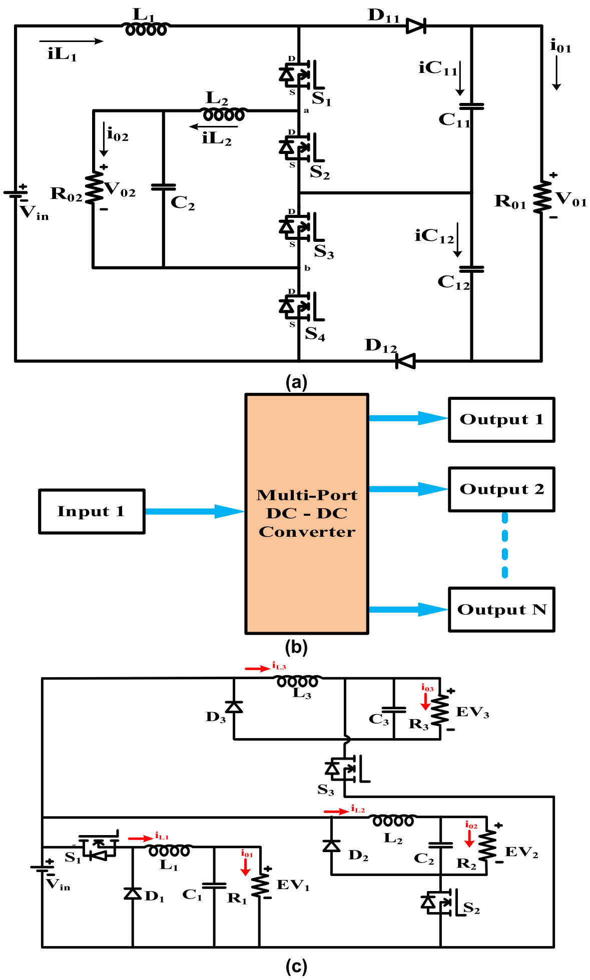


FIGURE 7. (a) Single input dual output DC-DC converter. (b) Basic Structure of SIMO Converter. (c) SIMO configuration [87].

IV. MULTI-OUTPUT NON – ISOLATED DC-DC CONVERTER

The development of multiport converter topologies will be stated in this section. The converters have multiple output ports which have multiple loads. Furthermore, the multiport structures extended the opportunity of making the entire system simpler and more compact. This multi-output converter is further classified into SIDO, SIMO & MIMO.

A. SINGLE INPUT DUAL OUTPUT DC-DC CONVERTERS

In [81], a non-isolated SISO DC-DC converter is introduced, as shown in Fig. 7 (a). This converter has the unique capability to generate and regulate both boost and buck outputs simultaneously. An interesting observation is that the frequency of the ripple current flowing through the inductors is twice the switching frequency. Additionally, the voltages across all the switches are below half of the boost voltage and are found to be equal. This enables the utilization of high switching frequencies, resulting in a reduction in the size of passive components. Consequently, this converter exhibits advantages such as low switching stress, compact passive component sizes, and high efficiency. The primary benefits of the converter listed in Table 6 include the need for fewer components, the possibility to use a variety of sources with various voltage and current characteristics, and the capacity to obtain high voltage gain without using high-frequency switching. The comparison of various single input dual output converter topologies is presented in Table 7.

Lyapunov's strategy deals with analysing the behaviour of dynamical systems over time. With a focus on stability analysis, it helps us to understand how a system will behave under different conditions with input and outputs. In [82], mainly focus on voltage and current dynamics of boost and buck converter segments. The utilization of current-source-mode (CSM) converters to mitigate the issue of cross-regulation through topological modifications [83] has been increasingly prevalent in various domains, including light-emitting diode backlighting, wireless transceivers, hybrid power source systems resulting in severe performance degradation. The converter in [84] presents two proportional-integral (PI) compensators applied to a dual output three-level converter (TLC), that combines the buck and boost converter, has low input current ripple and has critical issues, such

TABLE 6. SI-SIDO converters is derived from Buck, Boost, Buck-Boost.

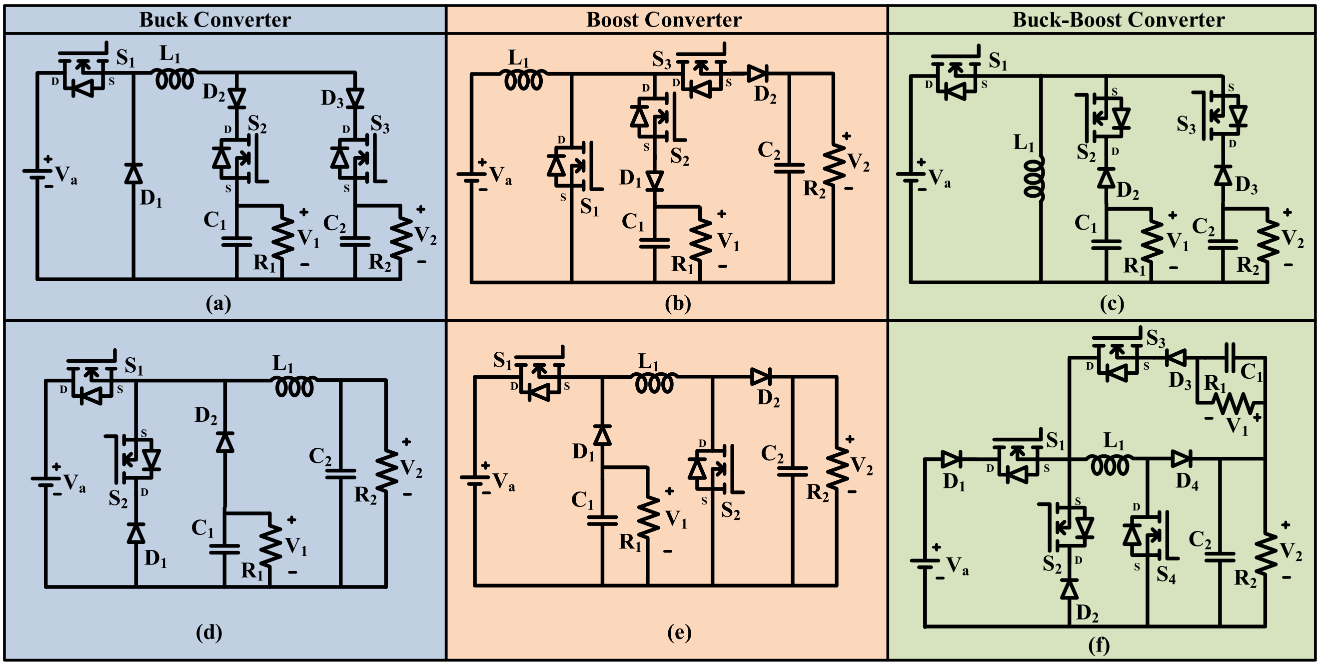


TABLE 7. Comparison of various topologies based on single input dual output converters.

Reference	Year	Type			Component Counts	Output Power/ Voltage	Efficiency (%)	f_s (kHz)	Voltage Gain	Advantages
		Input	Output							
		1	1	2						
[81]	2020	DC	DC	DC	15	400 W	96.2	20	Medium	➢ Low Switching Stress. ➢ Input and output current ripples are low. ➢ Harmonic distortion is reduced by designing inductor filter.
[84]	2018	DC	DC	DC	15	300 W	95.9	20	Medium	➢ Voltage stress across semiconductor devices is low. ➢ Size of inductor shrank and volume of capacitors are small. ➢ ON-state resistance and diode reverse recovery losses are less.
[85]	2021	DC	DC	DC	12	150 W	91	50	High	➢ Lower output capacitor stress due to dual output. ➢ Input current that is constant. ➢ Switches and diodes are subjected to low voltage stress.
[86]	2020	DC	DC	AC	14	60 W	-	10	Medium	➢ Less number of semiconductor devices. ➢ Better shoot through protection compared to VSI. ➢ Continuous supply for both AC and DC outputs from a single DC source.
[89]	2018	DC	DC	DC	7	10 W	95.8	10	Medium	➢ Efficient and economical solution for volume of DC grid. ➢ Low voltage distribution and multiple voltage levels.
[92]	2023	DC	DC	DC	10	17 W	92.03	25	-	➢ Faster load transient. ➢ Low cross regulation.
[93]	2022	DC	DC	DC	11	120 W	-	20	-	➢ DVMC is effectively eliminates the CC problems. ➢ High power density and size is compact.

as very slow dynamic and large undershoots/ overshoots. The hybrid converter [85] is implemented by replacing a voltage source inverter (VSI) bridge network for the switch of a typical boost converter. Extensive research has been conducted in the literature to examine the impact of a coupled inductor on the performance of different converters, including high step-up, interleaved, and multiple-output converters. The investigation of inductor coupling's influence on the continuous conduction mode (CCM) and discontinuous conduction mode (DCM) boundary of the CI-SIDO boost converter is explored in [86], [87], [88], [89], [90], and [91]. The uni-input Duple-Output Buck Converter plays a major role in maintaining the voltage levels of the microgrid. The expressions of the average value of inductor currents at the boundary condition for Dt = 0 are presented in [91]. In certain applications [88] where a high AC voltage is required, the voltage-source inverter (VSI) can only function as a buck inverter because an additional DC-DC boosting stage is necessary to achieve high gain. However, the VSI may not be suitable for all applications due to limitations in available DC input voltage. Pseudo-continuous conduction mode single-inductor dual-output (SIDO) DC-DC converters often suffer from slow load transient performance, potential cross-regulation, and low efficiency. To address these limitations, a voltage-ripple (VR)-based dynamic freewheeling (DF) control mechanism is proposed in [92] for hybrid conduction mode (HCM) SIDO buck converters. This mechanism aims to overcome the drawbacks associated with SIDO converters by improving their efficiency and load transient performance. Which can be generated by using a proportional-integral (PI) controller as a small-signal modelling-based cross-derivative state feedback controller proposed in [93].

B. SINGLE INPUT MULTI OUTPUT DC-DC CONVERTERS

DC-DC converters have recently been the subject of intensive research to increase their flexibility and dependability while at the same time lowering their overall cost. Incorporating both positive and negative layers, these converters can independently adjust voltage and achieve substantial amplification. Three different types of multiport DC/DC converters can be distinguished: those with numerous inputs and a single output, those with numerous inputs and multiple outputs, and those that combine both layouts [94], [95], [96], [97], [98], [99], [100], [101], [102], [103], [104], [105], [106], [107]. Multi-input multi-output DC/DC converters can use a variety of DC voltages with discrete V-I characteristics to provide a wide range of DC voltage levels at the output. The converter [99] uses a two-stage structure and a series connection of current-source-mode (CSM) converters to ensure strong individual control capabilities for a range of output voltage levels. A voltage-source-mode (VSM) buck converter is used in the first stage to reduce the voltage and deliver a steadily controlled, stable current. The second stage, in contrast, uses CSM converters that are coupled in series and have intrinsic independence from one another. By doing this, they can accomplish voltage step-up with a less complex control system and avoid any cross-regulation problems. The converter is often very simple to build, centrally regulated, incredibly reliable, and relatively affordable, and output ripple is less but synchronization is difficult. Non-isolated SIMO converters have the advantage of employing fewer components and switches to achieve a more compact circuit due to the need for a transformer to provide electrical isolation. [95] presents an application to a type of non-isolated SIMO in which the averaged model of the converter is generated utilizing the notion of quasi-Weierstrass transformation in conjunction with consistency projection operators.

The varied voltage levels were acquired to power various DC loads such as mobiles, routers, nano stations, laptop chargers, and so on [97]. The fundamental disadvantages of multiport and multi-input conversion systems are that they convert several inputs to a single output, increasing the cost of renewable energy generation and power loss. Reference [98] suggested a new single-input and multi-output (SIAMO) model for renewable energy converters. Fig. 7 (b) shows the basic structure of a single-input multi-output converter. The comparison of various single input multi output converter topologies is discussed in Table 8.

The large difference in switching frequency between the input and output stages in the DF-SIMO topology makes the dynamic and steady-state behaviour of these output controllers and the expressions that govern their operation and performance fundamentally different than when these same controllers are used in single-frequency SIMO topologies [107]. Moreover, the design trade-offs between performance and circuit complexity become quite different in the DF-SIMO topology due to the high switching frequency of the output stage.

The optimum strategy for controlling such a power converter topology is subject to many considerations, such as circuit complexity, stability, expected variability in operating conditions, and desired steady-state and transient performance. The advantage of superior dynamic response compared to ripple-based charge-mode and average-based voltage-mode controllers. power- the stage is conceived and switched appropriately to generate the unique floating output among others. Regulated floating dual-slope (RFDS) drivers are proposed [108] to limit the di/dt through the switches and to reduce the switching noise.

Portable electronic devices require multiple supply voltages with relatively large differences in load currents, causing serious regulation, EMI, and efficiency problems when adopting a single-inductor multiple-output (SIMO) DC-DC converter. To resolve these issues, [109] presents a reconfigurable SIMO system that utilizes a dual-bus multiple-output (DBMO) with ten-output having two buses, one for heavy-load and one for light-load outputs. By calculating the total energy needed by all outputs to draw the same amount of energy from the input, the output-voltage-aware charge control (OVACC) technique lessens cross-regulation. Many methods have been suggested to suppress cross-regulation, however, it is still unclear where the limit lies.

The differential evolution (DE) approach is then used in [110] and [111] to tackle this issue. Most SIMO converters face limitations concerning operating constraints related to duty ratio and inductor charging when producing multiple outputs. One particular challenge in the design of SIMO converters is the presence of cross-regulation issues.

TABLE 8. Comparison of various topologies based on single input multi output converters.

Reference	Year	Type		Component Counts	Output Power/ Voltage	Efficiency (%)	f_s (kHz)	Advantages
		Input	Output					
		DC/ AC	DC/ AC					
[94]	2022	DC	DC	4N	100 W	85.41	10	➢ Multiple outputs can be extended. ➢ At load variation, voltage regulation is better. ➢ Isolation of load
[96]	2022	DC	DC	4N	100 V	-	10	➢ Reliability and flexibility. ➢ Easy to implementation. ➢ Maximize the efficiency reduce the size and expense.
[97]	2022	DC	DC	3N	60 W	95	10	➢ It has better control methods and low cost. ➢ More efficient. ➢ It is flexible and reliable.
[100]	2021	DC	DC	3N+1	-	High	10	➢ Switching Loss and Cost is low. ➢ Reliability and availability are high.
[101]	2020	DC	DC, AC	5N+1	83.5	87.5	500	➢ Low cross regulation. ➢ Low overshoot and undershoot. ➢ Multi output hybrid power stage.
[102]	2018	DC	DC, AC	21	153V, 58V	-	5	➢ Fewer switches and passive components. ➢ Size is small. ➢ Low cost. ➢ Both DC and AC loads are used as outputs.
[106]	2022	DC	DC, AC	3N	20 W	88	400	➢ Simple, compact and low cost ➢ Less component counts. ➢ High power density. ➢ Better flexibility, scalability, and combinations of AC and DC loads.
[109]	2019	DC	DC	3N+1	2.83	88	1MHz	➢ Switching loss is low. ➢ In dual-bus multiple-outputs can be controlled.
[112]	2021	DC	DC	4N	100 W	-	5	➢ Low cost. ➢ Low voltage input power source. ➢ Different output voltages for low and high-power applications
[115]	2022	DC	DC	4N	200 W	-	50	➢ No constraints on inductor currents. ➢ Buck boost positive output voltage. ➢ Can generate three different output voltages. ➢ Simple structure.

However, this study introduces a novel SIMO topology aimed at addressing the aforementioned limitations as shown in Fig. 7 (c). In [113], [114], and [115], this topology offers the capability to generate three distinct output voltages without any constraints on the duty cycle or inductor currents. Importantly, this design effectively eliminates cross-regulation problems, ensuring that sudden fluctuations in the inductor and load currents have no impact on the output voltages. While Single Input Multi Output (SIMO) DC-DC converters offer several advantages, they also present some limitations or demerits: Limited Input Voltage Range, Complexity in Design, Cross-Regulation Effects, Potential Efficiency Trade-offs, Increased Component Count and Sensitivity to Load Variations. transitioning from SIMO to MIMO converters represents a significant advancement in power electronics technology, enabling more resilient, efficient, and flexible energy management solutions across a wide range of applications.

C. MULTI INPUT MULTI OUTPUT DC-DC CONVERTERS

A multi-input, multi-output DC-DC converter is a versatile power electronics device capable of handling power from multiple sources and providing regulated voltages to several components simultaneously. It excels in complex systems with diverse power requirements, integrating various energy sources efficiently. The converter focuses on high efficiency, independent control for each output, and adaptability to different industries. Its compact design, reliability features, and advanced control algorithms make it suitable for applications in telecommunications, automotive, renewable energy, and aerospace, offering customization options to meet specific needs. MIMO provides power supply configuration versatility, allowing for a range of input and output combinations to be used in complex applications. Suitable for incorporation into intricate systems where various parts or subsystems have distinct power needs. Despite managing several inputs and outputs, aims for a small form factor to satisfy space requirements in a range of applications. For the design of multiport converters in electric vehicles (EVs) and portable electronic applications, these integrated models appear to be quite attractive. However, it has assumptions on (i) output current ($i_{o1} > i_{o2}$) and (ii) due to the limitation of output current restricted the output voltage (i.e. $V_{i1} > V_{o2}$), other the inductor is continuously charged. Due to the intrinsic working principle and lack of restrictions imposed by traditional two-port converters, the investigation of numerous conceivable

SI-MIMO topologies is possible. The automated process's use of computer codes makes the topologies' rigorous derivation possible [116], [117], [118].

In parallel, 3D images were captured utilizing two distinct channels with overlapping field-of-views (FOVs). Using this method, [119] was able to simultaneously capture photos with big FOV and low resolution and small FOV and high quality. Developed a general unique model for the MIMO hybrid energy system, decoupling network, sub synchronous oscillations (SSOs) and systematic design of the linear controllers are introduced in [123] and [124]. The MIMO converters using Augmented Sinusoidal Pulse Width Modulation (ASPWM) technique, constraints on structure of state space controller matrices, relative gain array (RGA), participation matric (PM) method, Hankel interaction index array (HIIA), Linear matrix inequality (LMI), MPPT and PSO optimization algorithms to determining the phase sequence and integrated in working of DC-DC converters [128], [129], [130]. The dependability and stability issues related to the power generated by renewable energy conversion systems have been effectively handled and stabilized using a power converter system setup. Furthermore, the intermittency problems that could occur during the generation process have been successfully overcome using multiport converters [135], [136].

Fig 8 (a) shows the basic structure of a multi-input multi-output converter. A MIMO converter with a simple structure (Fig. 8 (c)) is described in [125], [132], and [138]. This setup successfully integrates different voltage and current characteristics of two energy sources using a time multiplexing concept. However, it has a drawback, requiring n+m+1 switch for n-inputs and m-outputs, with outputs connected in series. Additionally, during CCM operation, it faces cross-regulation issues. A Model Predictive Control-based MIMO converter is suggested in [139] as a solution to the issues raised in [133] and [137]. With the use of this control strategy, cross-regulation issues, voltage ripples, and converter output voltage regulation are all avoided. The comparison of various multi-input multi-output converter topologies is discussed in Table 9. A novel MIMO topology designed for electric vehicle applications is introduced in [140] and [141]. This configuration ensures that both output voltages exceed the input voltage, with the output switches restricting their levels. However, a limitation of this setup is that only one input source can supply energy at any given moment, potentially restricting the possibility of wide-ranging duty cycle operations. Fig. 8 (b) for a representation of the schematic circuit of the MIMO converter presented in [146].

G_{max} is the highest value in one port of voltage gain is higher than that of other ports in the converter. The normalized maximum voltage stress on the switch is $V_{S(max)}$, $I_{S(max)}$ is the average current stress on the switch and n_{out} is the number of output ports. The comparison of various high voltage gain with the advantages of DC-DC converter topologies is discussed in Table 10.

A different single-stage MIMO converter with a robust control approach is provided in [147] and [131] that uses

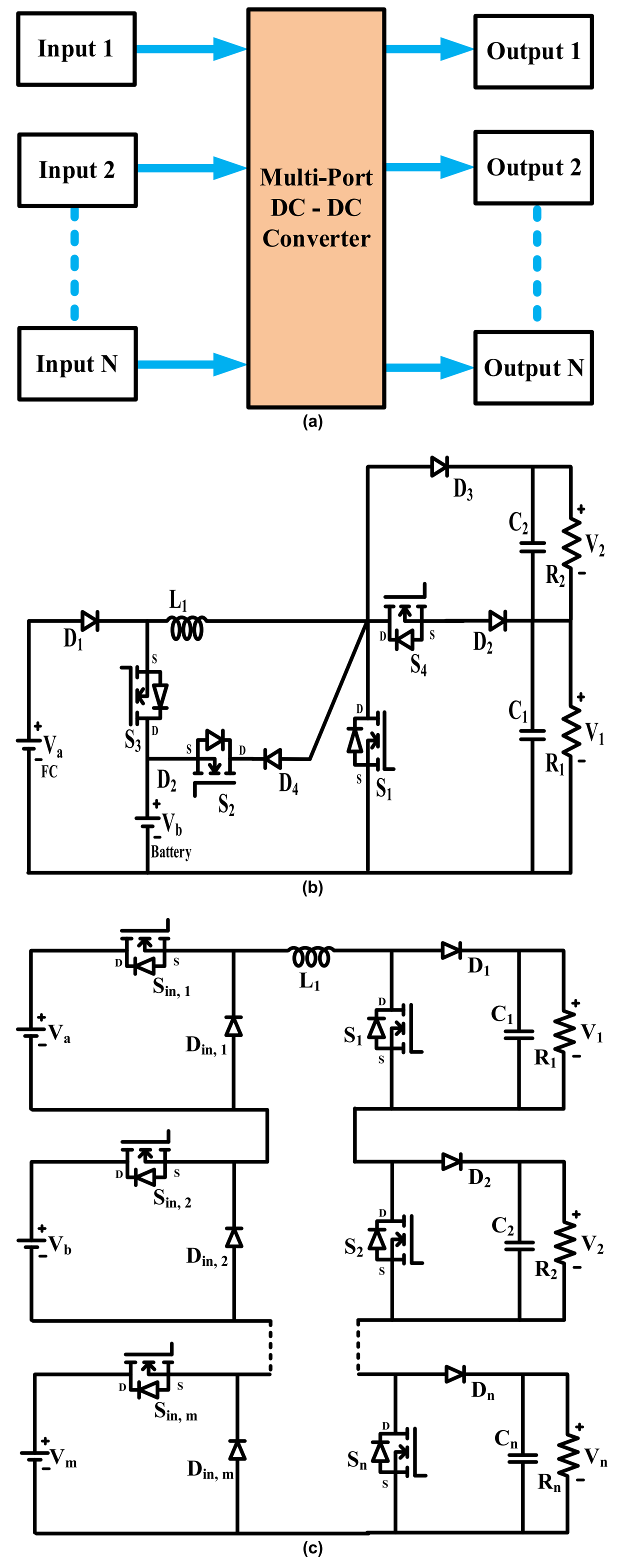


FIGURE 8. (a) Basic structure of MIMO converter. (b) Schematic circuit of MIMO converter. (c) MIMO configuration.

only one inductor, smaller in size and less expensive as a result. However, it requires an n+m+1 switch for n inputs and m outputs, which poses efficiency problems due to large switching losses and raises the converter's total complexity.

TABLE 9. Comparison of various topologies based on multi input multi output converters.

Reference	Year	No. of Input	No. of Output	Component Counts	Output Power/ Voltage	Efficiency (%)	f_s (kHz)	Advantages
[117]	2022	N-1	N	12+6N	225W, 250 W, 410 W	-	50	➢ High gain in voltage. ➢ Switch stress is minimal.
[121]	2021	N	N	7N	-	-	50	➢ Voltage and current stress on OFC are low. ➢ Negative voltages can supply. ➢ Simplifying in design and saving cost.
[122]	2020	N	N	12N	500 W	95	200	➢ Multicell reconfigurable maintaining high performance. ➢ Low power conversion stress. ➢ Matrix method reduced the circuit complexity.
[125]	2020	N	N	6N+1	2.4 W, 28 W	88	100	➢ Simple control, high flexibility ➢ No cross regulation. ➢ Extension capability is high. ➢ Low complexity control. ➢ Medium power density.
[126]	2019	N-1	N	10N	1 kW	96.8	40	➢ Switched capacitor to generate different output voltage level. ➢ Operate at low/ high power ranges. ➢ Low voltage stress across diodes and switches.
[127]	2018	N	N	7N	250 W	93.5	250	➢ Systematic synthesis, point to point power routing. ➢ Common ground between all ports. ➢ Less element counts.
[129]	2022	N	N	11N	800 W, 50W	-	40	➢ Large AC and DC output voltages can be obtained by cascading several micro-hybrid converters.
[134]	2021	N	N	8N+4	24 V, 12 V, 5 V	-	40	➢ Buck boost converter with any number of inputs and outputs.

TABLE 10. Comparison of high voltage gain converters.

DC-DC Converters	G_{max}	$I_{S(\max)}$	$V_{S(\max)}$	n_{out}	Duty cycle operation	Controllable output voltages at the same time	Expandable from input and output sides
[117]	$\frac{1}{(1-D)^2}$	$\frac{D_5 I_{05}}{1-D_5}$	V_{05}	5	$0 < D_1, D_2, D_3, D_4, D_5 < 1$	Yes	N-1 input and N output
[125]	$\frac{D}{1-D}$	$\frac{I_0}{1-D_4}$	V_{01}	4	$0 < D_1, D_2, D_3, D_4 < 1$	Yes	N input and N output
[126]	$\frac{4}{1-D}$	$\frac{I_{01}+I_{02}}{1-D_4}$	$\frac{V_{01}}{4}$	2	$0.5 < D_1, D_2, D_3, D_4 < 1$	Yes	N input and M output M<N

*G_{max} – Total voltage gain, $I_{S(\max)}$ – Current stress on switch, $V_{S(\max)}$ – maximum voltage stress on switch, n_{out} – number of output ports.

The synthesis of MIMO converters involves a three-step process: (i) Selecting and connecting the PSCs (Power Semiconductor Components). (ii) Choosing a configuration for the OFC module (Output Filter Components). (iii) Connecting the PSC and OFC modules to create the MIMO converter [120], [121], [122]. Moreover, there is a multicell reconfigurable multi-input multi-output (MR-MIMO) power conversion architecture designed for various multiport applications, including multisource energy routers, battery balancers, and photovoltaic optimizers.

In [137], a matrix converter-based MIMO buck-boost converter is introduced for microgrid applications. The original design is later expanded to support n-inputs and n-outputs after being first designed for a certain number of inputs and outputs. Unfortunately, this addition increases the size of the inductor and the number of switches, creating a complex system with increased costs and losses. The converter operates on the time-sharing concept, which may limit the efficient utilization of energy sources. In response to these challenges, an alternative diode-clamped converter configuration-based

MIMO converter is presented in [142]. The outputs in this particular structure are adaptable and independent in their functionality. This design's disadvantage is that it calls for the employment of extra switches, which leads to higher losses, a more complex structure, and a possible sensitivity to cross-regulation problems during CCM operation. To integrate multiple energy sources, achieve controlled output, and support bidirectional flow, an alternative MIMO converter is suggested in [143]. However, a drawback of this converter is that to avoid incorrect operation, both energy sources must run within specific duty cycle restrictions.

A MIMO boost converter designed primarily for applications involving renewable energy sources is introduced in [144]. However, it mandates the usage of n+m+2 switches and necessitates additional energy storage components when set for n-inputs and m-outputs. The calculation of these parameters in different types of non-isolated converters along with output voltage and voltage gain were presented in Table 11.

The converter grows and complexity as a result. A different strategy is provided in [145], where a converter is created by combining the traditional converter synthesis of DC-DC converters with dual input and single output (DISO) and single input and multiple output (SIMO). Several techniques have been developed to increase voltage levels, resulting in the creation of different types of high step-up DC-DC converters. There are a wide variety of bidirectional converters, some of which are classified and evaluated in [148]. In [149] enables the incorporation of various renewable energy sources, each differing in type and capacity, into a bipolar medium voltage DC microgrid. Its primary benefits lie in its high-power density and the diminished quantity of switches required compared to the distinct converters. To improve the voltage gain of power converters with proper duty ratio, many techniques, such as coupled inductors (CIs), diode-capacitor voltage multipliers (DCVMs), and their combinations, have been investigated. Using these techniques not only improves the voltage gain but also reduces the voltage stress across semiconductor elements. On the contrary, Multiphase interleaved high step-up DC-DC converters are widely studied in [150], which have better efficiency characteristics under heavy load. Indeed, the investigation of various multiport DC-DC converter configurations reveals that there is no universal structure that fulfils all the objectives, such as cost-effectiveness, reliability, part count reduction, flexibility, and modularity, simultaneously.

Each topology has its own set of advantages and disadvantages, making them suitable for specific applications and scenarios. The precise needs and limitations of the intended application determine the choice of a particular multiport DC-DC converter design. To choose the topology that is most appropriate for their specific use case, engineers and researchers must carefully analyse the benefits and drawbacks of each topology. The required features and trade-offs must be balanced while considering aspects like cost, dependability, part count, flexibility, and modularity.

The performance of the converters can be defined in terms of efficiency, switching losses and also the voltage stress on components. These parameters differ concerning the number of active and passive elements used, types of switches, switching frequency, inductor, capacitor design, and so on. Along with this, the converter functions like a buck, boost, and buck-boost rely on the capacitor and inductor design. These factors involve defining the boosting factor of the converter. Different non-isolated converters were discussed in the literature and their corresponding design considerations are given in Table 12. The non-isolated dc-to-dc converter is compared with features, benefits, and drawbacks of different topologies are discussed in Table 13.

V. CONTROL TECHNIQUES

Control techniques play a crucial role in achieving maximum efficiency for non-isolated DC-DC converters. These techniques optimize the overall operation of the converter topologies. The control parameters for DC-DC converters include input voltage, duty cycle ratio, reference voltage, and output voltage. Based on these parameters, a specific control technique can regulate the operation of the converters. For low input and output voltages, the control technique increases the duty cycle ratio to perform voltage step-up operations according to the reference output voltage. Conversely, if the input and output voltages are higher, the control technique reduces the duty cycle to perform voltage step-down operations. The control technique is applied in various scenarios to achieve optimum control of the DC-DC converters, ensuring that the switching operation meets the output requirements [151]. Numerous control techniques with different features, such as response time, efficiency, and robustness, are available [152], [153]. Different converter topologies possess unique characteristics that are considered before integrating them with DC-DC converters. However, it is not possible to optimize all aspects of the control technique simultaneously, necessitating trade-offs for certain parameters based on the priority of application requirements. Furthermore, specific converter topologies are best suited with control techniques [190], making them a significant combination for various applications.

A. PULSE WIDTH MODULATION CONTROL

Pulse width modulation (PWM) has been one of the most conventional modulation techniques for switching DC-DC converters. It compares the error signal with a sawtooth wave to generate the control pulse. Conventional PWM control technique suffers from slow dynamic response due to smooth error signal variation under step line or load variation. The pulse width modulation DC-DC converter attains a significant increase in voltage output using the right duty ratio, along with a coupled inductor and voltage multiplier technique.

The energy stored in the leakage inductor of the coupled inductor can be reused. Additionally, as both the primary and secondary switches can be activated with zero-voltage

TABLE 11. Parameter comparison of non-isolated DC-DC converter topologies.

Efficiency	Voltage Stress/ Switching Loss	Output voltage	Voltage Gain	References
$\frac{P_o}{P_o+P_{SW}+P_D+P_L+P_C}$	$\left(\frac{f_S(t_{ON}+t_{OFF})}{2D(1-D)}+\frac{f_S(t_{ON}+t_{OFF})}{2(1-D)}+\frac{R_{S1}D}{(1-D)^4R_o}+\frac{R_{S2}D}{(1-D)^2R_o}\right)P_o$	$\frac{V_{C1}D}{(1-D)}$	$\frac{D_1}{(1-D_1)(1-D_i)}$	[5]
$\frac{P_o}{P_o+P_{loss}}$	$\frac{(1+D)V_o}{3+D}$	$\frac{3+D}{(1-D)^2}V_{in}$	$\frac{3+D}{(1-D)^2}$	[4]
$\frac{V_2/V_1}{\frac{(1+d_1)}{(1-d_1-d_2)}+\frac{2\pi V_1^2C_1d_1}{T_s}+P_{SW}}$	$\frac{1}{T_S}\begin{pmatrix}(t_{r1}+t_{f1})(V_{s1}*I_{S1})\\+(t_{r1}+t_{f1})(V_{s1}*I_{S1})\\+(t_{r1}+t_{f1})(V_{s1}*I_{S1})\end{pmatrix}$	$\frac{V_1(1+d_1)}{R(1-d_1-d_2)}+V_1I_{C1}d_1+P_{S-sw}$	$\frac{(1+d_1)}{(1-d_1-d_2)}+\frac{2\pi V_1^2C_1d_1}{T_s}$	[23]
$\frac{M(1-D)}{2(n+1)}$	$\frac{V_0}{2(n+1)}$	$2n+2$	$\frac{2(n+1)}{1-D}$	[28]
$\frac{1}{1+\left(P_{loss}/P_o\right)}$	$\frac{V_0}{M+1}$	$M+1$	$\frac{M+1}{(1-D)^2}$	[29]
$\frac{P_o}{P_o+P_{SW}+P_D+P_L+P_C}$	$\frac{1}{2}I_{rms}^2R_{DS,on}+\frac{1}{2}C_{oss}V_{DS}^2f_{sw}+C_{snub}V_{DS}^2f_{sw}$	$\frac{1}{2}\left[\frac{V_1}{2}\left(n+\sqrt{n^2+\frac{4D_1^2}{k_1}}\right)+\frac{V_2}{2}\left(n+\sqrt{n^2+\frac{4D_2^2}{k_2}}\right)\right]$	$\frac{n(D_1+D_1')}{D_1'}$	[34]
$\frac{P_o}{P_o+P_{loss}}$	$\frac{k}{5Nk+(7k-2)}V_0$	$\frac{5Nk+(7k-2)}{1-D}V_{in}$	$\frac{5N+5)}{1-D}$	[35]
$\frac{P_o}{P_o+P_{loss}}$	$f_sC_s\left(\frac{V_{in}}{(1-d)}\right)^2$	$\frac{(1-d_1)V_{in1}}{(1-2d_1)}, \quad \frac{(1-d_1)V_g}{(1-2d_1)}$	$\frac{(1-d)}{(1-2d)}$	[36]
$\frac{P_o}{P_o+P_{loss}}$	$\frac{1}{(1-D)G_t}+\frac{1+n_sD}{(1-D)^2G_t}$	$\frac{(1+n_{s1})(1+n_{s2})D}{(1-D)^2}V_{i1}+\frac{1+n_{s2}D}{1-D}V_{i2}$	$\frac{(1+n_s)^2D}{(1-D)^2}+\frac{1+n_sD}{1-D}$	[58]
$\frac{V_oI_o}{V_oI_o+(I_{La}^2+I_{Lb}^2)R_L+(I_{Sa}^2+I_{Sb}^2+I_{Sc}^2+I_{Sd}^2)R_{ON}+(I_{Da}^2+I_{Db}^2+I_{Dc}^2+I_{Dd}^2)R_D}$	$V_o(1-\alpha_4)+V_1(3\alpha_2-1)+V_2(2-\alpha_1+3\alpha_2)+V_3(1-2\alpha_3)$	$\frac{[1+(\alpha_2+\alpha_3)(\alpha_4-2)]V_1+(2-\alpha_4)[(\alpha_1+\alpha_2)V_2+\alpha_3V_3]}{(1-\alpha_4)^2}$	$\frac{D}{2(1-D)}$	[79]
$\frac{P_u}{P_a}$	$R_{on_{Mos}}I^2_{Lieff,(0-d_2T)}$	$\widehat{V_1}=H_{11}\widehat{d_1}+H_{12}\widehat{d_2}+P_{11}\widehat{u_e}+P_{12}\widehat{\iota_{ch1}}+P_{13}\widehat{\iota_{ch2}}$ $\widehat{V_2}=H_{21}\widehat{d_1}+H_{22}\widehat{d_2}+P_{21}\widehat{u_e}+P_{22}\widehat{\iota_{ch1}}+P_{23}\widehat{\iota_{ch2}}$	--	[84]
$\frac{P_O}{P_O+P_S+P_C}$	$\frac{1}{6}R_Lf(t_{on}+t_{off})P_0$	$V_{01}=D_1V_{DC}$ $V_{02}=D_2V_{DC}$	--	[94]
--	$\frac{V_o}{m}$	$\frac{m}{1-D_{n+1}}[D_1V_1+\sum_{j=2}^{n}(D_j-D_{j-1})V_j]$	$\frac{m}{1-D_{n+1}}$	[142]

switching, the soft-switching technique helps in decreasing switching losses [178]. A simple Pulse Width Modulation (PWM) control technique is used in DC-DC converters to efficiently regulate the output voltage. It involves varying the duty cycle of a high-frequency square wave generated by a switching element (such as a MOSFET) in response to

TABLE 12. Design consideration of non-isolated DC-DC converter topologies.

Inductor Design	Capacitor Design	Reference
$L_{m1} \geq \frac{D(1-D)V_{in1}}{(5N+5)I_o f_s}$, $L_{m2} \geq \frac{D(1-D)V_{in2}}{(5N+5)I_o f_s}$	$C_1 \geq \frac{NI_oD}{1\%(1-D)V_{C1}f_s}$, $C_2 \geq \frac{2I_oD}{1\%(1-D)V_{C2}f_s}$ $C_3 \geq \frac{3I_oD}{1\%(1-D)V_{C3}f_s}$, $C_{4,5} \geq \frac{I_oD}{1\%(1-D)V_{C4,5}f_s}$ $C_o \geq \frac{I_oD^2}{2\%(1-D)V_{Co}f_s}$	[35]
$L_{1g} = \frac{R(1-2d)}{x_{L_1}\%f_s d}$, $L_2 = L_3 = \frac{R(1-2d)}{x_{L_{2,3}}\%f_s d}$	$C_1 = \frac{d}{x_{C1}\%R(1-2d)f_sD}$, $C_2 = C_3 = \frac{d}{x_{C1}\%R(1-2d)f_sD}$	[36]
$L_{1a} = \frac{(1-d_1)^2 d_1 V_1 R}{2V_o f}$, $L_{1b} = \frac{(2-d_1)d_1 V_1 R}{2V_o f}$ $L_{2a} = \frac{(1-d_2)^2 d_2 V_2 R}{2V_o f}$, $L_{2b} = \frac{d_2 V_2 R}{2V_o f}$	$C_1 = \frac{V_o}{RfV_1(x_{C_1}^{\%})}$, $C_2 = \frac{d_2V_o}{RfV_2(x_{C_2}^{\%})}$ $C_{m1} = \frac{V_o}{Rf(x_{C_{m1}}^{\%} * v_{C_{m1}})}$, $C_o = \frac{d_1}{Rf(x_{C_o}^{\%})}$	[40]
$L_1 = \frac{V_{PV}}{\Delta i_{L1} f_s} k_{S1}$, $L_2 = \frac{V_{PV}+V_{C1}}{\Delta i_{L2} f_s} k_{S2}$	$C_1 = \frac{V_o}{R\Delta V_{C1} f_s (1-k_{S1})} k_{S1}$, $C_o = \frac{V_o}{R\Delta V_{Co} f_s} k_{S2}$	[45]
$L_a = \frac{V_2(\propto_1 + \propto_2) + V_3 \propto_3 + V_1(\propto_4 - \propto_3 - \propto_2)}{f\Delta i_{La}}$ $L_b = \frac{V_2(\propto_1 + \propto_2) + V_3 \propto_3 + V_1(\propto_4 - \propto_3 - \propto_2)}{f\Delta i_{La}}$	--	[79]
$L_1 = \frac{TV_{in}(D_2 - \frac{1}{2})}{\Delta i_{L1}}$ $L_2 = \left(\frac{V_{01}}{2} - V_{02}\right)\frac{T(1-D_1)}{\Delta i_{L2}}$	$C_1 = \left(i_{L1} - i_{L2} - \frac{V_{01}}{R_{01}}\right)\left(\frac{1-D_1}{\Delta V}\right)T$ $C_2 = \left(i_{L1} - \frac{V_{01}}{R_{01}}\right)\left(\frac{1-D_1}{\Delta V}\right)T$	[81]
$L_1 = L_2 \geq \frac{RD(1-D)^2}{16 f_s}$	$C_1 = \frac{2V_0}{R\Delta V_{C1} f_s}$, $C_2 = \frac{DV_0}{R\Delta V_{C2} f_s}$ $C_3 = \frac{DV_0}{R\Delta V_{C3} f_s}$, $C_4 = \frac{(1+D)V_0}{R\Delta V_{C4} f_s}$	[85]
$L_{1min} = \frac{R_{L1max}(1-D_{1min})}{2f}$ $L_{2min} = \frac{R_{L2max}(1-D_{2min})}{2f}$	$C_{1min} = C_{2min} = \frac{D_{max}}{2r_c f_s}$	[94]
$L_1 = \frac{V_i D_1}{f\Delta I_{L1}}$ $L_2 = \frac{V_i D_2}{2f\Delta I_{L2}}$	$C_1 = \frac{V_1 D_1}{fR_1\Delta V_1}$ $C_2 = \frac{V_2 D_2}{2fR_2\Delta V_2}$	[112]
$L_{1min} = L_{2min} = \frac{2}{27}\frac{R_{L\,max}}{f_s}$ $L_{3min} = \frac{R_{L\,max}(1-D_{min})}{f_s}$	$C_{1min} = \frac{D_{max}V_{01}}{V_{CPP}R_{L1max}f_s}$, $C_{2min} = \frac{D_{max}V_{02}}{V_{CPP}R_{L2max}f_s}$ $C_{3min} = \frac{D_{max}}{2r_c f_s}$	[115]
$L_1 > (V_i D_1)/(2I_{L1} f_s)$ $L_2 > (V_i - V_{02})(1-D_2)/(2I_{L2} f_s)$	$C_{1min} = \frac{D_1 T_s({}^{I_{01}}/{}_{D_1})}{\{0.01V_{C1} - r_{C1}I_{01}/[D_1(1-D_1)]\}f_s}$ $C_{1min} = \frac{[I_{L1} - I_{02}/(1-D_1)](1-D_1)}{\{0.01V_{C2} - r_C[I_{L1} - I_{02}/(1-D_1)]/D_1\}f_s}$ $C_{01ESR} = \frac{(1-D_1)I_{01}}{[(0.01V_{C01} - r_c I_{01}/D_1)f_s]}$, $C_{01THT} = \frac{1}{[0.01R_{01}(0.1f_s)]}$ $C_{02ESR} = \frac{(D_2 I_{02})}{[(0.01V_{C02} - r_c I_{L2})f_s]}$, $C_{02THT} = \frac{1}{[0.01R_{02}(0.1f_s)]}$	[117]
$L \geq \frac{V_{01}+V_{02}}{2I_L f_s}$	$C_1 > \frac{I_{01}D_{S1}}{2V_{01}f_{S1}}$, $C_2 > \frac{I_{02}D_{S2}}{2V_{02}f_{S2}}$	[125]
$L_1 \geq \frac{D_1(1-D_1)V_{in1}}{2f_s \propto_1 I_{out1}}$, $L_2 \geq \frac{D_2(1-D_2)V_{in2}}{2f_s(\propto_2 I_{out1} + \beta_2 I_{out2}}$ $L_3 \geq \frac{D_3(1-D_3)V_{in3}}{2f_s(\beta_3 I_{out2} + \cdots)}$, $L_a \geq \frac{D_a(1-D_a)V_{in1}}{2f_s \propto_a I_{out1}}$, $L_b \geq \frac{D_b(1-D_b)V_{in2}}{2f_s(\propto_b I_{out1} + \beta_b I_{out2}}$, $L_c \geq \frac{D_c(1-D_c)V_{in3}}{2f_s(\beta_c I_{out2} + \cdots)}$	$C_{out_k} = \frac{I_{out_k}}{f_s \Delta V_{out_k}}$	[126]

TABLE 13. Comparison of non-isolated DC-DC converter topologies.

Converter Topology	Features	Benefits	Drawbacks	References
High Gain Transformerless Double-Duty-Triple-Mode DC-DC Converter	Complexity is Medium It Requires Precise Control. Cost is Moderate. Size is Medium.	Output is non-inverting. High output gain without the use of sophisticated procedures. applications with low input power (RES)	Voltage fluctuations during switching modes. Transient problem is brought on by capacitor charging and diode reverse recovery. Control the double duty cycle requires efficient control technique. Unidirectional power flow.	[23]
The High Gain Three-State Switching Hybrid Boost Converter	Complexity is Medium It Requires Precise Control. Cost is Moderate. Size is Medium.	Output is non-inverting. Duty cycle ratio is low. Output gain is high with voltage lift technique. Utilized for renewable energy application.	Control the double duty cycle requires efficient control technique. Unidirectional power flow. Transient problem is brought on by capacitor charging and diode reverse recovery. Transitions in the duty cycle are changed.	[24]
High step-Up DC-DC Converter	Complexity is Medium It Requires Precise Control. Cost is Moderate. Size is Medium.	Output is non-inverting. Capacitive filter values required less. Low input ripples and soft switching. Common ground for input and output.	Suitable for multi-input configuration. None of the switches should have a duty cycle of less than 50%. Due to coupled inductors, input conduction losses will occur.	[28]
Non-isolated high gain Quadratic boost DC-DC converter	Utilizes one switch that is active. High conversion ratio for voltage. Low voltage puts semiconductors under stress.	Diode -capacitor multiplier (VM cell) is added. Simplifies gate drive circuit, since additional switch is not added. Depends on number of multiplier cells.	Large voltage gain can achieve with coupled inductor.	[29]
Dual input DC-DC Converter	Medium complexity. Elimination of magnetic inductance saturation.	Soft-switched and integrate two low voltage energy sources. Voltage fed input structures with high current.	Dynamic performance load variation and source disturbance. Inherent overshoot, steady state error Suitable for multi-input configuration.	[34]
Couple Inductor High Step-Up DC-DC Converter	Independent power transfer to load. Medium size. Moderate cost.	Less voltage stresses. Common ground for input and output. Less EMI influences.	Lack of extendable input. Generates common and differential mode noises. VMCs blocked the voltage stress across switches.	[35]
High gain Z-Quasi Resonant DC-DC Converter	Individual energy glide manipulates.	High gain with low duty cycle. No isolation. Moderate cost.	High gain ZQR DC/DC Converter with multiple EV. Optimized control strategy for charging and discharging of battery. Winding conduction loss is more evident in maximum gain.	[36]
Non-Isolated High-Gain Triple Port DC-DC Converter	Medium complexity. Positive voltage polarity is maintained. Medium size.	Integrating with bidirectional converter. Simple working. Higher conversion gain. Simple circuitry arrangements.	It provides robust option for interfacing multiple renewable energy sources. Two unidirectional and one bidirectional power flow.	[45]
Non-Isolated DC-DC converter with High voltage gain and Zero ripple current	Medium complexity. Low voltage stress on switches. Input current ripples is almost zero with constant DC value.	High voltage gain. Achieving one voltage gain for whole range of duty cycle. Voltage regulation controller is simpler. Low cost on implementation of driver modules.	Number of inputs can be extended. Provided power of each converter with the extracted efficiency for the operating power rating.	[58]
Multilevel High Step-Up DC-DC Converter	Less components compared to counterparts. Medium size.	High output voltage-gain without using high duty rates. Absorbing energy simultaneously from several input sources. Simple PWM switch control method.	N number of inputs and M-level of converters can be extended. Diode-capacitor cell is used to enhance output voltage level. Current stress on each input voltage is reduced.	[59]
A Novel Step Up Multi-input DC DC Converter for Hybrid Electric Vehicles Application	High energy density. Temperature performance is high. Recyclable of Li-ion batteries.	In the absence of one or two resources, the converter can supply the required power to the load.	Since initial cost of PVs is high.	[80]

TABLE 13. ***(Continued.)*** **Comparison of non-isolated DC-DC converter topologies.**

High Gain SIDO DC-DC Converter	Voltage gain is 4 times higher than conventional boost converter. Continuous input current. Switches and diodes stress Voltages are low.	High gain voltage employs same gate pulse for two switches. Easy to control. Elements count is less.	Number of outputs can be extended. Switched capacitor network is used for high voltage gain.	[85]
Cost-efficient non-isolated three-port DC-DC converter	Handled diversified energy sources of different voltage. Delivering twice the input power from battery. TPB^2C is better performance.	The converter possesses a condensed configuration with fewer components and can provide power to the load.	The primary drawback is that a problem with one converter component will have an impact on the output of the entire converter system.	[116]
High step-up Transformerless DC-DC converter	Less component counts. Medium size.	Greater adaptability compared to analogue electronics. Ease of use. Reliability and stability will improve.	Expandable MIMO converter with high performance. Integration of energy source and deliver to multiple loads. Normalized low power stress on switches.	[117]
MIMO DC-DC converter without Energy Buffer Stages.	Combining of pulsating source cell and output filter cells.	Fewer passive components. Design, structure, and implementation is easy. Without energy buffer stages.	Low-power IoT applications. Generate various output voltages and distribute input power from multiple energy sources.	[121]
New High Step-Up MIMO DC-DC Converter	High output voltage levels. Diode capacitor VM stages can be utilized.	The capacity to utilize various input power sources. Being able to work at low and high-power levels. continuous current input	Simultaneously use the input source with different range of power feeding their output loads.	[126]
A Digital Method of Power-Sharing and Cross-Regulation Suppression for SI-MIMO DC–DC Converter	Variable switching frequency. Online optimization results in fast and dynamic response. Ability of power-sharing & cross-regulation suppression.	Load regulation, line regulation, response to output voltage reference step change, and response to input current reference step change make up the dynamic performance verification.	In continuous conduction mode, the cross-regulation issue with SIMO single inductor dc-dc converters exists.	[130]

an error signal derived from comparing the desired output voltage (reference voltage) with the actual output voltage.

The duty cycle determines the ON-time and OFF-time of the switching element, which, in turn, controls the average output voltage. By continuously adjusting the duty cycle based on the error signal, PWM control ensures stable and accurate output voltage despite changes in input voltage or load conditions. PWM control is widely used in various applications, including power supplies, motor drives, LED lighting, and more, due to its efficiency and versatility. In conclusion, implementing PWM for a DC-DC converter involves using a high-frequency switching element to regulate the output voltage by adjusting the duty cycle of the switch. This technique provides efficient voltage conversion, precise voltage regulation, and flexibility in adjusting output levels. To effectively translate and regulate DC voltage levels for various applications, it is frequently employed in electronics. Fig. 9 shows the basic structure of a multi-input multi-output converter.

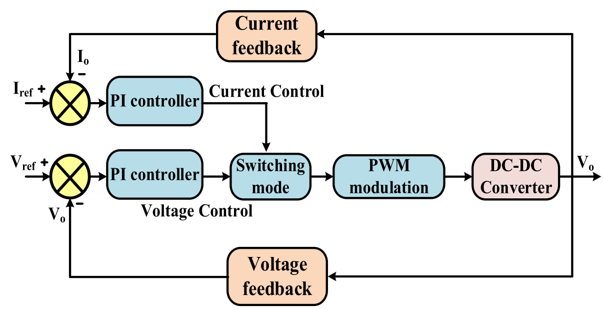


FIGURE 9. **PWM control techniques.**

B. HYSTERESIS CONTROL

A comparator generally changes its output states when the voltages between its inputs cross through approximately zero volts. However, the noise can cause voltage variations at the inputs, resulting in very quick changes between the two output states. Such unexpectedly quick changes may cause the converter to switch on or off unintentionally and at the wrong times. A small amount of hysteresis is added to the comparator to prevent this undesired output oscillation. A hysteresis comparator has two switching points: one switching point for rising voltages and another for falling voltages are present in a hysteresis comparator. A comparator gains hysteresis by including positive feedback. Hysteretic control (HC) operates

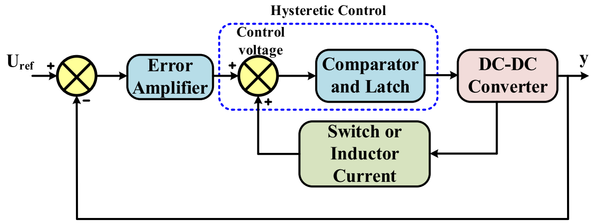


FIGURE 10. Hysteresis control techniques.

based on the concept of maintaining the output voltage within a specific hysteresis band centred around the desired set-point voltage of the converter. This method gives a quick reaction by avoiding the usage of slow feedback found in alternate methods. It also enables more configuration flexibility without any forced constraints. The duty cycle can be changed in the full range from 0 to 1. The dynamic control properties of hysteretic control allow for a reduction in the size of output filters, leading to decreased overall costs of DC-DC converters. Fig. 10 illustrates a schematic representation of a DC-DC converter employing the Hysteretic Control (HC) method [176]. The extent of the hysteresis range and any overshoot, which can be brought on by signal delays and the converter's structural properties, affect the amount of ripple in the output voltage.

In conclusion, implementing hysteresis control for a DC-DC converter is a simple and responsive feedback technique used in DC-DC converters. By comparing the output voltage to upper and lower thresholds (hysteresis band), it controls the output voltage and rapidly modifies the switching element in response to these thresholds. With this method, rapid voltage regulation, less ripple, and resistance to change are all guaranteed. However, it might not be precise enough and needs careful planning to prevent instability. Low-power converters for mobile devices and scenarios requiring prompt and accurate voltage regulation frequently employ hysteretic control.

C. PROPORTIONAL INTEGRAL DERIVATIVE CONTROL

The proportional integral derivative (PID) control is the most commonly used control technique in various industries and has gained universal acceptance for numerous applications, including renewable energy and motor drive systems. The preference for PID control over other techniques stems from its robust response across a wide range of operating conditions and its simple functionality, as demonstrated in Table 14. Despite being a conventional and effective control method, PID is still widely integrated into numerous applications, and one such example can be observed in Fig. 11, where PID control is employed to regulate the DC-DC converter. The PID control method works by receiving data from the DC-DC converter's output and modifying the input switching duty cycle, which controls gain. In many cases, this method delivers minimal efficiency. When compared to other control systems, PID has the additional benefit of having a low

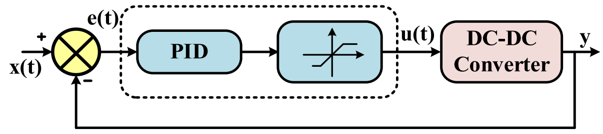


FIGURE 11. PID control with limitation techniques.

control complexity. In addition, there are ongoing initiatives to improve control and effectiveness in renewable energy applications [161], [162] by fusing PID with contemporary control methods, creating hybrid control systems that take advantage of the advantages of both methodologies. This hybridization is proving to be beneficial in achieving improved performance and efficiency in renewable energy systems.

In conclusion, one common method for controlling the output voltage or current of DC-DC converters is to use PID controllers. Proportional (P), integral (I), and derivative (D) terms are its three constituent parts. Current error is addressed by the P term, steady-state errors are eliminated by the I term, and future error changes are anticipated by the D term. PID controllers that have been properly tuned provide precise, reliable, and rapid regulation, enabling them to adapt to various conditions. Tuning complexity, noise sensitivity, and possible nonlinearities are difficulties. Despite these difficulties, PID control is frequently employed in DC-DC converters due to its adaptability and efficiency in establishing precise and responsive control.

D. MODEL PREDICTIVE CONTROL

The model predictive control (MPC) method falls under the category of non-conventional control techniques. Model predictive control techniques can be divided into two main categories: Continuous Control set MPC (CCS-MPC), and Finite Control-States set MPC (FCS-MPC). In CCS-MPC, a modulator generates switching signals from the continuous output of the predictive controller, yielding a constant switching frequency. On the other hand, FCS-MPC provides a benefit by addressing the optimization problem by using a constrained set of switching states.

The main advantages of FCS-MPC are a decreased computing load and the direct application of control actions to the converter without the requirement for a modulation stage [154]. The control algorithm is derived from the system's model to forecast future values of the controlled system. In renewable energy applications [155], MPC is infrequently mentioned as a means for coordinating multiple non-isolated DC-DC converters. MPC operates through a feedback loop that employs a control algorithm and based on increased stability for DC bus voltage for supplying loads is considered in [156]. However, virtual synchronous control is still in the promotion stage and requires to be further explored for the undesired transient instability and overcurrent. Power electronic converter-based MPC, including continuous control set MPC (CCS-MPC) and finite control set MPC

TABLE 14. **Characteristics of control techniques.**

Control Technique	Advantages	Limitations	Features	Ref
Pulse Width Modulation (PWM)	PWM provides more efficient controlling power compared to linear control methods. precise control over the output voltage. It can help in reducing electromagnetic interference (EMI)	Losses can reduce overall efficiency, especially at higher switching frequencies. Design and tuning a feedback control system can be complex and require careful consideration of stability and dynamic response.	It can be easily adapted to different input and output voltage levels. The rapid switching action helps in reducing high-frequency harmonics that contribute to EMI	[178]
Model Predictive Control (MPC)	Effective tracking using strategies based on estimation. Performance optimization for transients under external limitations. Quick response.	High computational. Detailed model should be known. Circuit parameters are sensitive	Iterate online is easy. Non-linear control and robust. Future state predictions.	[157]
Proportional Integral Derivate (PID)	Implementation is simple. Transient response is faster. Integration with numerous control techniques is easy.	It cannot respond to External disturbance load variation Overshoot, steady state error, and settling time is high.	Easy implement. Complexity is low. Suitable for linear control.	[161]
State Space Modeling (SSM)	Transient response will be improved. Load varying with less overshoots.	Detailed model should be known. Initial implementation requires more time.	It is suitable for MIMO systems. Non-linear control.	[163, 164]
Sliding Mode Control (SMC)	Implementation is simple. It can respond for external disturbance.	Chattering problems due to discontinuous control law. High overshoots.	It has robust control. Converge towards sliding surface.	[165, 166, 179]
Fuzzy Logic Control (FLC)	Less overshoots. Tracking response is efficient. Mathematical model is not required.	High computational burden. Settling time is high. It requires rule's for operation.	Robust and non-linear control. Stability over large variations. Suitable for systems having vague boundary conditions.	[168, 170, 174]

(FCS-MPC), is used to determine optimal switching states of semiconductor switches at the device level to achieve AC/DC, DC/DC or AC/AC power conversion and to stabilize voltages, currents, and different Master-Slave controllers were proposed in [157]. Similarly, more advanced predictive control with new mathematical formulations and holistic intelligent schemes plays a significant role in microgrids, especially in areas like DC microgrids and networked microgrids. The predictive control approach starts with the basic principle and it is applied in three control layers of microgrid hierarchical control. Additionally, the benefits of flexible integration of objectives, faster dynamic responses, challenges and limitations are analysed in [158]. Direct MPC is used to optimize the power flow between the energy sources and the motor. However, the designed MPC may produce better results because it is inherently more robust & better at disturbance rejection [159]. Furthermore, [160] improved the MPC by introducing a multi-level optimization approach in the aerodynamic prediction model of a flapping-wing.

As seen in Table 14, MPC demonstrates the ability to control multi-input, multi-output (MIMO) systems. The fact that it is a multivariable controller, which successfully manages numerous outputs and interactions between system variables at once, is its greatest advantage. MPC also contributes significantly to several other areas, including considerable cost function minimization, operational cost reduction, economic load dispatch, and optimized power flow management. Controlling a DC-DC converter is a critical task, even though the converter topology is highly efficient. The control technique

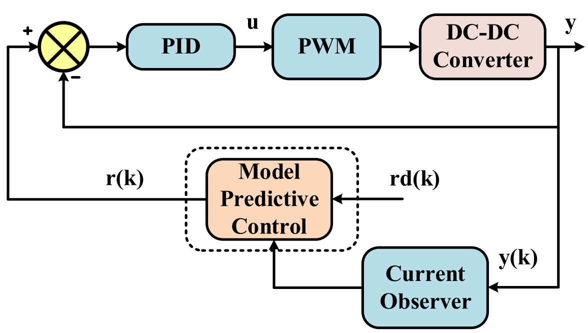


FIGURE 12. **MPC control techniques.**

must be responsive to the intermittent changes and uncertain behaviour that may occur in the DC-DC converter. The contemporary predictive control technique (MPC) is implemented for the DC-DC converter, as shown in Fig. 12. The control method uses the algorithm to forecast future values using the output feedback from the DC-DC converter. The control process is improved by this prediction capability, which results in a more seamless output operation. It is significant to note that changes related to the load being handled may occur at the input side as well as the output side of the DC-DC converter.

MPC can perform better than conventional control systems for DC-DC converters, especially when there are restrictions or disruptions. Additionally, it can be utilized to reduce energy consumption or improve the converter's performance under various operating conditions.

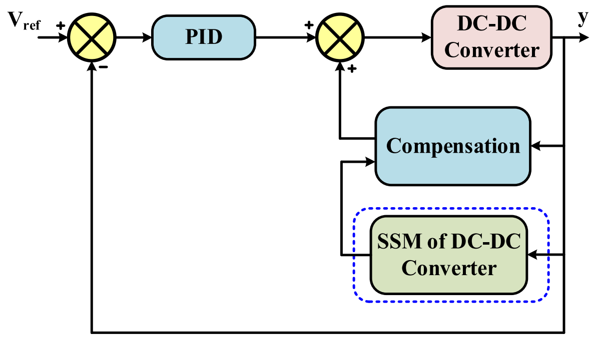


FIGURE 13. SSM control techniques.

In conclusion, to implement MPC for a DC-DC converter, we must:

a. Create a system model using state space modelling.

b. Create a cost function that measures how well the control technique performs.

c. To determine the ideal control action, solve an optimization problem at each time step.

d. Have the DC-DC converter carry out the control function.

E. STATE SPACE MODELLING CONTROL

State Space Modelling (SSM) is a mathematical approach used to represent a physical system using a set of inputs, outputs, state variables, and differential equations. It involves two types of equations known as the state equations. The order or complexity of an SSM, i.e., the number of differential equations required to represent a physical model, is determined by the number of input and output variables present in the corresponding physical system [163], [164]. By decomposing complex systems into state variables and the corresponding equations, SSM offers a systematic and thorough technique to characterize the dynamics and behaviour of complex systems. Numerous engineering disciplines use this modelling technique extensively because it enables the investigation, control, and optimization of dynamic systems. Using a time domain technique, it can easily depict higher-order physical systems. SSM-based control may analyse any non-linear system with many inputs and outputs since fundamental representations of physical systems are a prerequisite [191].

In Fig. 13, the implementation of the state space modelling technique for controlling the operation of the DC-DC converter is illustrated. State space modelling is a mathematical control technique that employs a mathematical model to regulate different states of the system. One of its key advantages is its higher efficiency compared to other control techniques. Additionally, it proves to be very effective when iterating parameters, facilitating fine-tuning for optimal performance. State space modelling stands out for its potential to reduce system complexity, which cuts down on calculation time. It streamlines control and enables quicker and more effective computations by simplification the system's representation. This trait is especially useful in situations where a prompt or real-time response is essential.

The state space model can be used to analyse the behaviour of the DC-DC converter under different operating conditions, such as changes in the input voltage or load current. It can also be used to design control strategies to regulate the output voltage of the converter.

In conclusion, to model the state space of a DC-DC converter, we must:

a. List the system's state variables, including the output voltage, inductor current, and capacitor voltage.

b. Create the equations that explain the state variable dynamics.

c. Combine the equations to create a group of first-order differential equations, which represent the system's state space.

d. Analyse the converter's behaviour and create control plans, using the state space model.

F. SLIDING MODE CONTROL

A non-linear discontinuous control method is sliding mode control (SMC). Even in the presence of external shocks and uncertainty, SMC can function properly. To reduce the error, the system converges to the sliding surface and seeks to glide on the sliding surface for continuous stability. During this process, an error known as the chattering effect is noticed [165], [166], [167]. The chattering effect is the oscillation that can be seen before the system tends to operate in constant sliding mode. SMC is combined with a variety of additional control methods to combat the chattering fault. Drive control, RES generation, and electric vehicles are just a few of the industries that can benefit from adaptive and reliable slide mode control technology. Maintaining output values that are equivalent to or nearly like the values assigned on the sliding surface is the goal of slide model-based control. In Fig. 14, the Sliding Mode Control (SMC) technique is integrated with the DC-DC converter topology to achieve optimum operation even during varying load conditions. The feedback from the system is fed into the SMC, which uses this information to perform iterations and determine the appropriate switching operation of the DC-DC converter. Sliding Mode Control is a robust control technique that aims to keep the system on a predefined sliding surface, ensuring stability and accurate tracking of desired outputs. By continuously adjusting the control inputs based on the system's state and reference trajectory, SMC can handle uncertainties and disturbances, making it suitable for applications with changing load conditions. By integrating SMC with the DC-DC converter, the system can adapt and respond effectively to load variations, ensuring stable and efficient operation under different circumstances. An integral terminal term is considered in the proposed control approach to increase convergence time and decrease steady-state tracking error [184]. The suggested controller has excellent transient stability performance during operating point changes such as dramatic shifts in load demands, solar irradiance fluctuations, and so on.

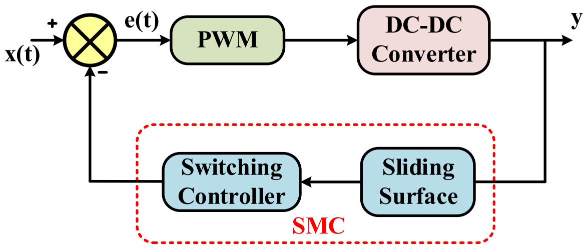


FIGURE 14. SMC control techniques.

Sliding Mode Control (SMC) is a robust technique used in DC-DC converters for regulating output voltage or current. It guides the system onto a predefined sliding surface in the state space, where dynamics maintain stability despite uncertainties and disturbances. SMC consists of switching and reaching control terms, ensuring accurate regulation and fast responses. It excels in uncertain conditions and doesn't rely heavily on precise modelling. However, challenges include the potential for chattering (high-frequency oscillations) and the need for skilful design. SMC offers resilience, adaptability, and rapid control in challenging scenarios, making it a valuable choice for DC-DC converter regulation.

In conclusion, to model the sliding mode control of a DC-DC converter, we must consider:

a. A reliable control method for managing the output of power converters (such as DC-DC and AC-DC) is sliding mode control. Creating a sliding surface that depicts the required system behaviour is necessary.

b. The control law that consists of reaching and sliding control terms to drive the system state to the sliding surface and maintain it there.

c. The system enters a sliding mode while it is on the sliding surface, making it immune to uncertainties and disturbances.

d. The main challenge is dealing with chattering, high-frequency oscillations that may arise during sliding mode.

e. Sliding mode control is appropriate for applications with uncertain or changing parameters because it gives resistance to parameter fluctuations and external disturbances.

G. FUZZY LOGIC CONTROL

Fuzzy Logic Control (FLC) belongs to the category of non-conventional and non-linear control techniques. It operates based on a heuristic approach that imitates the human thought process. To implement this thought process, FLC requires predefined rules. Linguistic rules are established for the input and output of the system, represented as membership functions. Compared to State Space Modelling (SSM), FLC is thought to be somewhat simpler because it doesn't call for an accurate mathematical description of the system. It also has nonlinearity handling capabilities, like Model Predictive Control (MPC) and SSM. The unique control process of FLC involves taking feedback in the form of crisp values from the system, converting it into linguistic form, and then comparing it with the membership functions, a process commonly known as fuzzification. FLC is suitable for systems with ambiguous or imprecise input because it can produce control decisions that are easier to understand and intuitive by employing these linguistic norms. After fuzzification, Fuzzy Logic Control (FLC) converts the linguistic form back into a crisp value, which is known as defuzzification. This process allows FLC to produce a precise and actionable control output based on fuzzy rules and linguistic variables. FLC does provide effective solutions, especially when it comes to tracking behaviour in non-linear control systems that may have confusing boundary conditions. It is ideal for a variety of real-world applications due to its capacity to manage ambiguous and imperfect information. However, like any control technique, FLC also has its drawbacks. One of the main concerns is the higher computational time, which can limit its real-time applicability in some cases. To address this issue, FLC is often integrated with other control techniques and used in offline mode [168]. By combining the strengths of FLC with other control methods, engineers can leverage the advantages of both approaches while mitigating the computational time limitations of FLC as illustrated in Table 14. This hybrid approach allows for improved performance and efficiency in control systems that require both accuracy and real-time responsiveness.

FLC is used in both household and industrial applications as a reliable control method. The autonomous automobile braking system and the charge control in electric vehicles also use FLC in the automotive industry [169], [170]. Additionally, it is used to monitor and direct maritime surface vessels and undersea vehicles [171]. Fuzzy Logic Control (FLC) is a versatile and effective control technique that finds applications in various domains, including both domestic and industrial settings. In the automotive sector, FLC is employed in advanced driver-assistance systems (ADAS), particularly for automatic car braking systems. By using FLC, the braking system can make real-time decisions based on inputs from sensors and the driving environment, leading to enhanced safety and collision avoidance. FLC is also utilized for charge control in electric vehicles, helping to optimize battery charging and discharging processes, thereby extending battery life FLC has also opted for industrial applications and the power generation sectors improving overall efficiency [173]. [172], [173], [174]. Multi-input non-isolated DC-DC converters used in power generation have FLC applied to them so they can run in a boost mode under a grid-connected scheme [175]. With the help of this application, renewable energy sources can be integrated into the grid and converted to power efficiently. The control design of a DC-DC converter using a fuzzy logic controller is shown in Fig. 15. FLC is a useful tool in a variety of applications because of its adaptability and capacity to manage challenging and uncertain circumstances, offering effective and intelligent control solutions for numerous systems and processes.

H. MAXIMUM POWER POINT TRACKING CONTROL

A solar panel or any other renewable energy source with variable output characteristics, like wind turbines, can be

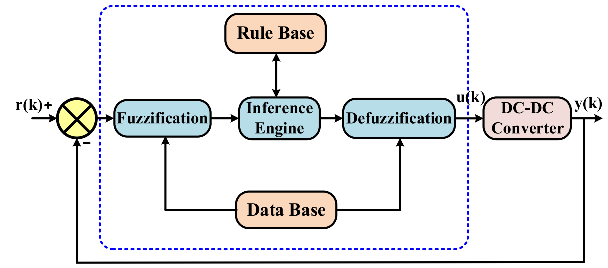


FIGURE 15. FLC Control Techniques.

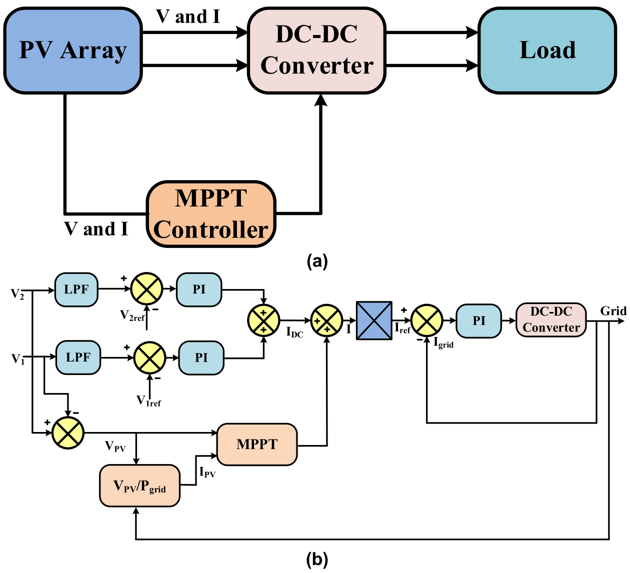


FIGURE 16. (a) Block diagram of the controlled MPPT system for DC-DC converter, (b) Scheme of the control system including the MPPT.

controlled to provide the most power possible using the MPPT approach. The goal of MPPT is to position the DC-DC converter so that it operates at the point on the IV curve, or voltage-current curve, of the source where the most power is being generated. With MPPT, power extraction from PV modules is optimized for a variety of environmental factors, particularly solar irradiance and temperature. By lining up the PV modules' Maximum Power Point (MPP) with the converter's operational voltage and current, this optimization is made possible. The fundamental block diagram of a typical PV system with MPPT and control scheme system including MPPT is shown in Fig. 16 (a -b). The DC-DC converter can be replaced with an inverter, which can then be connected to the utility grid, to transform the stand-alone DC-DC system seen in the diagram into a grid-connected system. The MPPT operates in the manner described below. An initial current and voltage sensor measures the current and voltage of the PV array. These numbers are passed into an MPPT block, which computes the MPP for that specific sampling cycle. The comparative chart of control techniques is illustrated in Table 15.

MPPT is crucial because it enables the system to continue operating at the MPP despite changes in the external environment. MPPT makes sure that the load receives the most power from the source by continuously altering the duty cycle or switching frequency of the DC-DC converter. It is necessary to use a maximum power point tracking (MPPT) controller to make fuel cell systems more effective. This study [186] proposes an effective approach for MPPT of proton exchange membrane (PEM) fuel cells based on particle swarm optimization (PSO) and PID controller (PSO-PID). The Perturb and Observe (P&O), Incremental Conductance, and Fractional Short-Circuit Current approaches, among others, are some of the MPPT algorithms that are used to do this. These algorithms keep track of the output power, voltage, or current and modify the DC-DC converter's operating point as necessary to maintain the MPP. To increase energy harvest and boost overall system efficiency, MPPT techniques are frequently utilized in solar power systems and other renewable energy applications. In such DC grid applications, a DC/DC converter is essential for interconnecting DC buses with different voltage levels, which needs to meet several requirements, including bidirectional power conversion capability, high power rating, high step-ratio, high power density, and high efficiency. A modified MPC MPPT [187] is based on a one-voltage sensor, one-current sensor, and one-output voltage observer.

In conclusion, MPPT maximizes energy conversion efficiency and overall energy yield by keeping operations close to the MPP and optimizing DC-DC converters for renewable energy systems.

1) PERTURBATION AND OBSERVATION (P&O)

The perturb and observe approach is straightforward, requires no prior understanding of the features of PV generators, or the measurement of solar intensity and cell temperature, and is simple to implement with analogue and digital circuitry. Even though the solar irradiance and cell temperature are constant, it disturbs the system's operating point, causing the terminal voltage of the PV array [182] to oscillate around the MPP value. Due to its ability to strike a compromise between performance and simplicity, it is also the most used and reliable MPPT algorithm. However, it struggles with a lack of speed and adaptability, both of which are essential for monitoring quick transients in a variety of environmental circumstances. In [181], fixed zone perturbs and observations (FZPO) are used to achieve efficiency, fast, and drift-free MPPT for PV systems. In the FC system, the MPPT controller, such as the perturbation and observation (P&O) is operated by the P–V curve of FCs. Finally, the activation voltage drop, ΔV_{act} can be expressed as follows [180]: where ϵ_i with i = 1, 2, 3, 4 represents the cell's parametric coefficient and C_{o2} is the dissolved oxygen concentration.

2) INCREMENTAL CONDUCTANCE (INCCOND)

The P&O approach has the two aforementioned significant drawbacks. (1) A minor power variation around the MPP is always present due to a constant amount of disturbance at the steady state, which adds to some power losses. (2) The

TABLE 15. Comparative chart of Control Techniques [177].

Control Technique	Design and Implementation	Operating Point	Reaction	Settling Time
Hysteresis Control (HC)	Design and implementation are simple. It doesn't required feedback.	The operating point variations and load disturbances are responds directly.	HC is free from disturbances. It provides stability against transient condition. Fast respond in dynamic responses.	Settling time is higher that MPC controller
Model Predictive Control (MPC)	Implementation has been restricted to slowly varying systems	suitability for directly addressing multi-variable systems. Controller behavior will be essentially linear.	MPC desaturation capabilities, without relying. It is still with tangible benefits.	Settling time is lower than FLC.
Proportional Integral Derivate (PID)	Design is simple. Self-governing model.	It won't react on operating point load disturbances. It operates directly on error signals.	PID cannot meet increasing necessities for fast dynamic response. High control accuracy.	Settling time is higher than SMC.
State Space Modeling (SSM)	Simple in design	Respond directly on large load disturbance	Better dynamic response.	Settling time is lesser than MPC.
Sliding Mode Control (SMC)	Execution and propose is extremely simple.	Unsettling influences are burden. Working point varieties react appropriately.	SMC is liberated from unsettling influences, and requirements. Lastingness against enormous aggravations. Unique reaction is quick.	Minimal settling time.
Fuzzy Logic Control (FLC)	Design and implementation are quite simple.	The operating point variations and load instability are responded directly	FLC is free from disturbances. It provides stability against large disturbances. Fast respond in dynamic response.	Settling time is higher than PID controller.

operating point is most likely to deviate from the genuine MPP in environments with fast environmental changes. To get around the drawbacks, the INC technique was suggested. Therefore, incremental resistance (ICR) rather than INC will be used to define the algorithm. The INC algorithm [189] is dependent on the perturbation value's "offset," just like the P&O algorithm. The large value of 'offset' will result in fast-tracking, but the system may oscillate at MPP. Instantaneous inductance (I/V) and incremental conductance (I/V) are not identical. In a double-stage configuration, the front-end DC-DC converter is used to extract the maximum power point tracking (MPPT) [174] power from the SPV array by using additional control. However, this issue can be solved with a smaller value of "offset," but tracking will become slower. As in the case of the P&O approach, the trade-off still exists. The fixed and adaptive values of "offset" can also be used to characterize two subgroups of the INC technique. Because they share the same purpose as the P&O approach, they are not described individually. Since INC and P&O are based on the same idea, INC is also unable to track the GMPP.

3) SOFT COMPUTING MPPT

For simplicity, they are grouped into several categories, and it is worth noting that for SC-based MPPT, not all techniques are used as MPPT controllers. Artificial Neural Network (ANN) is sometimes utilized to optimize certain parameters of other MPPT controllers [180], e.g. Fuzzy Logic Controller (FLC) [185], P&O [188] and HC. Furthermore, it is common to combine two or more techniques in a single MPPT controller. For example, ANN can be combined with FLC, or PSO with P&O. In most cases, the performance of the hybrid tends to be superior compared to a stand-alone SC method. Table 16 illustrates the comparison of different soft computing techniques. In Table 16, the standards for "fast" and "very fast" convergence are defined and differentiated based on the number of iterations required for convergence. For instance, a method may be categorized as having "fast" convergence if it typically converges within a moderate number of iterations in one minute, while a method classified as "very fast" convergence would converge in ten seconds significantly for fewer iterations.

VI. CHALLENGES AND FUTURE TRENDS

Recent research has extensively explored the modelling, design, and use of Multiport Converters across various applications, including hybrid generation systems, electric vehicles, fuel cells, uninterruptible power supplies, and microgrid telecom power systems.

A few key technical issues identified in Multiport converters are:

- ➢ Utilization of single energy sources at a given time, necessitates time-sharing concepts to mitigate power coupling effects, though imposing constraints on energy source utilization and output voltage due to duty ratio limitations.
- ➢ Limitations of existing solutions such as voltage dividers, lead to losses in passive components.
- ➢ Computational time and processing complexity emerge as significant challenges in addressing these technical issues and research gaps.

TABLE 16. Comparison of soft computing techniques.

Methods	PV array dependency	Convergence	Partial shading	Hardware implementation	Algorithm complexity
Fuzzy Logic Control (FLC)	Yes	Fast	Standalone – No coupled – yes	Easy	Moderate
Differential Evolution (DE)	No	Varies/ Fast	Yes	Easy	Moderate
Particle Swarm Optimization (PSO)	No	Fast	Yes	Moderate	Moderate
Ant Colony Optimization (ACO)	No	Fast	Yes	Moderate	Moderate
Artificial Neural Networks (ANN)	Yes	Fast	Standalone – No coupled – yes	Difficult	Moderate
Genetic Algorithm (GA)	No	Fast	No	Easy	Difficult
Bayesian network	No	Very fast	Yes	Difficult	Difficult
Chaotic search	No	Fast	Yes	Difficult	Very difficult
Non-linear predictor	No	Fast	No	Easy	Easy

These converters are useful for integrating diverse energy sources with varying power or voltage levels to achieve regulated output voltage. These converters follow specific operational conditions: a single energy source feeds the load at a given time, and time-sharing concepts are employed to avoid power coupling effects. However, this approach restricts energy source utilization and output voltage due to duty ratio constraints. By reducing operating time delays and implementing lower duty ratios, converter size can be reduced while maintaining output voltage quality, especially for applications requiring high voltage gain. Ensuring fault tolerance for alternate sources and switches is crucial in Multiport converter design.

A persistent challenge is the optimal control for both input and output voltages, particularly in cases requiring multiple output voltages. Existing solutions like voltage dividers cause losses in passive components. A proposed solution is creating new multi-input topologies that efficiently provide both DC and AC output voltages, reducing installation cost and size. Some efforts are also needed to enhance the optimal control of multiple outputs. While many converters can handle wide input voltage ranges, improvements are sought, especially for drawing energy from very low renewable energy sources. Future research should target circuit simplification, component reduction, enhanced voltage gain, and power scalability. These advances would lower costs, improve output, and contribute to the transition to renewable energy, making it imperative to address reliability, efficiency, and power loss issues in multi-input converters.

The evolution of hybrid control techniques is highlighted, comparing various methods in Table 14 based on features, advantages, and limitations. Factors such as response time, system complexity for higher-order systems, stability, and overshoots are considered. The simplest method, PID control requires basic parameter tuning but struggles with fast dynamic response, input imbalances, and optimization. SMC stands out for stable DC-DC converter operation during disturbances and rapid responses. However, it demands high switching frequencies, leading to efficiency loss. Multiport Converters are tailored to converter characteristics, and reduce losses by controlling duty cycles but are complex, especially with non-linear models. SSM excels in accuracy and robustness by aligning with converter energy equipment, accommodating nonlinearity easily. Fuzzy logic modern technique excels in tracking nonlinear systems with membership functions resembling human thinking, suitable for renewable energy control. Yet, it faces challenges of computational time and processing complexity.

VII. CONCLUSION

This review paper delved into the performance analysis of various non-isolated DC-DC converter topologies, emphasizing their application in renewable energy and hybrid vehicles. The advantages and drawbacks of multi-input converters, particularly in terms of reduced integration costs and improved reliability have been discussed. Various control techniques and ongoing efforts to enhance the efficiency and cost-effectiveness of multi-input converters have also been discussed. Multi-port converters in various applications are also discussed. From this review, the following has been observed and concluded.

- Non-isolated DC-DC converter topologies, including MISO, SIMO, and MIMO, offer distinct advantages in renewable energy and hybrid vehicle applications, with multi-input converters showing promise due to reduced integration costs and enhanced reliability through lossless soft switching circuits.
- Three-port converters, evolving towards multi-input-multi-output configurations, are gaining traction in renewable energy systems, particularly for their ability to optimize power flow.
- Control techniques such as PWM, Hysteretic, and MPC play a crucial role in voltage regulation and power transfer efficiency, with digital control advancements offering adaptability and sophistication.
- MPPT algorithms, notably P&O and Incremental Conductance, are pivotal in maximizing power generation efficiency in diverse converter types, while ongoing research explores complex soft computing methods.
- Multi-port converters find extensive application across hybrid generation systems, electric vehicles, microgrids, and telecommunications, facilitating efficient power management and integration of multiple energy sources.
- Challenges including reducing operating time delays, implementing lower duty ratios, and optimizing control for multiple output voltages are areas of focus for researchers, aiming to advance circuit simplification, component reduction, and power scalability in multi-input converters.
- The comparison of hybrid control techniques such as PID, SMC, MPC, and fuzzy logic provides valuable insights into choosing appropriate controllers based on factors like response time, stability, and complexity.

Overall, this review provides a comprehensive understanding of efficient multi-input converter topologies for both DC and AC output voltages, guiding researchers towards lowering installation costs and sizes while enhancing performance and functionality.

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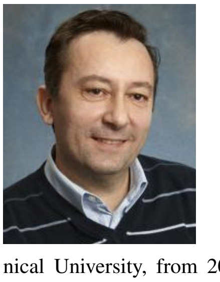

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