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REVIEW

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Bidirectional DC-DC converter circuits and smart control algorithms: a review

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Abstract

The entire article has been dedicated to cover the current state of the art in bidirectional DC-DC converter topologies and its smart control algorithms, identified the research gaps and concluded with the motivation for taking up the work. It covers the literature survey of bidirectional buck–boost DC-DC converters, and control schemes are carried out on two aspects, one is on topology perspective and another one is on control schemes. Different topologies with and without transformers of bidirectional DC-DC converters are discussed. Non-isolated converters establish the DC path between input and output sides while transformer-based converters cancel the DC path in between input and output sides since it introduces AC line between two DC lines just like in flyback converter. Transformer-less converter is preferred when there is no much protection needed for load from high voltage levels, also these converters are used in high-power applications. The bidirectional DC-DC converter can switch the power between two DC sources and the load. To do so, it has to use proper control schemes and control algorithms. It can store the excess energy in batteries or in super capacitors. In contrast, isolated topologies contain transformers in their circuits. Due to this, it offers advantages like safeguarding sensitive loads from high power which is at input side. In addition to it, multiple input and output ports can be established. With the isolation in DC-DC converters, input and output sections are separated from electrical stand point of view. With isolation, both input and output sections will not be having common ground point. The DC path is removed with isolation due to usage of transformer in DC-DC converters. In contrast to its features, it is capable to be used in low-power applications since transformer is switching at high frequency, the size of the coil reduces and hence it can handle limited rate of current. The bidirectional DC-DC converters are categorized based on isolation property so-called isolated bidirectional converters. Features and applications of each topology are presented. Comparative analysis w.r.t research gaps between all the topologies is presented. Also the scope of control schemes with artificial intelligence is discussed. Pros and cons of each control scheme, i.e. research gaps in control schemes and impact of control scheme for bidirectional DC-DC converters, are also presented.

Keywords: Batteries, Bidirectional power flow, Control systems, DC-DC power converters, Fuzzy logic control, Artificial neural networks control, Machine learning

Introduction

In the technology of power electronics, bidirectional power converters are identified as significant subsystems in the design of systems where power flow is required to flow in both forward and reverse directions. The control technology for power converters has been modernized over the past few decades. The advancements in the semiconductor industry have helped in the easier implementation of the control strategies. The power converter can find its own importance in the system of any applications only when the power converter can offer tight regulation of load and line of the power source. On top of that efficiency is also prime factor in deciding the best power converter. For that, entire controller plays a vital role to obtain tight regulation and efficiency. The next point of interest in choosing the best power converter is that reliability of power converter which can be enhanced with functions of monitoring the system added to it. In addition to it, optimization of controllability and minimization of component count and flexibility of settings in the control circuit [1–8]. The general block diagram of bidirectional converter is as shown in Fig. 1. Based on type of current mode control or voltage mode control, the control system regulates the voltage or current in the system. The DC-DC converter is a power switching system in power electronics. It accepts DC signal of certain voltage and converts it into another DC signal with certain voltage. The voltage levels will change in input and output sides. But on either side of input and output power levels remains same, i.e. power is not amplified. It is widely used in battery charging and discharging applications with constant voltage and constant current so that battery like is increased.

In addition to that it provides isolation between input and output sides by making use of transformers along with that it regulates output voltage with control signal applied to it. The control signal supposed to be pulse width modulation (PWM) signal. This is regulated by electronic circuit called as control circuit. This compares the sampled signal from the load with reference signal and produces error signal. Such aero signal is fed to compensator circuit which runs the control algorithm of user interest. With error signal, control algorithm generates controlled linear signal which in turn fed to the PWM circuit. This PWM circuit accepts one more signal high frequency signal in particular triangular signal whose frequency is equal to switching frequency of the converter. The DC-DC converter reduces ripple in the converted DC signal since it has inductor–capacitor (LC) filter along with switching device. The PWM signal with high switching

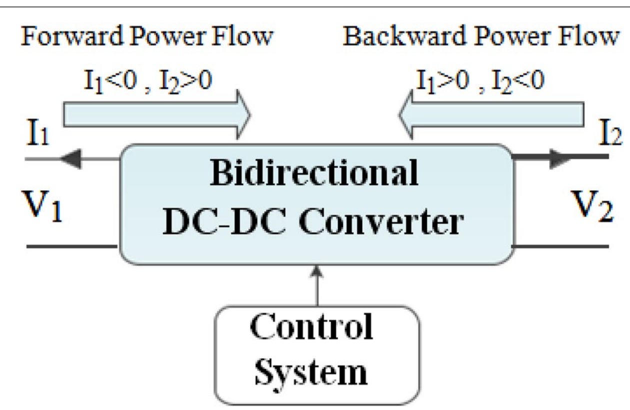

Fig. 1 The general structure of bidirectional DC-DC converters

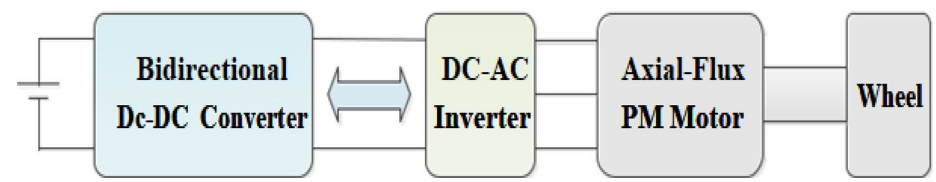

Fig. 2 The bidirectional DC-DC converter in EV powertrains

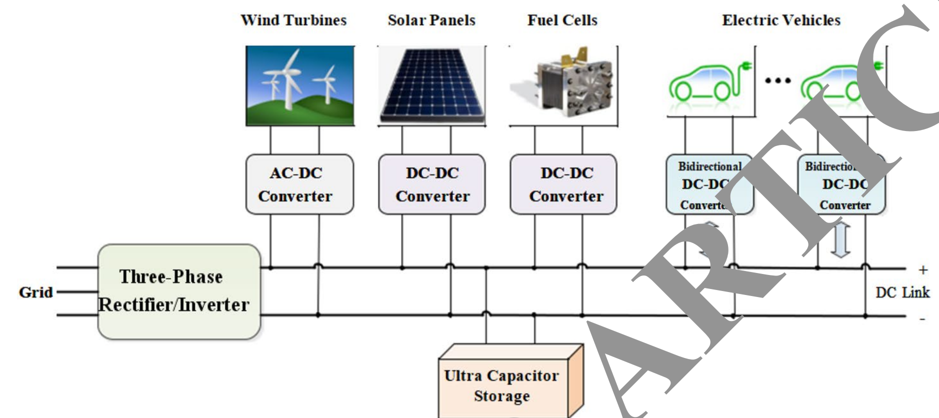

Fig. 3 The bidirectional DC-DC converter in vehicle to grid (V2G) architecture

frequency introduces switching losses in the circuit that in turn results in degradation of efficiency of the converter.

The bidirectional buck–boost converter (BBBC) can supply the current in both directions based on the mode of operation decided by the requirement of the application. For example, application of power train of EVs is shown in Fig. 2 [9]. The additional battery is connected with bidirectional DC-DC converter. This particular battery is utilized during some events when more power is needed to step up the voltage particularly during up lifting.

The BBBC provides peak current from the battery during the start-up time. During deceleration, BBBC supplies regenerative energy from motor to auxiliary battery. BBBC can transfer the current on both sides of the systems connected to it. For example, let us see the vehicle to grid (V2G) architecture as shown in Fig. 3 [10]. This architecture fits in the applications like smart grids and plug-in hybrid electric vehicle (PHEV) where BBBC charges the vehicles from the grid side and discharges the energy to grid from PHEV batteries in case of demands. Therefore, BBBCs with low cost, high efficiency, and stable are essential for the charging stations.

This article tries to review the BBBCs from different perspectives because the BBBC is used not only in electric vehicles but also in broad area of renewable energy systems where BBBC is used to charge the battery when the load is running smoothly from source. This is called reverse mode of operation. When transients and overload condition occur across a load, BBBC starts working in forward mode to discharge the battery to the load [11]. If the load is AC load, DC-AC converter is connected between BBBC and the load. Such architecture is as shown in Fig. 4.

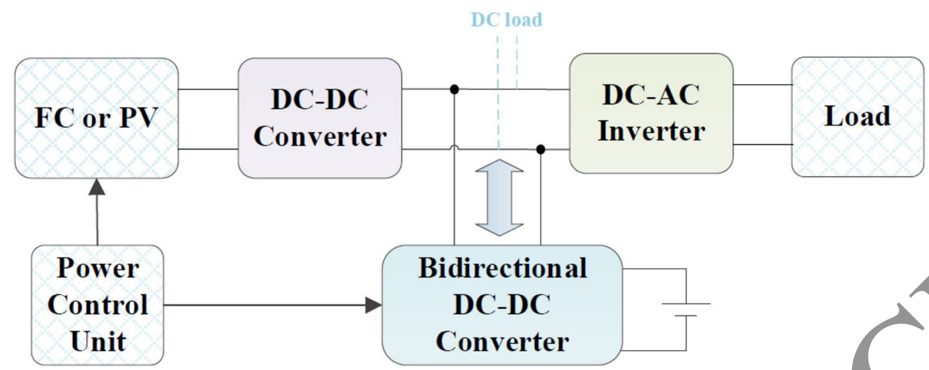

Fig. 4 The bidirectional DC-DC converter in FC or PC systems

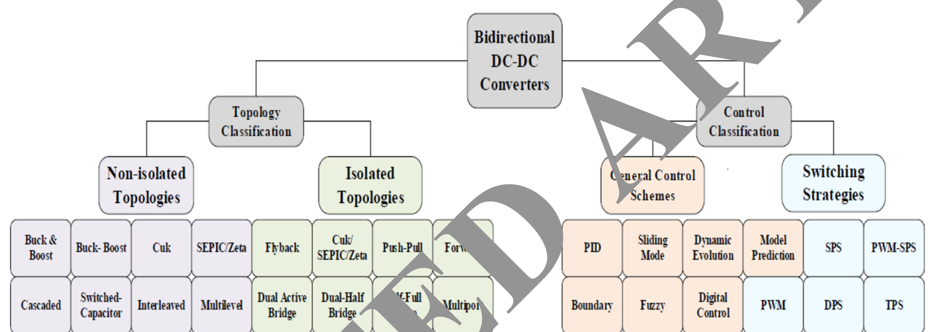

Fig. 5 Flowchart of classification of bidirectional DC-DC converters

Bidirectional DC-DC converter circuits

Literature survey on bidirectional buck–boost converter (BBBC) system is carried out on two aspects, one is on *topology perspective* and another one is on *control algorithms* as shown in Fig. 5.

The topologies of BBBC are divided into two main types such as isolated bidirectional DC-DC converter and non-isolated bidirectional DC-DC converters. The non-isolated topologies convert one level of DC-voltage to another level of DC-voltage, and they do not contain transformer which offers galvanic isolation in the system of circuits. Therefore, these topologies lack the advantages like high step-up voltage gain ratio and isolation between source and load. Nevertheless their weights are reduced since no transformer is used and system is going to be compact without transformer. When the transformers are used with converter, it generates reactive power in supply lines so more compensation is required. Since transformer is used with high frequency, size of the coil reduces and hence the size of the transformer reduces; therefore, it cannot handle high current. Also the transformer usage with the converter can cause core loss and skin effect with the conductor. With all these impacts non-isolated converter finds the applications in high-power applications (Fig. 6).

Fig. 6 The universal structure of DAB

Table 1 Assessment of non-isolated bidirectional DC-DC converters

Topology	V_H/V_L	Inductors	Capacitors	Switches	Characteristics	Applications
Basic buck and boost Fig. 7a	$\frac{1}{1-D}$	1	2	2	Low number of elements; Discontinuity of input current	Photovoltaic system and uninterrupted power supply
Buck–boost Fig. 7b	$\frac{-D}{1-D}$	2	2	2	Negative output voltage capable to step-up/step-down the voltage	Electric vehicle
Cuk Fig. 7c	$\frac{-D}{1-D}$	2	3	4	Continuous input and output currents	Battery storage system
Sepic/Zeta Fig. 7d	$\frac{D}{1-D}$	2	3	2	Positive output voltage and reduced current ripple using an auxiliary circuit	Distributed power system
Cascaded Fig. 7e	$\frac{1}{1-D}$	1	2	4	Higher voltage gain and lower current stress	Electric vehicle and smart grid
Switched capacitor Fig. 7f	2	0	3	4	Low size and weight since no inductor, continuous input current	Distributed energy resources
Interleaved Fig. 7g	$\frac{1}{1-D}$	n = 2	2	2n = 4	Low switching frequency current ripple and smaller EMI filter required	High-power applications and distributed energy storages
Multilevel Fig. 7h	n = 3	0	n(n + 1)/2 = 6	n(n + 1) = 12	Low size and weight since no inductor, self-voltage balancing	Dual voltage architecture (Automotive systems)

Non-isolated bidirectional converters

These converters establish the DC path between input and output sides while transformer-based converters cancel the DC path in between input and output sides since it introduces AC line between two DC lines just like in flyback converter. Transformerless converter is preferred when there is no much protection needed for load from high voltage levels also used in high energy requirements. The BBBC can switch the power between two DC sources and the load. To do so, it has to use proper control schemes and control algorithms. It can store the excess energy in batteries or in super capacitors. The comparative analysis is carried out and listed in Table 1.

Non-isolated buck and boost-derived bidirectional DC-DC converter [12]

This converter is the first basic converter in the family of BBBC. In particular, its transformer-less bidirectional DC-DC converter as shown in Fig. 7a. It replaces two different basic converters for bidirectional power flow and hence reduce the component count. It pushes the energy from VH to VL in step-up time while it pushes the power from VL to VH in step-down time. The mode of transition is an automatic

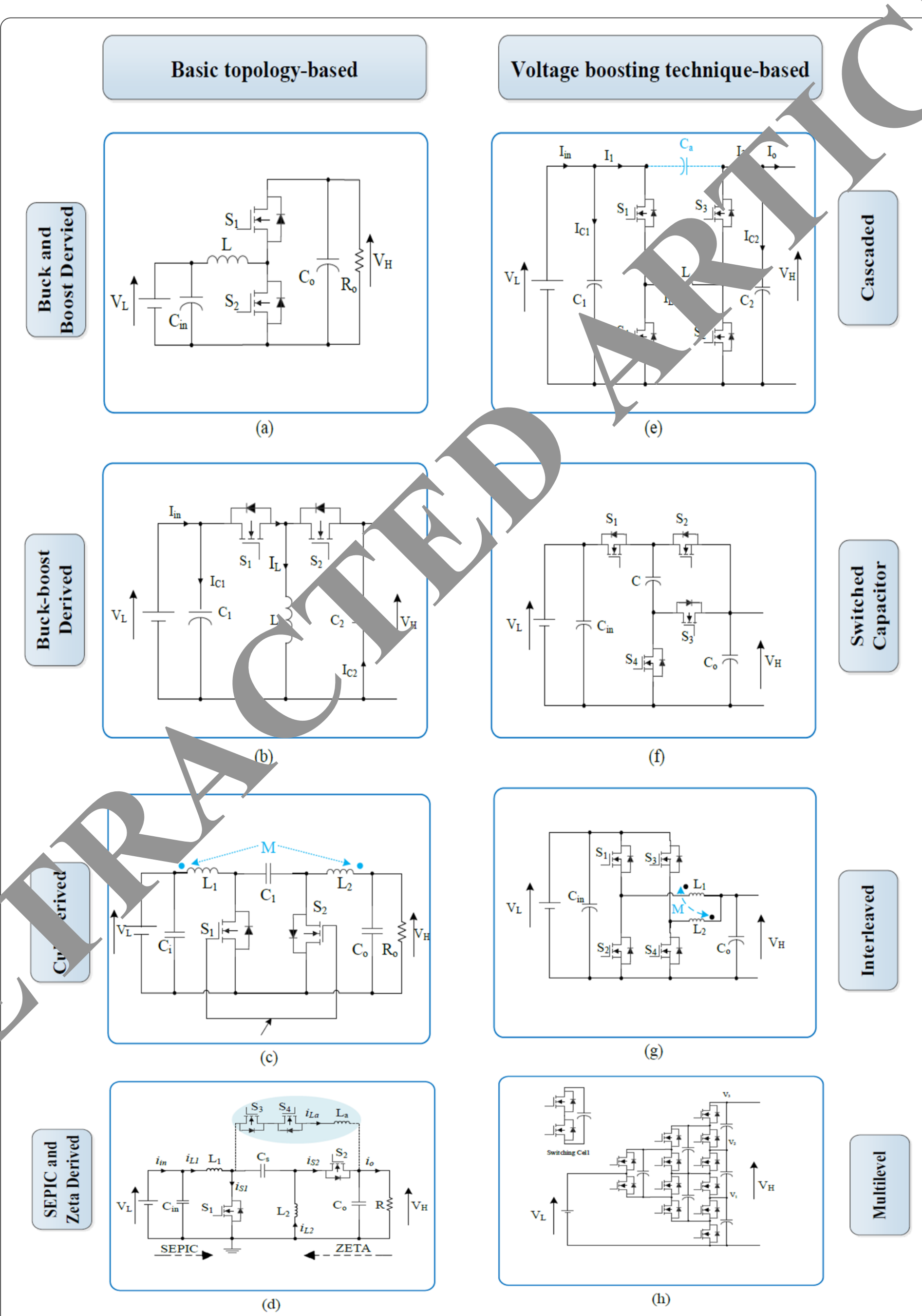

Fig. 7 Non-isolated Bidirectional DC-DC converters

process by the controller. It can find the applications starts from renewable energy systems to automotive systems.

Non-isolated buck–boost-derived bidirectional DC-DC converter [13]

The topology of this converter is constructed by adding one more switch to the basic structure of unidirectional step-up/step-down converter and it is as shown in Fig. 7b. As usual, it transfers the power in both the directions but the only thing is the voltage available across the load is of the opposite polarity than the input. There are many applications where negative voltage is required in electronic systems.

Non-isolated Cuk-derived bidirectional DC-DC converter [14]-[16]

The topology of such converter is as shown in Fig. 6c where the filter is constructed with L-C type filter. This filter helps to minimize the ripple current which is obtained by inductor. The magnitude of ripple current is less compared to buck–boost bidirectional converter [15]. On top of that input current is going to be continuous for the converter in input as well as output side of the converter since the capacitor used in the converter makes it possible to be continuous. In contrast it is not so in case of buck–boost converter. But the issue with Cuk converter is that more number of reactive components are used and this is going to be impact on switch as a stress [16]. Cuk converter transfers the power in both the states of switch, i.e. both on and off states of the switch. Contrast buck converter transfers the power when the switch is in on state while boost converter transfers the power when the switch is in off state.

Non-isolated zeta- and sepic-derived bidirectional DC-DC converter [17]-[18]

The topology of such converter is as shown in Fig. 6d where the sepic stands for single-ended primary-inductor converter. It makes it possible to avail the voltage at the output section. The voltage at output section can be more or less or equal to that of the input voltage. The output is avail so because the circuit is constructed with two different converters. Boost converter is connected with buck–boost converter back to back to form a sepic converter. Since the capacitor is coupled at any side of converter, it is capable to cause true shutdown. Due to this property, it finds the system needs intended voltage. For instance, the sepic is more useful when load requires constant voltage of 3.3 V while battery voltage is varying between 5 and 2 V [18].

Cascaded bidirectional DC-DC converter [19]-[20]

This topology is made up of two buck–boost converter cascade back to back and it is as shown in Fig. 7e. It finds the applications in EV systems. This topology is constructed with two bidirectional converter connected back to back as shown in Fig. 6e. This converter can step up the voltage at the load side and minimizes the current stress. This topology obtains output voltage which is much better than the input voltage with the particular duty cycle. But with the same duty cycle, the basic bidirectional cannot obtain the same value of voltage ratio. Since only one inductor is present in this topology and it is common for both the bidirectional converters, the current stress over all the components in the converter is decreased so converter can be used in systems where current stress and high voltage boosting capacity output current ripples [20].

Switched capacitor bidirectional DC-DC converter [21]

The voltage boosting ability of the converter is increased by the cell made up of switched capacitor. Figure 7f shows the switched capacitor-based BBBC. The bidirectional switched cells are made with the unidirectional switched cells [22]. In this topology, there is no magnetic utilization and high weight of the converter since there is no inductor used. By connecting strings made up of cells in parallel results in availing a continuous input current and those can be operating in all additive storing cells.

Interleaved bidirectional DC-DC converter [23]-[26]

The smaller electromagnetic interference (EMI) due to high speed operating devices can get cancelled with interleaving technique used in this converter. Several stages of interleaved topology as shown in Fig. 6g particularly for automotive applications where these converters can switch the pattern of dynamics so avail the power at the required rate for the loads which are dynamics [24]. There are various types of converters. For instance, some topologies of this type of converters are proposed in [25]-[26]. In this topology, inductor in the circuit plays a vital role of minimizing ripples in the current due to which there is a scope for better transient response.

Multilevel bidirectional DC-DC converter [27]

In this topology high gain voltage gain is obtained by switching module connected in repeating pattern in each level. This topology finds application in electric vehicle where two voltage bridges are required to obtain regenerative process and hence to store the energy in the battery. Since no inductor is used in this topology, the weight of the converter is considerably lower than those of the converters which uses inductors and it is as shown in Fig. [illegible] Table 1 arranges for a comparison of above said different converter configurations with different parameters as shown in Table 1.Section 3 contains the control schemes for these converters.

Isolated bidirectional DC-DC converters

These topologies contain transformers in their circuits, due to this, it offers advantages like safeguarding sensitive loads from high power which is at input side. In addition to it, multiple input and output ports can be established. With the isolation in DC-DC converters, input and output sections are separated from electrical stand point of view. With isolation, both input and output sections will not be having common ground point [28]. The DC path is removed with isolation due to usage of transformer in DC-DC converters. In contrast to its features, it is capable to be used in low-power applications since transformer is switching at high frequency, the size of the coil reduces and hence it can handle limited rate of current. The bidirectional DC-DC converters are categorized based on isolation property so-called isolated bidirectional converters which are classified as follows. The comparative analysis is carried out and listed in Table 2.

Table 2 Assessment of isolated bidirectional DC-DC converters

Topology	V_H/V_L	Inductors	Capacitors	Switches	Characteristics	Applications
Fly back Fig. 8a	$\frac{ND}{1-D}$	0	2	2	Basic isolated topology and discontinuity of I_{in}	Uninterrupted power supply
Cuk Fig. 8b	$\frac{ND}{1-D}$	2	4	2	Continuous Iin/Io	
Eliminated ripples of Iin/Io by coupled inductor	Low-power application and photovoltaic systems					
Push–pull Fig. 8c	*ND*	1	1	4	Continuous output current and number of winding more than two	Medium power (2φφ)–high-power applications (3φφ)
Forward Fig. 8d	*ND*	1	1	3	Continuous Io, limited duty cycle, low power-level applications	Low- and medium-power application
DAB Fig. 8e	Dynamic with control scheme	0(V-fed)	2	8	The most popular isolated bidirectional topology and suitable for high-power applications	High-power applications and automotive systems
Dual half-bridge Fig. 8f	Dynamic with control scheme	0(V-fed)	[illegible]	4	Less no. of switches and suitable for low-power applications than DAB	Battery management, automotive and fuel sell systems
Multiport DAB Fig. 8g	Dynamic with control scheme	0(V-fed)	4	6	Suitable for UPS systems, for integrating two-switch buck–boost converter	UPS systems, electric vehicles
Multiport- DAB Fig. 8h	Dynamic with control scheme	0(V-fed)	n = 6	4n = 12	Many inputs inclusions and decoupled power flow	Multi-sustainable sources and generation systems

Isolated bidirectional buck–boost DC-DC converter [29]

The isolated bidirectional converters are obtained by introducing high-frequency transformers in the existing bidirectional DC-DC converters. The voltage gain ration is achieved by introducing transformer to basic bidirectional buck–boost converter named it as flyback converter where no inductor is present and it is as shown in Fig. 7a. The snubber components are incorporated with transformer to cancel the generation of leakage current along with reducing the current stress for the switching devices [30]. From Fig. 7a it is clear that input is DC which will be converted into AC by using transformer and switching devices. This AC is again converted back to DC for the load. On either sides of transformer, switching devices are connected and they both operate at the same time or different intervals of time. In addition to it, capacitors are placed on both sides of input and output to minimize the ripple in the switching current since switching takes place at high frequency in order to diminish the size of the reactive element like transformer [31].

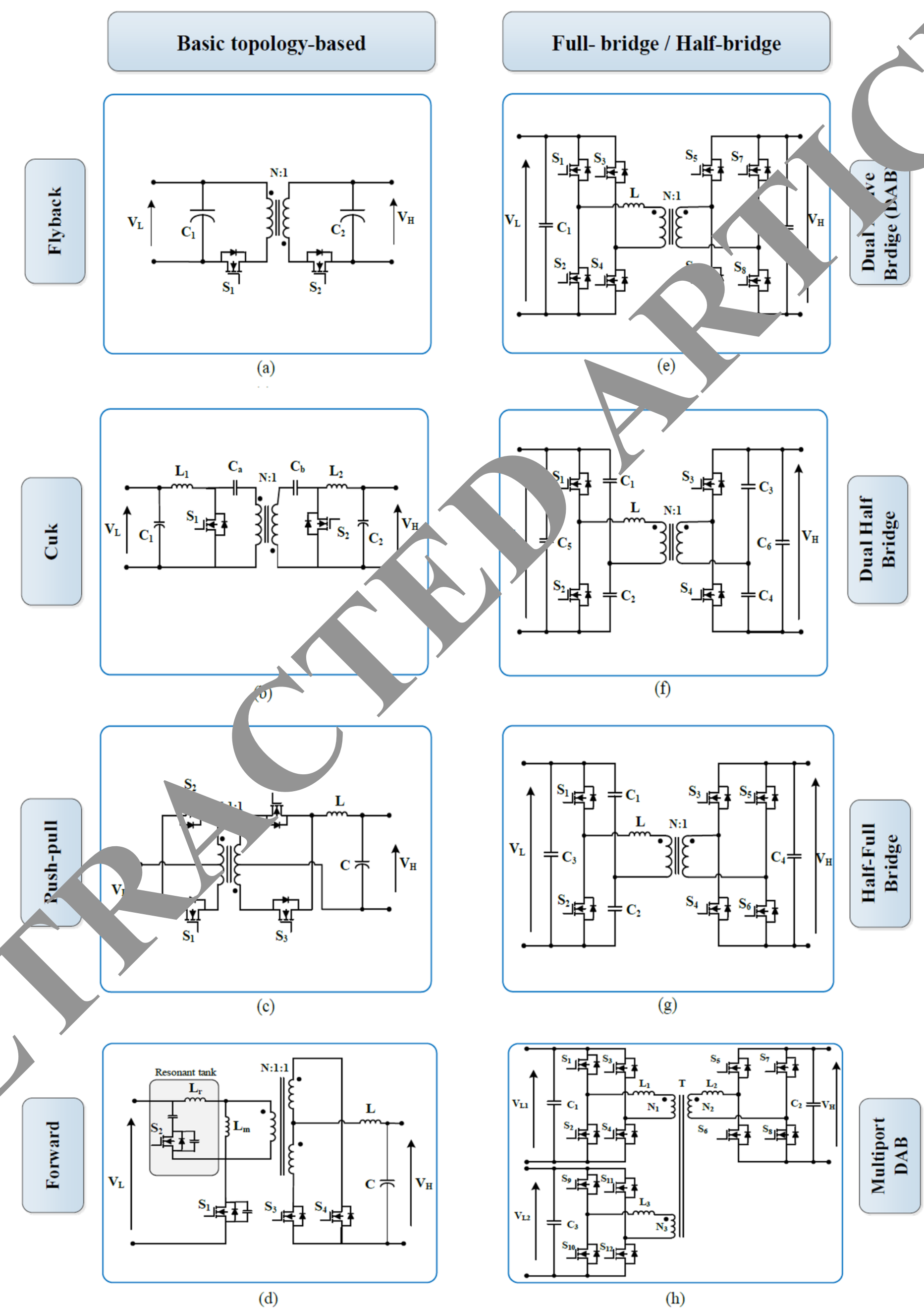

Fig. 8 Isolated bidirectional DC-DC converter topology classification. (**a**) Application of smart control in power electronics, (**b**) usage of metaheuristic methods in power electronics, and (**c**) usage of machine learning methods in power electronics

Isolated Cuk and sepic/zeta bidirectional DC-DC converter [29, 32]-[33]

Figure 7b shows the isolated bidirectional cuck converter which is taken into account to showcase the use of having two different grounds for input side and output side with use of transformer of non-isolated bidirectional cuck converter. The current in this topology is in continuous mode from input side to output side. The capacitor connected between two subcircuits make the current to be continuous. The loads are protected from high power at input side by incorporating transformer in between input and output. This also benefits step-up/step-down of voltage to be available at output side, also eliminates input and output current ripples by coupling the inductor at input and output sides [32]. This topology is highly suggested to use in the application of non-conventional energy systems [33].

Push–pull bidirectional DC-DC converter [28]-[34]

The bidirectional push–pull converter is as shown in Fig. 7c. It is derived from unidirectional push–pull converter in order to have the power flow in either directions. It uses transformer to get it in terms of power. The current in this topology is continuous in all directions. This happens because of the presence of capacitor in between input and output side. The loads are protected from high power at input side by incorporating transformer in between input and output sides. This also benefits step-up/step-down of voltage. The circuit of push–pull converter contains two semiconductor switches connected in between input and the transformer particularly at the primary side of transformer. The current from input is going to be continuous towards output side. The current is continuous because of two switches connected in symmetrical fashion so in both the switching states, i.e. on tome and off time of each switch, the current is flowing towards output side. This results in less noise on input line. With all this, efficiency of the system increases [34].

Forward bidirectional DC-DC converter [35]-[39]

The bidirectional forward converter was proposed in [35] by considering the unidirectional forward converter and it is as shown in Fig. 7d. A zero voltage switching is achieved in this converter by incorporating clamped circuit. Advanced research was carried out with respect to bidirectional forward DC-DC converter [36]. With forward converter, multiple outputs are made available since secondary sides of transformer will have multiple output terminals so higher and lower output voltages can be made available simultaneously. It looks like flyback but works in different ways [37]-[38]. The transformer does not store large amount of energy unlike inductor [39].

Dual active bidirectional DC-DC converter [40]-[45]

The general circuit is as shown in Fig. 7e [40]. This topology is made up of already existing circuits like full-bridge circuit or half-bridge circuit, and these circuits are driven with voltage or current. The usage of the number of switches in the converter will proportionate the amount of power transfer [41]. The issue of switching losses by using more number of switches in the topology can be addressed by taking low loss semiconductor switches. Since there are two bridges involved, one is at primary side and another one is at secondary side. Each bridge gets complimentary switching signals to operate the each bridge. Phase shift is taken into consideration for the purpose of operation of each bridge [42]. Soft switching phenomenon can be adopted easily for this topology to lower the overall switching losses since this topology has more number of switching elements. As the circuit is complex, digital control is used to simplify the control logic. Energy transfer can be controlled from input side to output side. By using efficient control techniques, efficiency of these converter can be optimized.

The universal structure of dual active bidirectional (DAB) is presented in Fig. 6. The first stage of the converter which can be either voltage-fed- or current-fed-based control can convert DC signal into AC signal. The second stage of the converter will step-up the voltage level using transformer and ZVS/ZCS is achieved by using resonant tank circuit with transformer that results in high efficiency in the system [43]-[45]. The third stage of the converter contains full-bridge AC-DC converter which will convert AC signal fed from transformer into DC signal using control signals. These control signals can be with the association of voltage mode control or current mode control. Furthermore, the specific control schemes for DAB are surveyed in Sect. 3.

Dual half-bridge bidirectional DC-DC converter [46]-[49]

The topology is as shown in Fig. 7f. It finds the application where low-power requirement is needed. Since it uses four switches instead of eight switches as can be the case in DAB. This uses voltage-fed topologies on either sides of transformer [46]-[47]. It does not have magnetic component in the circuit; therefore, stability can be achieved easily as the parameter zero of the transfer function of the converter cannot lie on right-hand side of the S-plane that results in minimum-phase behaviour of the converter and hence the design of controller for such converter becomes easy. Basically this converter uses voltage and current sources at different sides of transformer. However, it has another variant [49]. There are applications where continuous current is desirable. In such case current-fed topology is preferred as it supports continuous current. Furthermore, there have been studies on interleaved dual half-bridge topology which increases the voltage [50] (Fig. 8,9).

Half-bridge and full-bridge bidirectional DC-DC converter [51]-[53]

The combination of two topologies are connected back to back with transformer which can operate at high frequency and hence reduce the size of the system. The low voltage signal is applied at half-bridge side through the capacitor which can reduce the ripples in the system when the input is applied at the input section as shown in Fig. 7g. The anti-parallel switching pattern is applied at the input side of the system, i.e. at the lower output voltage side, later switching pattern is applied [51]. In the meantime the full bridge is operating at different switch patterns where two switches operate at the same time by keeping the DAB in mind [52]. It uses less count of switches so that control requirement goes easy than DAB [53].

Multiport dual active bus bidirectional DC-DC converter [54]-[56]

The multi-winding transformer was proposed in [54] to use it with isolated bidirectional converter with isolation using magnetic components as shown in Fig. 7h. Some

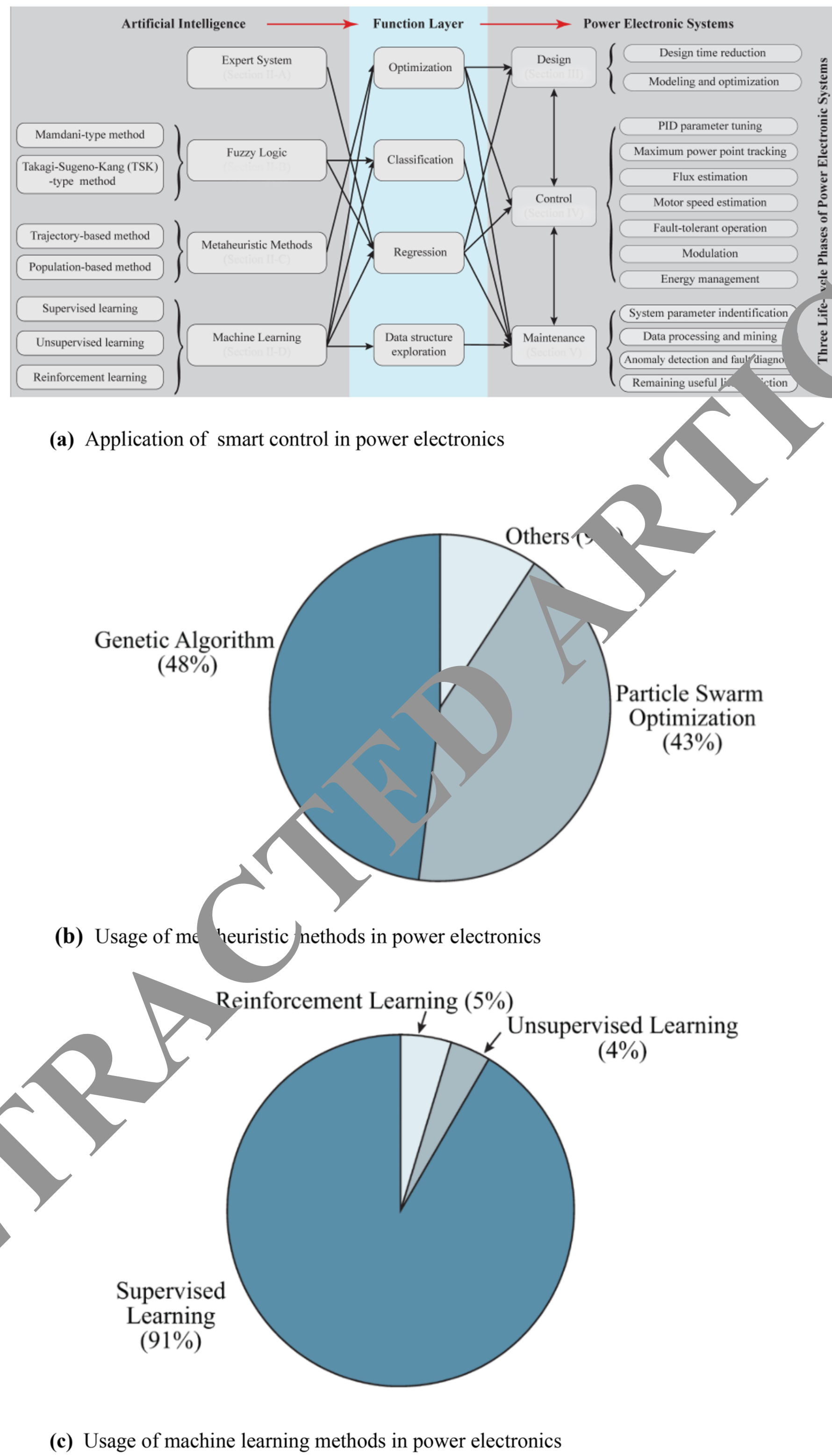

Fig. 9 **a** Application of smart control in power electronics, **b** usage of metaheuristic methods in power electronics, and **c** usage of machine learning methods in power electronics

applications have multiple inputs; therefore, in these applications, multiport DAB bidirectional converter is picked [55]. In the next section, optimization of characteristics of multiport converters is presented by using duty cycle control of converter and power flow control.[56].

Smart control algorithms for bidirectional DC-DC converters

The smart control is class of control techniques which uses artificial intelligence computing approaches like experts system, fuzzy logic, metaheuristic methods, and machine learning for power electronic systems [87]-[88]. The application of smart control algorithms in three life cycles of power electronic systems including design, control, and maintenance is as shown in Fig. Smart control algorithms are used in terms of expert system, fuzzy logic, metaheuristic methods and machine learning with classical control methods like PID and SMC [91].

Expert system is the earliest method and as of now it is used in the applications for 0.9% only. Due to its certain limitations, advanced algorithms like fuzzy and machine learning are used since they have superior capabilities.

Once the optimization of application is formulated, the optimal solution can be obtained with the non-deterministic method, i.e. metaheuristic method as shown with the direction in Fig. 7a. Due to enormous advantages, most of the optimization tasks are solved with metaheuristic methods like genetic algorithm and partial swarm optimization algorithm in power electronics. The usage statistics of metaheuristic methods in optimization for power electronic systems is as shown in Fig. 7b.

Machine learning is designed with datasets of the system to be controlled. To use machine learning in power electronics, it is classified as supervised learning, unsupervised learning, and reinforcement learning. The usage statistics of machine learning methods in power electronics system is as shown in Fig. 7c. Supervised learning is used in power electronics where system models are difficult to formulate [89]. It has dataset having input and output pairs. Supervised learning methods are classified as the connection-based method like neural network (NN) method, probabilistic graphical method, and memory-based method. When it comes to unsupervised learning, it has no output data for learning system during the learning process.

Data clustering and data compression are achieved with unsupervised learning in power electronics [90]. Unlike supervised learning and unsupervised learning, reinforcement learning does not require a training dataset, instead it obtains the experience from the iterations between systems. It is preferred in the application where system is with less knowledge or difficult to formulate [92]-[93].

Real-time applications with bidirectional converters decide to choose the right control technique. Thus, this section projects the strategies connected with isolated and non-isolated bidirectional DC-DC converter topologies. Non-isolated topologies are preferred over isolated topologies for medium-power applications since they are less costly and less complex as there is no transformer used. But in case of high-power applications, isolated topologies are preferred since isolation is required between high-power source and low power load. In addition, just because of usage of transformers as they operate at high frequency in isolated converters, it offer advantages of ZVS and ZCS, electrical isolation, and high reliability.

The task of controlling the power converters like DC-DC converters in order to get high efficiency and better dynamic response is the major issue. To address such control issues in the view of getting high efficiency and better dynamic response, there are couple of control algorithms like genetic algorithms (GA), improved GA, partial swarm optimization (PSO), evolutionary programming (EP), hybrid evolutionary strategy, seeker optimization algorithm (SOA), bacterial-foraging optimization (BFO), gravitational search algorithm (GSA), differential evolution (DE), and artificial bee colony algorithm (ABC). Recently, few more advanced algorithms such as whale optimization algorithm, enhanced red wolf optimization, improved social spider optimization (ISSO), antlion optimization algorithm (AOA), JAYA algorithms ,PSO extended algorithms like R-PSO,L-PSO,PSO-CFA, improved PSO based on success rate (IPSO-SR), fruit fly optimization algorithm (FFOA), and modified fruit fly optimization algorithm (MFFOA) are also used with basic control laws like PID and SMC for the control of power converters [78].

To find the solutions for the issues which exits in the control of BBBC systems, the following control strategies are proposed. The comparative analysis is carried out and listed in Table. 3.

PID Control

The general structure of proportional integral derivative (PID) controller is as shown in Fig. 10. This control is combined with other control schemes in order to have hybrid control strategies to obtain optimization of operation of systems w.r.t efficiency. It is used in different control problems which arise in different converter configurations.

To control is the common problem in bidirectional DC-DC converters, there are two main transitions of controllers due to the converters. In case of battery charging using conventional methods where V_L and V_H are used, large transients occur during transition from V_L to V_H control. To avoid such large transitions, PID controller is used with pulse width modulation (PWM) scheme. This controller reduces the size of the capacitor used at DC bus side of the converter and also reduces the transition time [58].

In case of inverters connected with bidirectional converters, active and reactive currents to be controlled in sequence to control the powers independently and then the inverters can control active and reactive powers at AC sides. Later, PWM with reference values can control the inverter [57]. Another issue with bidirectional power flow with bidirectional converters is the delay during mode transition. This can be resolved by using axillary switch with main switch which usually have fixed turn-on time [59]. Even though control problems are implemented using digital signal processing (DSP), the discrete current sampling creates some issues like large power loss. Then again the conventional control method is unable to control switching time of auxiliary switch as the cause of resonant current sensing problem therefore to obtain higher outcome with PID controller is used by availing discrete voltage sampling. In bidirectional DC-DC converters, the dead-time of switches may affect the performance of the system. This dead time is taken into consideration for the effects of nonlinear dependency of the current on duty cycle [60]. PID controller may not be the choice for this condition to regulate the current in an entire range. On the other hand, control scheme is prepared based on either continuous current or discontinuous current. The current is discontinuous with positive

Table 3 Control algorithms in bidirectional converters

Control algorithms	Control issues	Advantages	Disadvantages	Recommended Applications
PID control	-Power flow control issues	-Minimum cost	-Minimum efficiency	Smart grid systems[57]
	-Analysis of mode of operation	-Good dynamic response	-Lack of robustness in presence of disturbance and uncertainty	Electric vehicles[59],
	-Reducing the time delay and dead time during switching	-High reliability	-Poor in avoiding large transients between directions	Fuel cells and satellite applications [60]-[70]
	- Safeguarding the devices from over current			
Sliding mode control	-Taking the account of external perturbations in large signal	-Tracking the reference signal	Exact information of state variables and parameters are required	Hybrid electric vehicle[61],
		-Speed of response in defined time		DC motor control[63],
	-Large variations with load and line	-Powerful against variation of parameters and external disturbances		Dc micro-grid [64], Energy storage applications [67]
		- Capable enough to estimate the system under both small and large signal conditions		
Dynamic evaluation control	Voltage drop is avoided to the maximum extent for the change in load current	-Robust to the variation of load signal	Division parameter appears in the estimation of duty cycle of control signal which results in complexity in the implementation of analogue control form	Ultra-capacitor-based energy storage, fuel cell system [72]
		-Exact knowledge of design model is not required		
		-Good performance		
		-Well tracking of reference		
Model predictive control	-Power flow control issues	-Tracking the reference signal	This model can allow the algorithm to use mathematical model of the time linear with some limitations	Hybrid power trains[72]
	-Establishing load and line regulation	-Fast dynamic response		DC distributed power system[73]

Table 3 (continued)

Control algorithms	Control issues	Advantages	Disadvantages	Recommended Applications
		-Easy to implement, this credit goes to programmable devices like DSP		Battery applications [74]
Fuzzy control	-Minimizing control time	-No mathematical knowledge of the system is required	Vague approach to design control law	Automotive systems [75], consumer electronic goods [56], domestic goods, environmental control [63]
	-Better dynamic response compared to PID control and reduces steady-state error	-Fast response	Approachable only when the things are simple	
			Needs heavy computation while converting the linguistic control rules into its respective control actions	
		-Flexible in setting design rules		
		-Easy to design, understand and expressing control rules in human language		
		-It can reduce the impact of imprecise noisy and distorted input information on control action		
Artificial neural network control	-Power flow control issues	-Expert law like MPC can be removed once data sets are ready for tuning ANN	-Large complexity of network structure	Battery applications [74]
	-Establishing load and line regulation	-Less computation burden	-It needs the training to operate	Automotive systems [75], Consumer electronic goods [56], domestic goods, Environmental control [63]
	-Minimizing control time	-Decreases the inaccuracy of the system model even with inaccurate parameters	-For large neural network needs huge processing time	
	Superior system response	-The accuracy of the trained model is about 97%	-It has to balance number of neurons used in the system and system performance in DC-DC conversion system	

Table 3 (continued)

Control algorithms	Control issues	Advantages	Disadvantages	Recommended Applications
		-Easy to implement on microprocessor-based system		
		-High computation rate		
Digital control	-Precise small signal modeling	-Increase the efficiency with charge and discharge speed	-Cause delay with ADC processing-control loop gain crosses more than one	Hybrid electric vehicle[61],
	-With inrush current protection, changing the power flow directions smoothly	-Better EMI immunity		DC motor control[63],
		-Use to use		DC micro-grid [64], energy storage applications [67]
		-Low cost		Power management[72]
		-more flexible than analogue design		
		-More reliable		

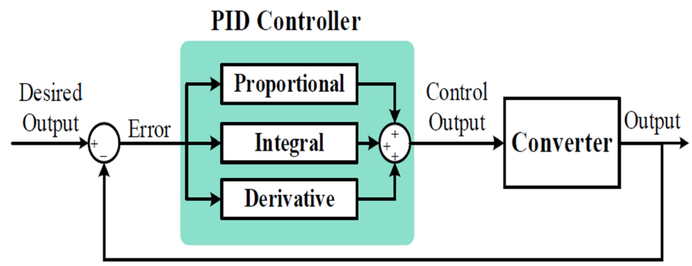

Fig. 10 The basic structure of PID controller

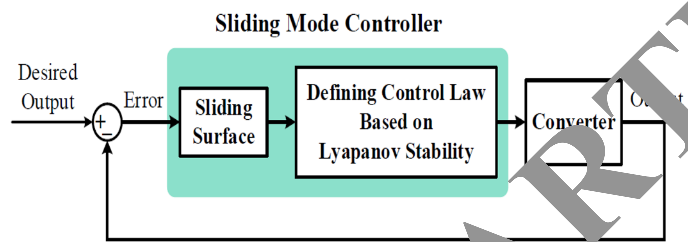

Fig. 11 General structure of sliding mode controller

and negative peaks along with DC value, in between those two peaks of signals provided dead time occurs in inductor current. There should be fast and stable transition between continuous conduction mode (CCM) and discontinuous conduction mode (DCM) provided if both modes are involved. Thus, PID controller regulates the current in DCM while PID requires a preset with control algorithm in CCM.

To have optimization with respect to power conversion efficiency and low cost of the systems like multiple converters which will have multiple inputs and multiple outputs (MIMO), designing proper control scheme is a very important step in case of bidirectional DC-DC converters [61]. The capacitor at DC bus side or battery source side will have voltage regulation with logic of voltage controller due to PI control algorithm while current control algorithm with PI controller regulates flow of electronic in magnetic device and duty cycle is set for switches in converters. Switching devices are protected from over current with proper regulation of inductor current and also load is protected with zero abnormal current into the load. In order to analyse performance of bidirectional DC-DC converters which are nonlinear systems, closed loop control scheme is linearized around its equilibrium point even though the stability analysis is same for both step-up and step-down modes. Bode plot is the one of the linear methods to analyse the stability of transition between bidirectional power flow [62]. Therefore, the development of mathematical model is needed. The proper control scheme is designed based on stability condition given by bode plot analysis.

Sliding mode control

There are some reasons why sliding mode control as shown in Fig. 11 is coming into picture when there is PID controller. The reasons are: in bidirectional DC-DC converters, nonlinear elements are existing which will make the dynamic equations of the converter nonlinear and the existing linear method is used to stabilize the system [63]. However, these methods accomplish the linearization and characterize the right devices. Also these models neglect dynamic changes. Unlike these methods, sliding mode control which is nonlinear control scheme is capable to offer exact control action by considering the presence of perturbation and disturbance.

Furthermore, in a control loop of bidirectional converter, if large signal enters the control loop, there is chance that external perturbances also can come along with it then the earlier method, i.e. state-space averaging model may not be able to detect the behaviour of regulator. Sliding mode control scheme can overcome this condition since it has property of dynamic change. But still this control method is more complicated as it requires the right message.

In bidirectional Cuk converter, three specific switching states are studied with three different sliding surfaces. The analysis shows that the system is insensitive to the variation of output voltage under steady state. This happens when magnetic coupling between inductor is negative and incoherence surface is a linear set of power parameters [64].

When BBBC is connected to nonlinear load, in this converter states of operation are indeterministic. Therefore, the conventional control method cannot solve the control problem since the conventional control method can design a linear controller by linearization of system at a region of interest [65]. In this case sliding mode controller is designed in terms of high-pass filter which ensure robustness to parameter variations and hence reduce the transient response and regulate the DC bus voltage under nonlinear load variations. However, this approach also finds difficulty in controlling the converters that have poles and zeros in right half planes and prediction of stability in large signal behaviour since this is designed with modelling of converter. Therefore, to address such issues two configurations are proposed [66].

Based on this control method, controller is designed with the numerical study for BBBC used in applications like power backup systems. In this case some assumptions are made that dynamics of inductor current and capacitor voltages are faster than the supercapacitor dynamics. At the end this control technique shows that it is highly insensitive to structural perturbations. In some applications like micro-grid systems where BBBC offers nonlinear property with state-space modelling of the load and converter and also in this it is with time. Hence, in this case it finds good for stable voltage [68]. Sometimes two or more control techniques are required to integrate to solve the problems which cannot be possible by single control technique. For instance, two PI controllers are used in the cascade control method. One PI controller stabilizes all controls but then due to severe variations of load and line, PID alone cannot accomplish required performance.

Thus, PID is a controller to have better performance [69]. In another instance, sliding mode is integrated with fuzzy logic controller to get rid of chattering process in the usage of sliding mode control alone. In an application like regenerating the energy of an ultra-capacitor [70], fuzzy logic and sliding mode controller are combined since the combined controller accomplishes strong robust in changes and minimizes the variation required to the expected point.

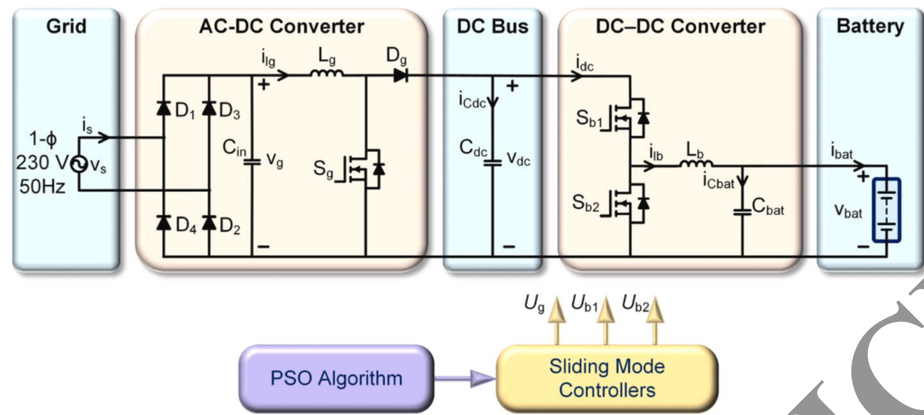

Fig. 12 PSO-SMC control model

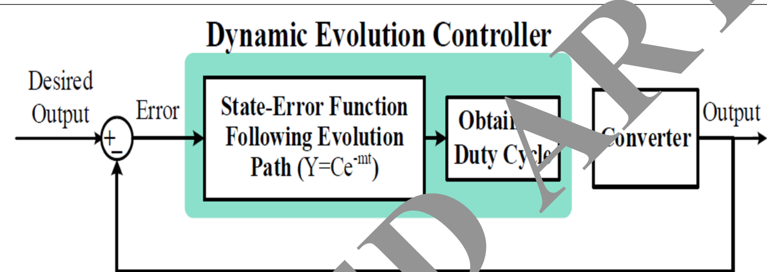

Fig. 13 General structure of dynamic evolution controller

Partial swarm optimization (PSO) with sliding mode control (SMC) [77]

The PSO can be applied for bidirectional DC-DC converter along with well-established control laws like SMC as shown in Fig. 12. Here we have discussed w.r.t to electric vehicle to charge the battery with tight regulation and efficiency. The SMC control parameters are selected using PSO. The PSO is integrated with SMC to achieve optimization in the control actions. The PSO minimizes objection function which is the sum of errors by inductor current error, Dc bus error, and battery voltage error. The PSO evaluates the objection function at each iteration, and the best value of particle is saved and later compared to get the best value known as global values out of the group of best values for the SMC.

Dynamic evolution control (DEC)

The dynamic evolution controller is as shown in Fig. 13. This controller is suitable for nonlinear systems. It works with the principle of following evolution path irrespective of disturbance existence and hence minimizes the dynamic state error. It's with respect to time. The advantage of this controller is that avails better performance of the system even though it does not require exact values of the parameters belong to the system.

For instance, in electric vehicle the frequent acceleration and deceleration take place and hence fast dynamic response is needed. When fuel cell-based electric vehicle is considered, such fast response may not be offered. This issue can be resolved by connecting storing element with fuel cell [71]-[72] along with bidirectional power converter with above said control technique. The outcome of this controller used with such applications shows that controller can meet dynamic loads and get battery charges when battery with fuel cell voltage is bigger than the load demands or during regenerative braking.

Model predictive controller (MPC)

The model predictive controller is as shown in Fig. 14. It is the extended version of the predictive control method. It takes functions to make the system variables follow the reference values. And hence, it offers fast system with easy rig-up of system due to microprocessor technology [73]. This controller at first needs to be designed by applying mathematical models for the future predicted value and previous values are taken into model of algorithm. The predicted values are forwarded to optimizer which will solve the optimization problem based on predefined cost function and predicted values at each time step. This process will obtain the optimal control actions for converters.

In the system, working of the system is divided as: idle, charge, and discharge modes. This division is done based on available and desired values of voltage. Then control algorithm decides everything for the system. The algorithm tested the BBBC for any applications. The extended versions of these models are linear MPC, multi-MPC, and dynamic matrix control [74]. The converter model is supposed to be linear model inside the control algorithm. This would be the limitation associated with linear MPC algorithm. To overcome this limitation multi-MPC is coming into picture and this will use multi-models system to linearize the nonlinear models locally at different operating points. It will take nonlinearity effect at each stage of sampling. Further it will take the difference between linear and nonlinear models into account to get minimized. Thus, this method will solve the constrains associated with multiple MPC algorithm.

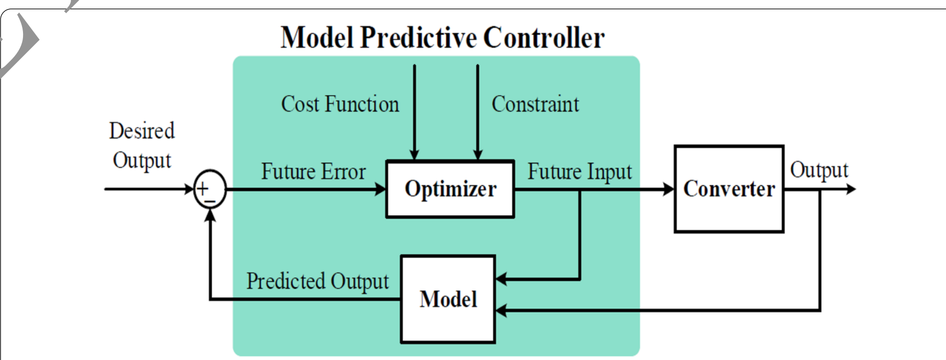

Fig. 14 Basic structure of model predictive controller

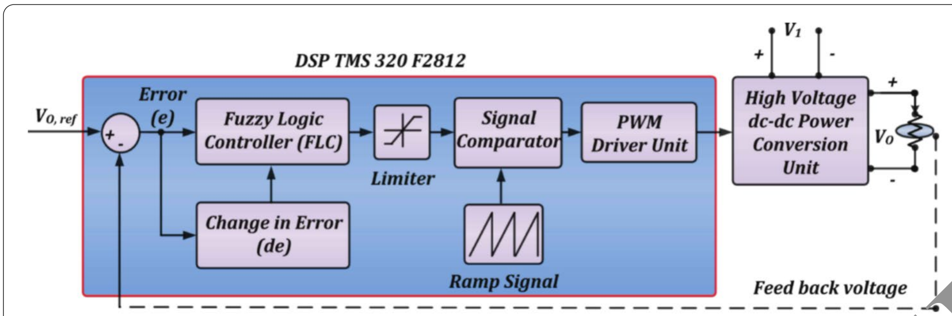

Fig. 15 Basic structure of fuzzy logic control of DC-DC converters

Fuzzy logic control (FLC) [75]

The basic fuzzy logic control for power converters like DC-DC converters is as shown in Fig. 15. Since the DC-DC converters are nonlinear system which can be controlled accurately without mathematical model. This is possible with fuzzy logic where human brain analysis is applied to determine system characteristics. Such analysis can be modelled to construct control logic so-called rule base with uncertain inputs. For power converters like bidirectional buck–boost system, FLC receives two inputs like error signal e(k) and change in error signal de(k). Fuzzy rule is set for these two inputs based on dynamic behaviour of error signal. Different algorithms can be applied for fuzzification and de-fuzzification process. For instance, the fuzzy rule is antecedent: IF X is Medium AND Y is Zero, Consequent: Then Z is Positive. For both the antecedent and consequent, the degree of fulfilment is determined by the membership functions. The type of fuzzy interference technic is classified as Mamdani type [81]-[84] and Takagi–Sugeno–Kang type [80]. The output of de-fuzzification process represents control signal to generate switching signal for the switching device. This can replace traditional PID control logic where complex mathematical modelling is carried out. The fuzzy base rule is to set the hybrid model of fuzzy control and fuzzy-PID control which can offer a better transient response over a load change.

Artificial neural network (ANN) control [76]

The computation burden with FLC for generating precise control signal can be reduced by using ANN. Also the better system performance can be achieved with ANN control. In case of DC-DC converter control, ANN plays a very important role as it works with prediction control which is better than fuzzy control since intelligent control techniques involving ANNs are found to be simpler for implementation. ANN-based PID control gives better system response than fuzzy-based PID control. Nevertheless, the expert experience can be copied from fuzzy logic and incorporated with conventional neural networks (NN) techniques like feed-forward neural network (FFNN) and radial basis function network (RBFN) form various control algorithms like fuzzy neural network (FNN) and adoptive neuro-fuzzy interference system (ANFIS) [85, 86]. The architecture of whole system of DC-DC control with ANN is depicted as shown in Fig. 16. The traditional PID is not enough to better control of bidirectional buck–boost converters (BBBC) since BBBC load parameters change with time. Such change cannot be

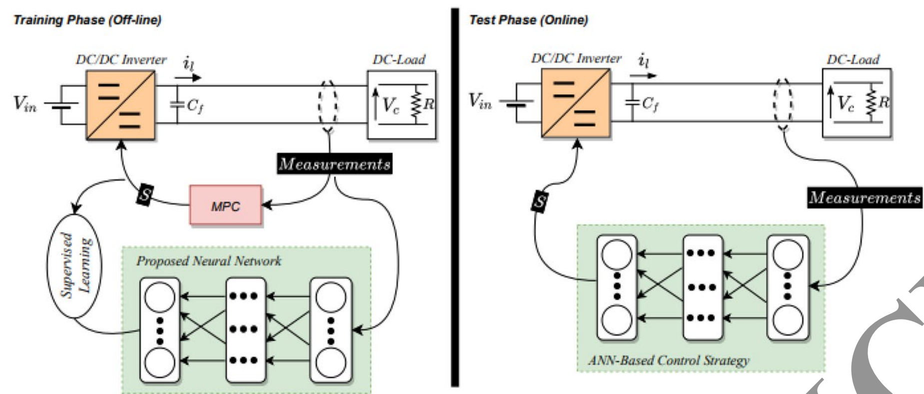

Fig. 16 Basic structure of ANN control of DC-DC converters

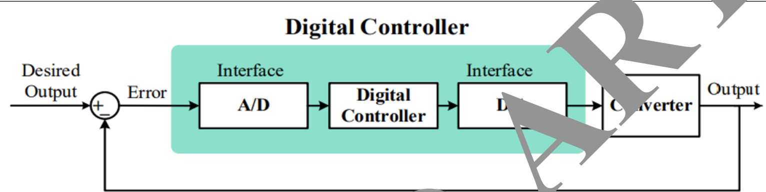

Fig. 17 Typical architecture of digital controller

controlled precisely by the PID control as its linear control model; therefore, for better control, model predictive control algorithm is used as expert and it provides the data to train the ANN which can be tuned finely to better control of BBBC so as to get highest efficiency and performance.

Digital control [76]

In this method of control, either voltage/current signals are taken by sensors from either source side (feed-forward control) or load side (feedback control). Such a sensor signals are converted into digital signals by A/D converter as shown in Fig. 17.

Later it will be compared with the desired output value. Based on the value of error signal (either +ve value, -ve value or zero value), the control algorithms like PID, PIDN, PSO-PID, fuzzy, fuzzy-PID, and adoptive-network-based fuzzy interface system (ANFIS) are used to reduce the error signal equal to zero by adjusting the control parameters so as to obtain stable output signal. Finally the control signal will be fed to the digital pulse width modulation (DPWM) unit which will generate control signal for the power converter. In high-power converters, DSP/FPGA control boards are used to implement such control algorithms since those control boards are having highly computational performance at low cost because of its high processing cores like cortex cores in DSPs and Spartan cores in field programmable gate array (FPGA) boards. Also these boards are having high immunity to electromagnetic interference. For the change of power flow, the intelligent control algorithms like dead-band, switch, and soft-start control are proposed in [45] to change the power flow directions in the converter at smooth space in order to protect the converter from rush current at the rise time or fall time duration.

Conclusion

The literature survey of bidirectional buck–boost DC-DC converters and control schemes is carried out on two aspects, one is on topology perspective and another one is on control schemes. Different topologies with and without transformers of bidirectional DC—DC converters are discussed. Non-isolated converters establish the DC path between input and output sides while transformer-based converters cancel the DC path in between input and output sides since it introduces AC line between two DC lines just like in flyback converter. Transformer-less converter is preferred when there is no much protection needed for load from high voltage levels, also these converters are used in high-power applications. The BBBC can switch the power between two DC sources and the load. To do so, it has to use proper control schemes and control algorithms. It can store the excess energy in batteries or in super capacitors. In contrast, isolated topologies contain transformers in their circuits. Due to this it has advantages like safeguarding sensitive loads from high power which is at input side. In addition to it, multiple input and output ports can be established. With isolation in DC-DC converters, input and output sections are separated from electrical stand point of view. With isolation, both input and output sections will not be having common ground point. The DC path is removed with isolation due to usage of transformer in DC-DC converters.

In contrast to its features, it is capable to be used in low-power applications since transformer is switching at high frequency, the size of the coil reduces and hence it can handle limited rate of current.

The bidirectional DC-DC converters are categorized based on isolation property so-called isolated bidirectional converters. Feature and applications of each topology are presented. Comparative analysis between all the topologies is presented. Also the scope of smart control schemes is discussed. ANN control scheme with many intelligent laws called as hybrid ANN can be best suited in control applications. Pros and cons of each control scheme for bidirectional DC-DC converters are also presented.

Abbreviations
BBBC: Bidirectional buck–boost converter; PID: Proportional integral derivatives; DSP: Digital signal processing; ANN: Artificial neural network; FLC: Fuzzy logic control; MPC: Model predictive controller; PSO: Partial swarm optimization; SMC: Sliding mode control; DEC: Dynamic evolution control; GA: Genetic algorithms; SOA: Seeker optimization algorithm; ABCA: Artificial bee colony algorithm; FFOA: Fruit fly optimization algorithm; MFFOA: Modified fruit fly optimization algorithm; AOA: Antlion optimization algorithm; PWM: Pulse width modulation; AI: Artificial intelligence; ML: Machine learning.

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Author contributions
1. VV has compiled the data and established the comparative analysis of bidirectional buck–boost converter. 2. RAC has compiled the data and established the comparative analysis of control algorithms for bidirectional buck–boost converter. 3. VSRR has performed review, validation, and editing work. All the authors read and approved the final manuscript.

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Declarations

Competing interests
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