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Topologies and Control Schemes of Bidirectional DC–DC Power Converters: An Overview

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ABSTRACT Bidirectional DC-DC power converters are increasingly employed in diverse applications whereby power flow in both forward and reverse directions are required. These include but not limited to energy storage systems, uninterruptable power supplies, electric vehicles, and renewable energy systems, to name a few. This paper aims to review these converters from the point of view of topology as well as control schemes. From the point of view of topology, these converters are divided into two main categories, namely non-isolated and isolated configurations. Each category is divided into eight groups along with their respective schematics and a table of summary. Furthermore, the common control schemes and switching strategies for these converters are also reviewed. Some of the control schemes are typically applied to all DC-DC power converters such as PID, sliding mode, fuzzy, model predictive, digital control, etc. In this context, it should be noted that some switching strategies were designed specifically for isolated bidirectional DC-DC converters in order to improve their performance such as single phase shift, dual phase shift, triple phase shift, etc. The features of each topology and control scheme along with their typical applications are discussed, in order to provide a ground of comparison for realizing new configurations or finding the appropriate converter for the specific application.

INDEX TERMS Batteries, bidirectional power flow, control systems, dc-dc power converters.

I. INTRODUCTION

The study of bidirectional power converters has become a significant field of research in power electronics. As opposed to conventional unidirectional converters, the power flows in both directions in bidirectional converters. As such, these converters are flexible and are widely used in electric vehicles (EVs) or hybrid electric vehicles (HEVs) [1], smart grids [2], uninterruptable power supplies (UPS) [3], aerospace applications [4] and renewable energy systems such as photovoltaic (PV) arrays, fuel cells (FCs), and wind turbines [5]–[7]. By interfacing between power sources and energy storage elements, the bidirectional configurations reduce the size and improve the efficiency and performance of the system as there is no need to use two individual converters for the forward and reverse power flow. The general structure of the bidirectional DC-DC converters is depicted in Figure 1 [8]. Depending on the location of the energy storage

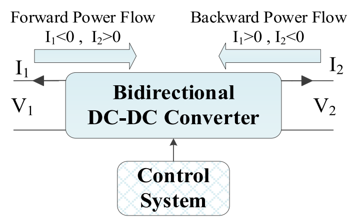

FIGURE 1. The structure of bidirectional DC-DC converters.

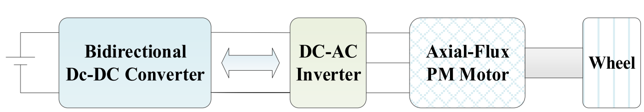

FIGURE 2. The of the bidirectional DC-DC converter in EV powertrains.

system, the converter acts as a buck or boost type and the respective control system is used to regulate the voltage or current of the system.

Due to its specific features, a bidirectional converter is applicable in systems where the current is required to be

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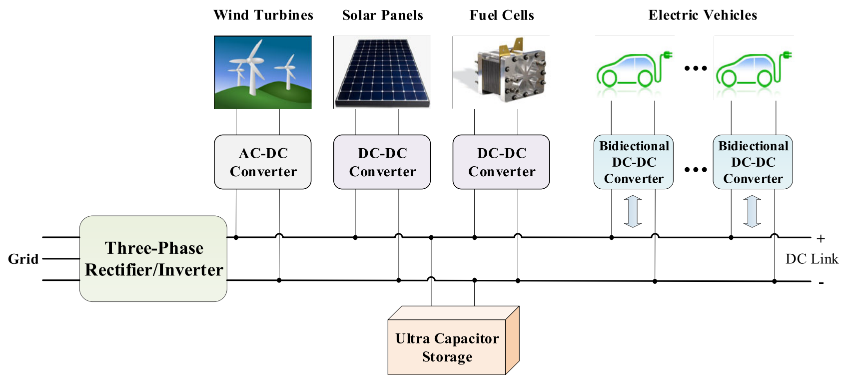

FIGURE 3. The layout of the bidirectional DC-DC converter in PHEV charge stations.

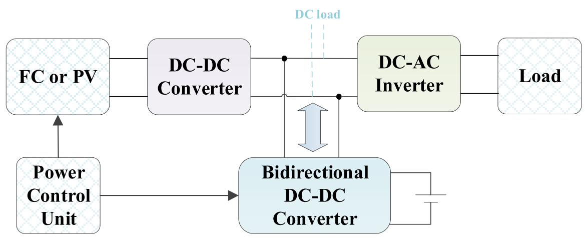

FIGURE 4. The bidirectional DC-DC converter in FC or PV systems.

supplied in both directions based on the operating mode. A sample diagram of these applications in the powertrain of EVs is shown in Figure 2 [9]. In order to start, accelerate or enable the vehicle to drive uphill, extra power is needed to boost the high voltage bus. This power can be obtained by the auxiliary battery of a bidirectional DC-DC converter, which supplies the peak current from the battery when starting the motor. Unlike the unidirectional topologies, they can reverse the direction of current flow and power, i.e. the auxiliary energy storage battery absorbs the regenerative energy fed back by the electric motor during deceleration.

The bidirectional DC-DC converter is also used in the smart grids and plug-in hybrid elective vehicle (PHEV) charge stations as shown in Figure 3 [10]. In this vehicle to grid (V2G) architecture, the bi-directional DC-DC converters are used to charge the vehicles from the grid side and to feedback the energy stored in PHEV batteries to grid in case of demands. Therefore, bidirectional DC-DC converters with low cost, high efficiency and high reliability are essential for the charging stations.

The application of the bidirectional power converter is not limited to electric vehicles. As shown in Figure 4, another application of this converter is in the broad area of renewable energy systems such as FC or PV based system when supplying either DC load or AC load via an inverter. In order to combine these sources of energy, the multi-input version of a unidirectional DC-DC converter may be used to regulate the output DC voltage. The bidirectional DC-DC converter is required to process the power from batteries to the load during transient and overload condition in the forward mode and to charge the battery pack in the reverse mode [11]. Therefore, due to their popularity in electrical systems, this paper attempts to review the bidirectional converters from different perspectives.

This paper is organized as follows: Section 2 presents the classification of bidirectional DC-DC converters from a topology perspective. From this point of view, these converters have been divided into isolated and non-isolated categories respectively in subsections 2.1 and 2.2. Along with respective explanation, the layout of each group and tables of comparisons have been provided for better understanding. Section 3 reviews the control schemes that have been used in bidirectional converters. Based, on the topology classification the control schemes have been categorized in two main groups. Finally, section 4 sums up the discussion and concludes the review. Figure 5 shows the flow of the study.

II. TOPOLOGY CLASSIFICATIONS OF BIDIRECTIONAL DC-DC CONVERTERS

The bidirectional DC-DC converters can be classified into two main general groups of configurations, namely isolated and non-isolated topologies.

The non-isolated topologies transfer the power without magnetic isolation. Though the non-isolated topologies do not use a transformer and lack the advantages of galvanic isolation such as high step-up voltage gain ratio, they benefit from a simpler configuration and do not suffer from disadvantages of galvanic isolation such as magnetic interference or high weight. These characteristics make them suitable when size and weight are important concerns in particular applications. In contrast, the isolated topologies basically convert the DC voltage to AC voltage waveform which passes through a high-frequency transformer and then is rectified to DC waveform. The voltage gain of isolated topologies is generally higher than their non-isolated counterpart. However, the transformer design procedure and alleviating the leakage inductance effect is an important factor in these converters. The following subsections review these converters from the topology point of view.

A. NON-ISOLATED TOPOLOGIES

A non-isolated bidirectional converter is basically realized by adding an antiparallel diode to the switch (if it is not already

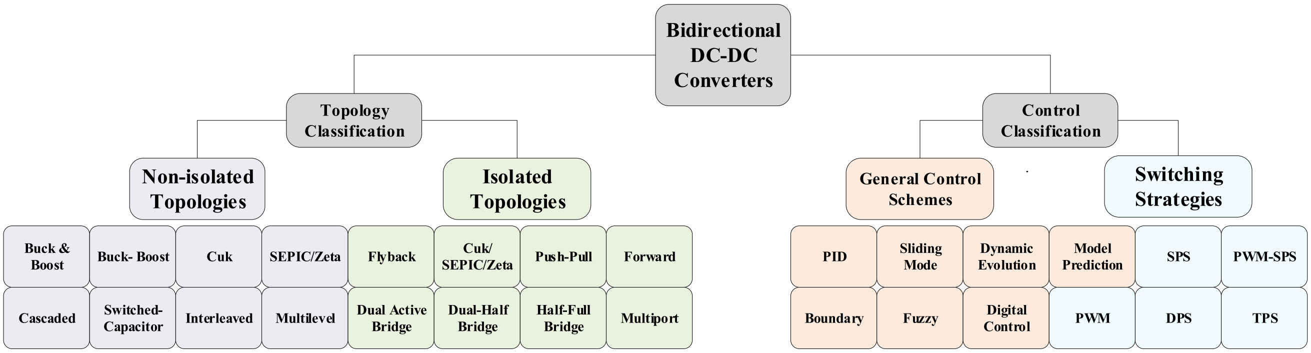

FIGURE 5. Flowchart of the review.

included) and by adding a controllable switch to a diode of the unidirectional converter topology. Some of the non-isolated configurations are presented based on the basic DC-DC converters such as buck, boost, buck-boost, Ćuk, etc. There are also some other configurations that are essentially designed based on the voltage boosting techniques such as switched capacitor, interleaved multilevel, etc. Hence, the non-isolated configurations are classified into eight groups as below.

1) NON-ISOLATED BUCK AND BOOST DERIVED BIDIRECTIONAL DC-DC CONVERTER [12]

The fundamental bidirectional converter was presented based on the original buck and boost converter. This bidirectional topology, which is depicted in Figure 7 (a), is actually realized by an evolvement in the unidirectional buck and boost converter. In other words, if the bidirectional power switches replace the unidirectional switches of the traditional buck and boost converter, the bidirectional buck and boost derived converter will be derived. The converter works as a boost converter from the V_L to V_H and performs as a buck converter while operating in the reverse direction.

2) NON-ISOLATED BUCK-BOOST DERIVED BIDIRECTIONAL DC-DC CONVERTER [13]

Based on the same method that was used to evolve a unidirectional to the bidirectional converter, the bidirectional buck-boost converter may be derived, i.e. using a bidirectional switch instead of any unidirectional switch in its topology will lead to a bidirectional topology as illustrated in Figure 7 (b). As well as the feature of the fundamental buck-boost converter, namely the ability to buck or boost the voltage level, the bidirectional buck-boost converter benefits from the capability of providing this feature in both directions of power flow with a negative output voltage.

3) NON-ISOLATED ĆUK DERIVED BIDIRECTIONAL DC-DC CONVERTER [14]–[16]

The Ćuk converter, which is known for its features such as continuity of the input current and output current, can be transformed to a bidirectional topology (Figure 7 (c)) by using two bidirectional power switches in the position of the power switch and diode of the original circuit. There

FIGURE 6. The general layout of DAB.

have been some variations of the bidirectional Ćuk converter. Originally, the coupled inductor version of the unidirectional Ćuk converter was presented to eliminate the input/output current ripples [15]. This technique has also been applied to the bidirectional Ćuk converter, which was the ground for further study on the control of bidirectional coupled-inductor Ćuk converter [16].

4) NON-ISOLATED SEPIC AND ZETA DERIVED BIDIRECTIONAL DC-DC CONVERTER [17], [18]

Single-ended primary-inductor (SEPIC) and Zeta are the other two types of the DC-DC converter, which are realized by rearrangement of the Ćuk converter elements to obtain a positive output voltage. Figure 7 (d) shows the bidirectional SEPIC/Zeta DC-DC converter. This topology acts as a SEPIC converter when power flows from VL to VH terminals and acts as a Zeta converter when power flows from VH to VL. The auxiliary branch which is highlighted in this converter has been proposed to form a new direct power delivery path between input and output and reduce the current ripples [18].

5) CASCADED BIDIRECTIONAL DC-DC CONVERTER [19], [20]

In order to increase the voltage boost ability of the converter and reduce the current stress, one can connect two or more converters in a cascaded formation. Figure 7 (e) shows the basic cascaded non-isolated bidirectional DC-DC converter which was originally devoted to EV applications. This converter is the resultant of cascading two buck-boost bidirectional converters. Though using more number of elements in comparison with the basic bidirectional buck-boost converter, this configuration benefits from higher voltage gain ratio with the same duty cycle of the switch. Furthermore, the current ripples and the current stress of the inductor, current stress of switches, capacitors and diodes have been reduced that enables the converter to operate in higher power ratings.

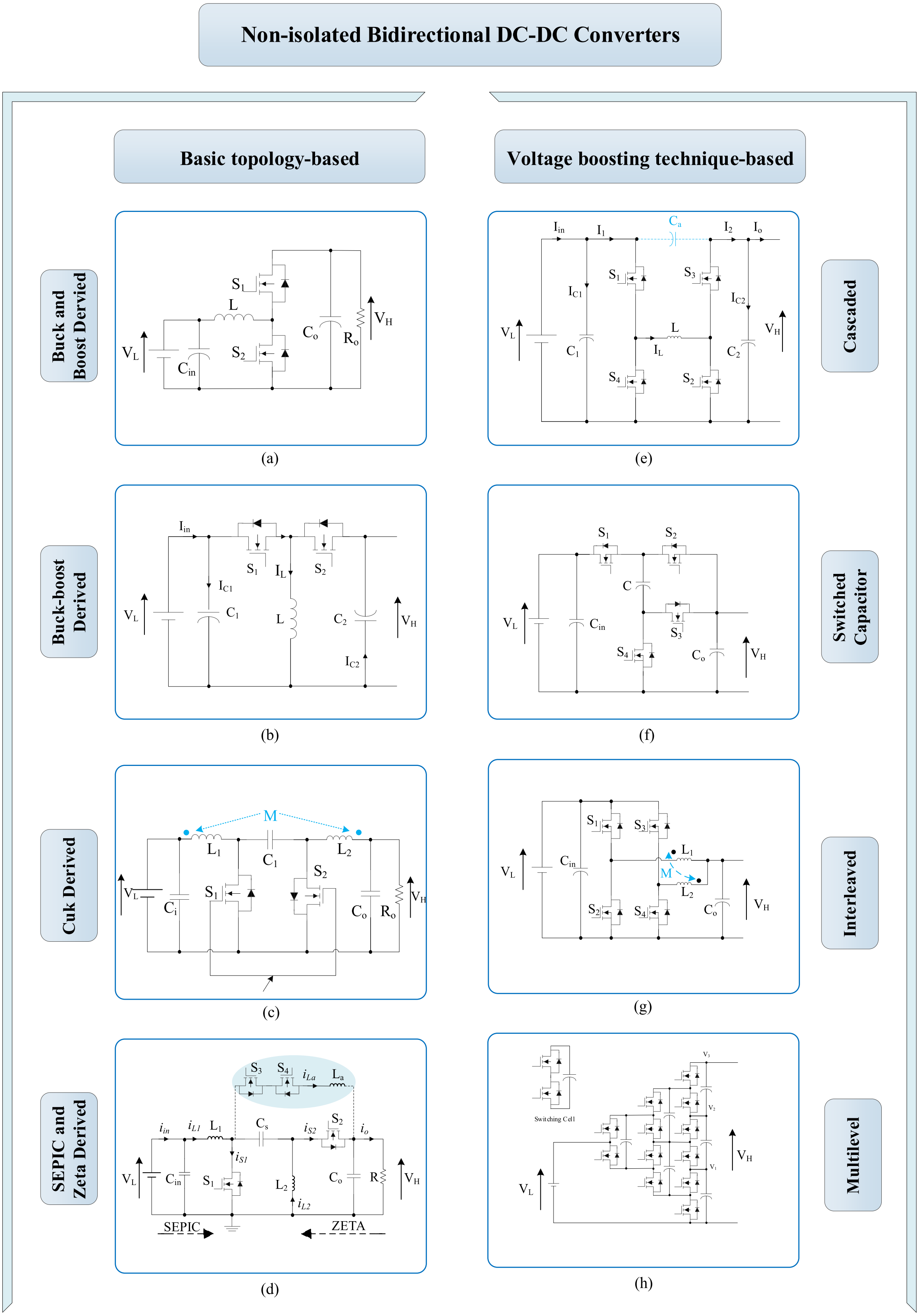

FIGURE 7. Non-isolated bidirectional DC-DC converters topology classification.

TABLE 1. Comparison of non-isolated bidirectional converters.

Topology	V_H/V_L	inductors	Capacitors	Switches	Characteristics	Applications
Basic Buck & boost Figure 7 (a)	$\frac{1}{1-D}$	1	2	2	- Low number of elements; - Discontinuity of Iin.	Photovoltaic System [12] , Uninterruptable Power Supply [17]
Buck-Boost Figure 7 (b)	$\frac{-D}{1-D}$	2	2	2	- Negative output voltage; - Ability to step-up or step-down the voltage.	Electric Vehicle [13]
Ćuk Figure 7 (c)	$\frac{-D}{1-D}$	2	3	4	- Continuous I_{in} and I_o ; - Eliminated ripples of I_{in} by coupling the inductors.	Battery Storage System [14]
SEPIC/Zeta Figure 7 (d)	$\frac{D}{1-D}$	2	3	2	- Positive output voltage; - Reduced current ripples using an auxiliary branch.	Distributed Power System [17]
Cascaded Figure 7 (e)	$\frac{1}{1-D}$	1	2	4	- Higher Voltage gain; - Lower current stress	Electric Vehicle [19], Smart Grid [20]
Switched Capacitor Figure 7 (f)	2	0	3	4	- Low size and weight (no inductor); - Continuous input current (needs parallel strings to operate in anti-phase).	Distributed Energy Resources
Interleaved Figure 7 (g)	$\frac{1}{1-D}$	n =2	2	2n =4	- Low switching frequency current ripple; - Smaller EMI filter required.	High power Applications [23], Distributed Energy Storages [26]
Multilevel Figure 7 (h)	n = 3	0	n(n+1)/2 = 6	n(n+1) =12	- Low size and weight (no inductor); - Self-voltage balancing.	Dual Voltage Architecture (Automotive Systems) [27]

In order to reduce the output current ripples, an auxiliary capacitor (Ca) has been added to the converter [20].

6) SWITCHED-CAPACITOR BIDIRECTIONAL DC-DC CONVERTER [21]

The switched-capacitor (SC) cell can be used to enhance the voltage boosting the ability of the converter. Figure 7(f) shows a bidirectional converter that utilizes an SC cell to enhance the voltage conversion ratio. The cells of the converter are realized by the evolution of a unidirectional SC cell to a bidirectional configuration [22]. There is no inductor in SC-based topologies and hence the magnetic utilization and the high weight imposed due to the inductor is avoided. Though no inductor has been used, the converter may own a continuous input current by paralleling two similar strings made up of cells and operating them in the anti-phase, which can be extended by adding cells.

7) INTERLEAVED BIDIRECTIONAL DC-DC CONVERTER [23]–[26]

Figure 7 (g) shows a bidirectional DC-DC converter that benefits from the interleaving technique to cancel the switching frequency current ripple, which leads to a smaller EMI filter. In a bidirectional interleaved topology for automotive applications based on several stages, it has been shown that interleaving technique can significantly contribute to filter size reduction, better dynamic response, and thermal management [24] There are some variations in interleaved converters. As an instance, some interleaved bidirectional topologies have been proposed in [25]–[26], of which the inductors are coupled in either direct or reverse, in order to reduce the current ripple and improve the dynamic response of the converter.

8) MULTILEVEL BIDIRECTIONAL DC-DC CONVERTER [27]

Figure 6(h) shows a multilevel bidirectional DC-DC converter. In this topology, a switching module is used as a repeating pattern in each level to provide a high voltage gain. The converter was originally used for dual voltage automotive systems. Due to having no inductor, the weight and size of this converter are considerably lower than those that use magnetic elements.

Table 1 provides a comparison of the aforementioned non-isolated bidirectional converter topologies in terms of the voltage gain ratio, number of inductors, capacitors, power switches and the circuit characteristics. The control schemes for these converters are discussed in section 3.

B. ISOLATED TOPOLOGIES

Galvanic isolation is one of the promising methods to achieve a high gain boost ability by adding an extra degree of freedom to the gain of the converter, namely the turn ratio of windings, and making it suitable for the applications with wide ranges requirement of the input voltage and load regulation [28]. As well as providing a high voltage gain ratio, isolation will provide further benefits such as the possibility of realization of multi-input or multi-output topologies and providing isolation between the input and output side for the sensitive loads that are vulnerable to faults and noise and the safety is a major concern in them. The isolated bidirectional converters are good choices for applications such as aircraft, electric vehicles, renewable energy sources, etc. These topologies are classified and summarized as below.

1) ISOLATED BUCK-BOOST BIDIRECTIONAL DC-DC CONVERTER (BIDIRECTIONAL FLYBACK) [29]

There are various methods to increase the voltage boost ability of the buck-boost converter to achieve a higher voltage gain without isolation [30]. However, in case of the magnetic isolation requirement, the well-known Flyback converter is realized when a transformer replaces the inductor of the buck-boost converter. Following the bidirectional evolution procedure in the non-isolated topologies, a bidirectional isolated buck-boost converter can be obtained, which is shown in Figure 8 (a). By applying the volt-second and charge-second balance, the gain of the converter in forward power flow is obtained, which is the same as the voltage gain ratio of the Flyback converter as expected. It is worth noting that the transformer design procedure needs to be taken into account and a voltage clamp snubber is required to suppress the leakage current of the Flyback transformer. There have been further variations of this topology in the literature in order to improve its voltage gain [31].

2) ISOLATED ĆUK & SEPIC/ZETA BIDIRECTIONAL DC-DC CONVERTER [29], [32], [33]

Based on the non-isolated bidirectional Ćuk converter, an isolated bidirectional Ćuk converter was realized to introduce the benefits of magnetic isolation to the original version. Hence, the new converter, which is depicted in Figure 8 (b) owns a continuous input/output current and provides isolation between input-output sides with a high voltage gain ratio that incorporates the turn ratio of the transformer. Same as what has been discussed in 2.1.3, coupling the input and output inductor leads to the elimination of the input and output current ripples [32], which is highly recommended in renewable energy systems. The same theory was used to obtain an isolated version of the bidirectional SEPIC/Zeta converters [33].

3) PUSH-PULL BIDIRECTIONAL DC-DC CONVERTER [28], [34]

Based on the unidirectional push-pull converter, the bidirectional push-pull converter (Figure 8 (c)) was suggested in order to enable the power to flow in both directions. Same as the unidirectional push-pull converters, the bidirectional push-pull converters use a multi-winding transformer, to convert the power. To operate this topology in high power applications, a three-phase bidirectional push-pull converter was also proposed [34].

4) FORWARD BIDIRECTIONAL DC-DC CONVERTER [35]–[39]

Considering the unidirectional forward converter, the bidirectional forward converter was proposed in [35], which is illustrated in Figure 8 (d). A clamped circuit may be used to achieve zero voltage switching in the converter. Further investigation on bidirectional forward DC-DC converter was done in [36], where the transformer leakage inductance is used as the resonant inductor to propose the resonant version of the converter.

There have been hybrid configurations of the mentioned isolated topologies in the literature based on the desired application and features such as Forward-Flyback [37], Push-pull-Forward [38] and Flyback-Push-pull [39]. In these converters, the primary side of the transformer is derived from one of the mentioned isolated topologies and the secondary is derived from another, either current-fed or voltage-fed.

5) DUAL– ACTIVE BRIDGE (DAB) BIDIRECTIONAL DC-DC CONVERTER [40]–[45]

One of the most popular techniques is to use back-to-back bidirectional topologies that are isolated by a high-frequency transformer. The back-to-back converters may be either voltage-fed or current-fed, half-bridge or full-bridge. Figure 8(e) shows the basic topology of the DAB converter [40], which uses two full-bridge topologies in both sides of the transformer. The power transmission of bidirectional converters is proportional to the number of switches [41]. Hence, having eight power switches in this topology along with the galvanic isolation makes it suitable for high power applications with a high voltage gain ratio such as automotive systems [42]. The concern about the loss of the high number of switches may be resolved by using low-loss silicon carbide (SiC) or gallium nitride (GaN) power switches. The energy transfer of this converter is controlled by adjusting the phase shift between the AC voltage waveforms of the transformer's primary/secondary windings. An efficient control scheme may lead to efficiency optimization, which bolds the study of control schemes of this converter.

As DAB topologies are one of the most popular isolated bidirectional topologies, comprehensive reviews on DAB-derived topologies were carried out in [42]. Briefly, the general layout of the DAB-derived converter is presented in Figure 6. where: a) in the first stage, based on the desired application, either a voltage-fed or a current-fed full-bridge performs the DC-AC conversion; b) in the second stage, a high-frequency transformer steps-up the ac voltage and provides galvanic isolation. A resonant tank may be used along with the transformer to achieve ZVS/ZCS and hence improve the efficiency [43]–[45]; c) in the third stage, based on the desired application, either a voltage-fed or a current-fed full-bridge performs the AC-DC rectification. Furthermore, the control schemes that are specifically used in DAB, are surveyed in section 3.

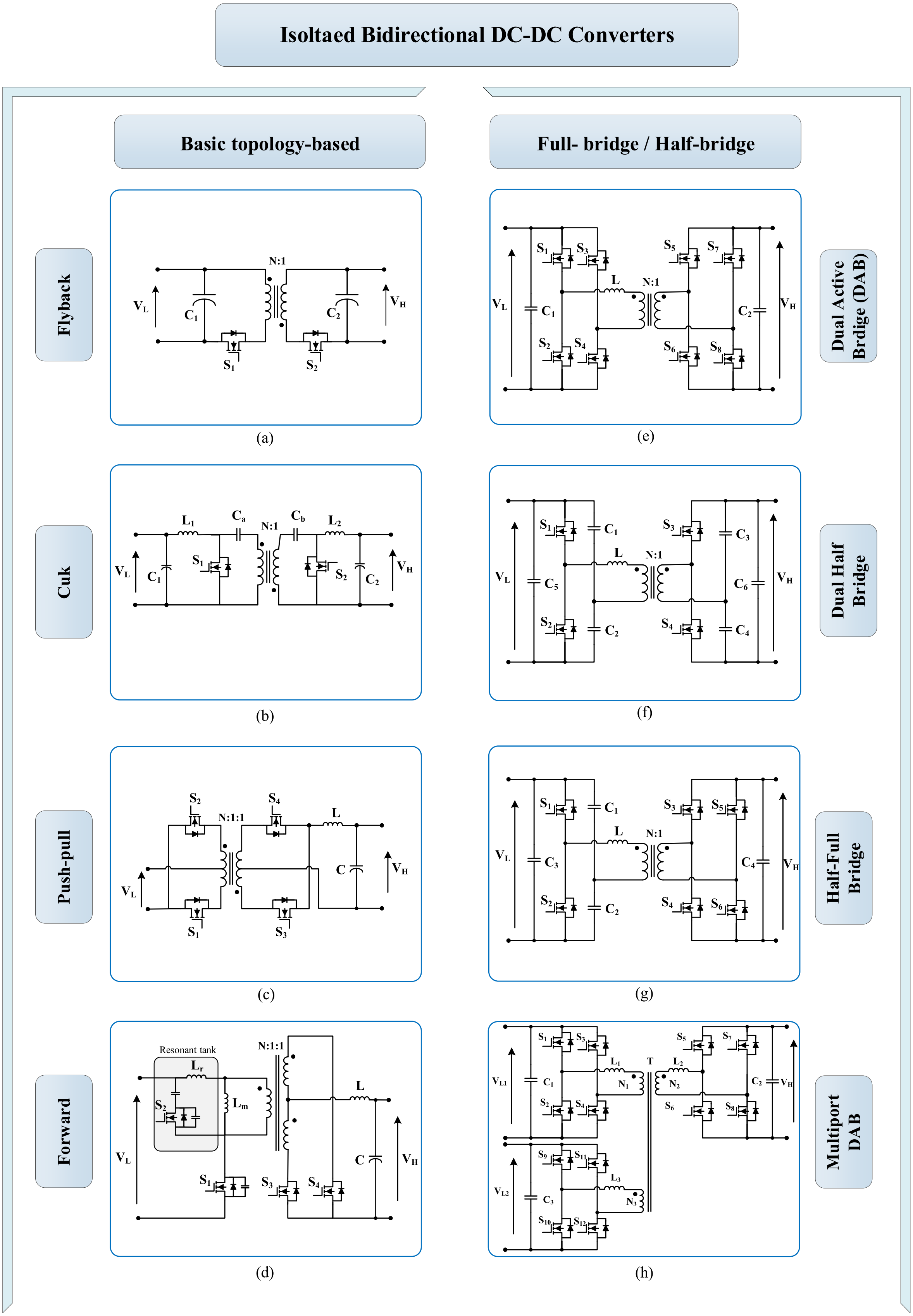

FIGURE 8. Isolated bidirectional DC-DC converters topology classification.

6) DUAL HALF-BRIDGE BIDIRECTIONAL DC-DC CONVERTER [46]–[49]

In comparison with DAB, the half-bridge topology may be useful when the converter is applied in lower power applications and the number of power switches can be reduced from eight to four. Figure 8 (f) shows a bidirectional isolated converter, which uses voltage-fed half-bridge topologies in both sides of the transformer [46]–[47]. By having no inductor in the topology, there is no right half-plane zero (RHPZ) and hence, the minimum-phase behavior of the converter eases the controller design procedure. The converter was proposed based on the dual half-bridge converter, which was originally proposed in [48], and used a current-fed half-bridge topology in the primary side and a voltage-fed half-bridge topology in the secondary side of the transformer. As expected, the dual-half bridge converter has another variant which uses a voltage-fed topology in the primary side and a current-fed topology in the secondary side of the transformer [49].

Using a current-fed topology will enable the continuous current waveform that may be desired in certain applications. There have been further studies on dual-half bridge converters such as interleaved dual half-bridge topology, as an attempt to increase the voltage boost ability and to reduce the transformer ratio and current stress [50].

7) HALF BRIDGE -FULL BRIDGE BIDIRECTIONAL DC-DC CONVERTER [51]–[53]

Considering DAB, in case of a UPS design, an isolated bidirectional DC-DC converter was proposed [51], which uses a voltage-fed half-bridge topology in the primary side and a voltage-fed full-bridge topology in the secondary side of the transformer (Figure 8 (g)) [52]. Due to having less count of switches, it allows simpler control requirements than DAB. Specifically, it is suitable for integration of two-switch buck-boost converter in the half-bridge side for obtaining a complete UPS topology.

There have been other variants for this configuration, such as full-bridge half-bridge bidirectional DC-DC converter that has been combined with impedance networks to achieve better performance [53].

8) MULTIPORT DAB BIDIRECTIONAL DC-DC CONVERTER [54]–[56]

The multi-input converters are a good choice in case of integrating multiple input voltage sources in renewable energy systems and hybrid electric vehicles [55]. An isolated multi-input bidirectional DC-DC converter based on DAB using multi-winding transformer was proposed in [54] along with decoupled power flow management, which is also shown in Figure 8 (h).

The control of the power flow and utilization of the duty cycle control for optimizing the system behavior is an important topic in multiport converters that will be inspected further in the next section [56].

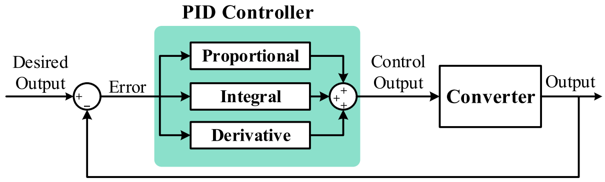

FIGURE 9. The general structure of the PID controller.

III. GENERAL CONTROL STRATEGIES USED IN NON-ISOLATED AND ISOLATED BIDIRECTIONAL DC-DC CONVERTERS

A. CONTROL SCHEMES

Picking a suitable control scheme for bidirectional converters depends on the topologies and the control problems that happen in real applications. Therefore, this section investigates the actual control strategies used in non-isolated and isolated topologies.

For applications that do not require isolation, non-isolated configurations can be both less costly and less complex by providing a transformer-less implementation. However, for high power applications, when isolation between sources and load is required, isolated topologies provide advantages, such as electrical isolation, high reliability, easy realization of soft-switching control, bidirectional energy flow and protecting the equipment and operators for safety reasons. These advantages come from using transformers generally operating at high frequencies. Apart from the topology selection for bidirectional DC-DC converters, a high efficiency and unified control strategy is required for these converters.

The following control strategies are proposed for different applications to solve various control problems that occur in non-isolated and isolated bidirectional DC-DC converters.

1) PROPORTIONAL–INTEGRAL–DERIVATIVE (PID) CONTROL

Due to the simple implementation procedure, the first choice to design a control strategy is a PID controller. The general structure of the PID controller is shown in Fig. 9. This control strategy is applied in many topologies and different control problems and even it may be combined with other control schemes. The most common control problem in non-isolated bidirectional DC-DC converter is to control the power flow in both directions.

In [57], in order to control the active and reactive power independently, the active and reactive currents are controlled respectively, so that the active and reactive powers for AC side are controlled by the inverter and the inverter is controlled by PWM with the reference values. Simultaneously, the DC bus voltage is tuned by a PI controller and by proposing the power leveling unit, the input and output power is controlled.

There are two transition modes in bidirectional converters: the transition from the low voltage side to high voltage side and the reverse one. The low voltage (V_L) and high voltage (V_H) are the control inputs of the system. The conventional control method uses V_L and V_H for the battery charge and discharge, and therefore may not be able to avoid large transient during the transition from low voltage control to high

TABLE 2. Comparison of non-isolated bidirectional converters.

Topology	V_H/V_L	inductors	Capacitors	Switches	Windings	Characteristics	Applications
Flyback Figure 8 (a)	$\frac{ND}{1-D}$	0	2	2	2	- Basic isolated topology; - Discontinuity of $I_{in.}$	Uninterruptable Power Supply [17], Low - Medium Power Application [36]
Ćuk Figure 8 (b)	$\frac{ND}{1-D}$	2	4	2	2	- Continuous I_{in}/I_o - Eliminated ripples of I_{in} /I_o by input/output coupled inductors.	Low Power Application, Photovoltaic System
Push-pull Figure 8 (c)	ND	1	1	4	4	- continuous I_o - no. of windings more than 2.	Medium Power (2φ) -High Power Application (3φ) [34]
Forward Figure 8 (d)	ND	1	1	3	3	- continuous I_o - limited D - low power level apps.	Low - Medium Power Application [36]
DAB Figure 8 (e)	Varies W.R.T Control scheme	0(V-fed)	2	8	2	- The most popular isolated bidirectional topology; - suitable for high power/ voltage applications	High Power Application [40], Automotive Applications [41]
Dual Half-Bridge Figure 8 (f)	Varies W.R.T Control scheme	0 (V-fed)	6	4	2	- less no. of semiconductors; - suitable for lower power applications than DAB.	Automotive [46], Fuel cell, Battery [49]
Half-Full Bridge Figure 8 (g)	Varies W.R.T Control scheme	0 (V-fed)	4	6	2	- suitable for UPS systems; - suitable for integrating two-switch buck–boost converter.	Uninterruptable Power Supply [51], Electric Vehicle [52]
Multiport-DAB Figure 8 (h)	Varies W.R.T Control scheme	0 (V-fed)	n =3	4n =12	n =3	- Several input incorporations; - decoupled power flow.	Multi Sustainable Sources Generation System [54]

voltage control. To overcome this, a PI regulator is used based on the PWM scheme that provides uninterrupted power to the critical AC loads and reduces the size of the DC bus capacitor and the transition time [58].

Another control problem is the switching time between two directions. If the turn-on time of the switch is considered to be fixed, an excessive power loss will appear. Hence, an auxiliary switch turn-on time control is useful, which is generated by a prepared look-up table composed of the load current and the switch turn-on time difference of the main and auxiliary switches [59]. However, since the control algorithm is generally implemented on a DSP, the discrete current sampling would be a problem, which can also cause larger power loss. On the other hand, due to the resonant current sensing problem, the conventional control method cannot be used to select the auxiliary switch time control. Thus, in order to achieve higher more efficiency in zero voltage zero current transition, a discrete voltage controller may be used, based on a PI controller.

Under the operation of a bidirectional DC-DC converter, the dead-time of switches may affect the performance of the system. To find the effects of the nonlinear dependency of the current on the duty cycle, this parameter is taken into consideration in [60]. Considering this condition, the conventional PI may not be a proper controller to regulate the entire current range. Then, a control scheme is designed considering whether the converter is operating in continuous conduction mode (CCM) or discontinuous conduction mode (DCM). When a dead-time occurs the current becomes discontinuous for all currents with a DC value between the negative and positive amplitude of current ripple. For any other values, currents are considered continuous. Since it is very common that the inductor current falls into zero levels, the control strategy should last a long period of time in DCM and also the transition between DCM and CCM need to be fast and stable. Therefore, in DCM a PI controller is used to regulate the current, but the PI parameters in CCM requires a preset with a control algorithm.

Multiple converters are often able to provide an optimal integrated solution with high power conversion efficiency and lower cost. Designing a proper control scheme for a non-isolated Multi-input Multi-output (MIMO) multilevel DC-DC converter is a control challenge that can provide an arbitrary number of controllable voltage nodes with bidirectional power flow capability [61]. The control algorithm regulates the capacitor voltages of each module, based on a given set of reference values given for each node voltage. Accordingly, each row of the converter equipped with an outer-loop PI controller to regulate the capacitor voltage of the corresponding row, and similarly each module of the

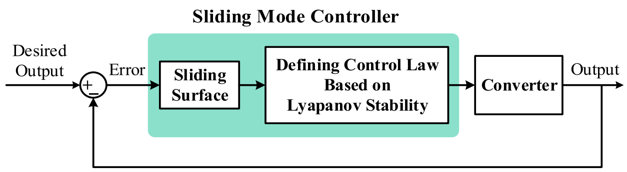

FIGURE 10. Sliding mode control design for converter.

converter equipped with a high-bandwidth inner-loop PI current controller. The current controller would regulate the inductor current of the corresponding module and set its operating duty cycle. The proper regulation of the inductor current protects the switch elements from the overcurrent.

The stability analysis procedures of step-up and step-down configuration are the same. The main idea of local stabilization analysis is to judge through the eigenvalues of the linear system. Nevertheless, the converter dynamics and the proposed control schemes are nonlinear and in order to be able to analyze the stability, the closed-loop system should linearize around its equilibrium point. One of the linear methods that are used to analyze the stability of the power flow transition between the two step-up and step-down mode of the bidirectional DC-DC converters is the bode plot [62]. Hence, the linear transfer function is needed, which can be obtained by state-space averaging (SSA). Based on the stability situation that is obtained by bode plot analysis the proper control approach must be designed.

2) SLIDING MODE CONTROL

There are nonlinear elements in the topology of bidirectional DC-DC converters that make the dynamic equation of the converter nonlinear. One way to design a control strategy for a nonlinear system is to linearize the nonlinear system around its equilibrium point using the existing linearization method [61]. However, these methods accompany with estimation and do not represent the exact model of the system. On the other hand, the perturbation and disturbance are neglected in linear models. Therefore, in order to obtain a reliable result and be able to control the system considering the existence of perturbation and disturbance, it is better to use the nonlinear strategies to control these converters. Fig. 10 shows how a sliding mode controller can be applied to the converter.

Sliding mode control is one of the nonlinear control strategies that is well known for its fast and finite-time response, robustness against parameter variation and external perturbation that can apply either on linear or nonlinear systems. In [63], the rotor angular position of a DC motor used in the bidirectional DC-DC converter is controlled by a variable structure sliding mode method.

When a large-signal appears in the bidirectional converter, external perturbations come along and the small-signal analysis based on the state space-averaging model cannot predict the regulator behavior. Finite-time convergence and low sensitivity to external perturbations of the sliding mode control makes it a suitable control scheme to overcome this condition. However, in this control strategy, the accurate parameters and the state information are required that make it more complicated. In [64], three different sliding surfaces are proposed to analyze the three specific states of switching in a bidirectional Ćuk converter. The analysis shows that if the discontinuity surface is a linear combination of the output voltage, the output current, and the magnetic coupling between inductors is negative, the system will be insensitive to the output voltage variations in steady state.

In conventional techniques, the common method to solve a control problem was to linearize the converter model around the operating point of interest and to design a linear controller. However, this approach is not suitable for problems that the dynamics and the targeted operating points are uncertain such as a bidirectional DC-DC converter connected to a nonlinear load [65]. In this case, a sliding mode control based on a high pass (washout) filter, will ensure robustness under parameter variations regulates the dc bus voltage and reduces the transient response under this nonlinear load variation.

On the other hand, the existing control approaches find it difficult to control the converters that have right half plane poles and zeros base on their linear transfer functions and the stability prediction of the converter in large signal behavior may not be possible, because the control strategy is designed based on the low-frequency small signal model of the converter. Therefore, in [66] two different configurations are implemented based on a general sliding mode controller that can be used to regulate a large type of switching converters based on a nonlinear model. The first configuration includes an op-amp which operates in voltage mode and the second structure includes a transistor that operates in current mode. The results show the fast response and insensitivity to parameter variations.

In [67], a numerical study is carried out to control a bidirectional DC-DC converter used in supercapacitor energy storage systems based on sliding mode control. To design the controller, the dynamic model of the converter is obtained based on the assumption that the supercapacitor dynamics is slower than inductor currents and dc-link capacitor voltage. The proposed sliding mode control strategy shows high insensitivity against structural perturbations.

The bidirectional DC-DC converters are also used in the storage unit of micro-grid systems. The state space average models of these systems are nonlinear and hence the equivalent load would be nonlinear. Since the energy source and load demand fluctuate over time, a robust sliding mode controller would be a suitable approach for regulating the DC bus voltage [68]. In order to overcome the drawback of a single control strategy to solve a problem researches sometimes combine two or more techniques to use the benefits of varied control schemes. For instance, the conventional cascade control method consists of two PI controllers, the outer one regulates the high-side capacitor voltage and the inner one controls the inductor current. However, due to some issues such as severe variation of load and line, PID may not ensure the required performance and the PI regulator

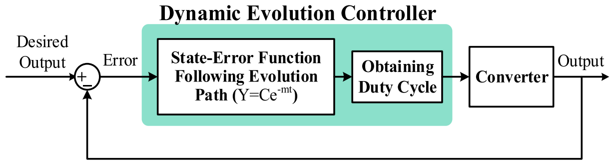

FIGURE 11. Basic structure of dynamic evolution controller.

is combined with a nonlinear fixed-frequency sliding mode control method to achieve a robust dynamic response and better performance [69]. In order to reduce the chattering phenomenon in sliding mode control, a fuzzy sliding mode controller is designed for regenerating the energy of an ultra-capacitor battery [70]. Combining this two control method leads to strong robustness even in the presence of perturbation and it will reduce the fluctuation of the actual response around the desired one.

3) DYNAMIC EVOLUTION CONTROL

An electric vehicle needs to frequently accelerate and decelerate. Thus, a fast dynamic response is a requirement in this system. The electric vehicle powered by fuel cell may not be able to provide a fast dynamic response, which will be solved by using ultra-capacitor in the secondary power source of the fuel cell [71], [72]. The ultra-capacitor is connected to the DC bus of the fuel cell electric vehicle through a bidirectional DC-DC converter and the control problem in these systems is to minimize the voltage drop even after an instantaneous change in the load current. A useful control strategy that works on nonlinear systems is the dynamic evolution (See Fig. 11). The basic idea of this method is to reduce the dynamic state error by forcing it to follow the evolution path regardless of the disturbance existence. This method ensures the dynamic characteristic of the system that operates on the target equation by time. The control law in this method does not require precise knowledge of the model parameters, so it can compensate all of the variations in the input and output voltages and also the change of inductor current, which is another advantage of this controller that causes better performance of the system. The results show that the designed controller is able to respond to fast-changing loads and get charged back to its nominal voltage when the fuel cell power is bigger than the demanded load or when the vehicle is braking.

4) MODEL PREDICTIVE CONTROL

Model predictive control (MPC) is a derivative of predictive control family which uses a predefined cost function to make system variables follow their reference values (See Fig. 12). Due to its fast dynamic response, reference tracking characteristic and its simple implementation thanks to the sophisticated available microprocessors, it is used in the classic bidirectional DC-DC converters in battery application [73]. For general MPC, first, an accurate discrete-time model of the system is required, then the prediction and optimization block needs to be designed. In the prediction stage of the control algorithm, the measurements are imported from the previous discrete-time model and the future predicted value is defined by a function of current values of control variables in each switching state of the converter. Finally, all predictions are forwarded to the optimization stage. In the optimization stage, in each time step, an optimization problem is solved online based on predicted values and the predefined cost function, which leads to the optimal controlling actions.

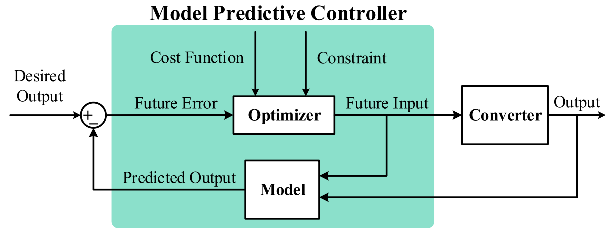

FIGURE 12. General structure of model predictive controller.

Based on the difference between the DC bus voltage and predefined rated range, activation of switches can be divided into three modes: charge, discharge and idle. The controller algorithm should decide which mode to be activated as fast as possible [73]. The model predicted control is able to handle the constraints easily and also since there is no restriction on the type of the model used in the prediction, it can be applied to both linear and nonlinear converters. These features are investigated on bidirectional DC-DC converter for distributed power systems, proposing different models predictive control strategies such as linear MPC, multi MPC and extended dynamic matrix control [74].

The linear MPC requires a linear input-output model to represent the process. One of the major limitations of MPC technique is that in order to have good performance, the converter dynamic model inside the algorithm should be completely linear or act linearly within the operating region. To overcome this, the multi MPC is proposed that uses a multi-model system to linearize the nonlinear process of each model locally at the different operating points. However, multiple MPC cannot handle severe nonlinear dynamic behavior. The extended dynamic matrix control uses the nonlinear model to obtain a precise local linear model at every sampling time. In this method, the linear model updated in each optimization interval to take the nonlinearity effect into consideration in each step. Then the difference between the linear and the nonlinear model will be minimized by another algorithm. This technique handles the drawback that multiple MPC faces with.

5) FUZZY LOGIC CONTROL

For a nonlinear and inaccurate system with uncertainty, parameter variation, and load disturbance, fuzzy control can achieve a robust response. The nonlinear and time-variant nature of converter switches makes it difficult to model the dynamics of the single-stage converter. In addition, the charger and discharger in single stage converters have a wide range of variation. Therefore, the fuzzy logic controller

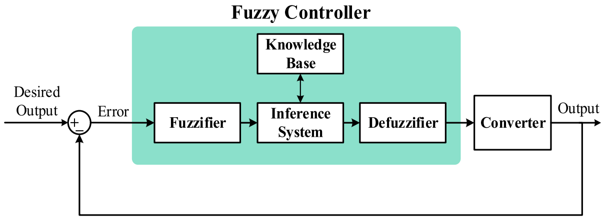

FIGURE 13. The general structure of the fuzzy controller.

became popular in the bidirectional DC-DC converter. The main idea of designing a fuzzy logic controller for bidirectional dc-dc converters is shown in Fig. 13.

In [75], a fuzzy logic controller is designed in photovoltaic power lighting systems that assure the fast dynamic response. Due to its intrinsic adaptive and robust characteristic, the charging and discharging current is regulated in the presence of variations in the parameter. Another control problem that is solved by the fuzzy logic controller is to minimize the power consumption of the grid and also to attain smooth charging and discharging performance of the super-capacitor [76]. For instance, if the braking energy of the electric elevator is accumulated in an energy storage device such as super-capacitors, the energy that is provided from the grid is reduced and thus, the total efficiency of the elevator will improve. If the influence of grid voltage variation on the performance of the super-capacitor is taken into account, a fuzzy-logic controller would be a robust control approach to regulate the dc-link voltage. In some cases that are difficult to implement the electronic configuration of nonlinear control law on the system, the fuzzy logic controller is a good choice due to its simple implementation. In [77], minimum time control is achieved using the fuzzy logic controller.

To control the battery charge/discharge of a DAB converter, two control strategies are developed in [78]: fuzzy logic control and sliding mode control. The main advantage of the fuzzy controller is that no prior knowledge is needed about the system parameters and in comparison with sliding mode, less measurement is needed to design the controller.

Another Type of intelligent control method is an artificial neural network (ANN), which can be applied to any system due to its learning process, so it is suitable for nonlinear control systems. The useful advantages of this method such as no need to detailed information of the system, learning by studying the previous data, the capability to handle large and complex systems makes it an alternative way to solve complex problems. In [79], an ANN controller is designed to stabilize the output voltage of the boost converter and improve the performance over the transient operation. The simulation results show that it can mimic the operation of a PI controller with a faster dynamic response that decreases the overshoot.

In designing the fuzzy logic controller, expert knowledge is important to control law and affects the performance of the system. Therefore, the minimum error needs precise knowledge. In order to reduce the expert error,

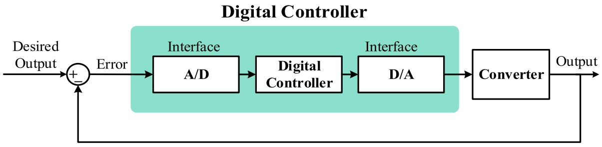

FIGURE 14. The general structure of the Digital controller.

adaptive-network-based fuzzy inference system (ANFIS) is used to adjust the controller parameters that are based on a least square error estimation and a gradient descent during the learning phase [77].

6) DIGITAL CONTROL

The digital control system receives the continuous-time error signal and converts it to the form that can be processed by the computer (A/D interface). After processing, the discrete signal is fed to a controller the output of which is injected to the system (converter). The general structure of the digital controller is depicted in Fig. 14. Due to the presence of high-speed microcontrollers, the digital control strategy become a popular scheme to employ on the bidirectional fly-back converter, [80]. The control problem in this converter is to reduce the capacitive switching loss and electromagnetic interference without sensing high voltage (HV) side signals in either charging or discharging mode of the capacitive load. The proposed method is based on the valley switching technique using a digital controller. In this method, the input supply voltage and the drain-source voltage of low voltage (LV) MOSFET are compared using a high-speed comparator and then, the output signal of the comparator is sent to the microcontroller to detect the comparator output change and produce a fixed on-time pulse. This control method is used to drive a specific actuator. The control scheme shows high efficiency and fast charge/discharge speed.

To develop an accurate small-signal model for a DAB converter, a precise knowledge of the modulation method is required and the EMI filters need to be included in order to consider their interactions with the DAB, [81]. For many high-power converters, DSPs are increasingly employed, mainly because by now, high computational performance is available at a comparably low cost. Advantages of a digital implementation are a considerably higher flexibility compared to analogue electronics, a high electromagnetic interference (EMI) immunity, and the enhanced possibility of process and fault monitoring using an external interface or a network connection. Therefore, a digital control platform is employed for the control of the presented DAB, and thus, the discrete-time transfer function obtained with discrete modelling could be used readily for the controller design.

Intelligent digital control algorithms such as dead-band, switch, and soft-start control are proposed in [45], to smoothly change the power flow directions in the converter and to protect the converter from inrush current at the start-up duration. This converter can control the bidirectional power flow and improves the power conversion efficiency of low-voltage DC distribution systems. This topology can operate under the ZVS for the primary switches and the soft commutation for the output rectifier. In addition, the converter does not require any clamp circuits and snubbers to reduce voltage stresses of the power switches. All the proposed control algorithms are digitally implemented in a commercial digital signal processor (DSP).

Future power management and distribution systems will require the integration of a variety of loads, renewable energy sources and storage elements. The design and implementation of the FPGA-based digital control discussed in [82], in which a wide range of loads and sources are integrated using identical, digitally controlled, software-reconfigurable power modules connected to the same dc bus. This approach offers exceptional flexibility, ease of use and improved reliability, along with the best possible use of energy through software reconfiguration of each module. The use of identical modules reduces development time and cost and simplifies the operation of the system.

Advances of digital control in dc-dc power converters attract the researchers' attention to design more advanced controllers. In order to improve transient responses in synchronous buck dc-dc converters, in [83], the idea of proximate time-optimal digital control is adapted to propose a hybrid digital adaptive (HDA) controller. In this method, the inductor and capacitor currents are estimated by an adaptive adjustment of the linear switching surface slope and lead to HDA controller that achieves near-time-optimal responses for a wide range of step-load transients, for a given fixed input voltage. A stability analysis using piecewise-quadratic Lyapunov functions and discrete-time sliding-mode approach shows that the HDA-controlled converter is stable under all operating conditions and arbitrary disturbances.

The requirement for fast power converter in load regulation, audio amplification, microprocessors, pulsed power, and servomotor applications motivate researchers to work on the main three factors of converter speed: topology, circuit component, and control. The nature of minimum-time solutions requires the creation of a new digital geometric control implementation, which is verified on synchronous boost and buck converters using the same minimum-time framework and digital controller [84]. All power electronics geometric controls use vector surfaces. Vector surfaces are closed-form analytic equations easily constructed using analog math circuits with fixed gains and references. Adjustable curved surfaces, which is needed in the minimum-time surface, would require a great analog/digital processing effort. A well-known control method used to accommodate the solution is raster control surfaces. In this method thanks to substantial memory of digital processors, the pre-processed memory is stored in a table called a raster surface, which is a surface stored as a compressed image inside the digital control. In fact, in this paper, generalizing the minimum-time necessary for a circuit is obtained by switches, passive elements, two storage components, and an energy source to recover from parameter and control disturbances.

7) BOUNDARY CONTROL

Based on the large-signal trajectories of the converter, a switching surface is defined to dictate the switching actions. An ideal switching surface can achieve global stability, good large-signal operation, and fast dynamics. Boundary control is a geometrically-based control method suitable for switching converters having time-varying circuit topology. Among various boundary control methods with first-order switching surfaces, sliding-mode control, and hysteresis control are widely used in power converters. Although these methods generally provide good large-signal performance and stability, the transient dynamics is not optimized. A boundary control using the second-order switching surfaces in buck converters, proposed in [85], can achieve near-optimum large-signal responses and enhance the tangential velocity of the trajectories along the switching surface.

Although boundary control becomes a case of interest due to its effort in achieving minimum-time responses, ideal time-optimal control is sensitive to parameter variations and accuracy of the model which makes it hard to achieve. Therefore, a concept of proximate time-optimal control has been proposed to get close to the time-optimal response in large-signal disturbances. Based on the combination of linear or nonlinear switching surface and standard linear (e.g., PID) control, a proximate time-optimal digital control proposed in [86], which considers arbitrary load disturbances and realistic component tolerances. The approach shows its advantage is voltage regulation of synchronous buck dc-dc converters.

Boost converters are non-minimum phase systems that present slow dynamic response when controlled with traditional compensators. Using nonlinear curved switching surfaces, move state variables toward the desired operating point faster. To achieve the best performance possible, a minimum time control method is proposed, considering the inaccuracy of converter parameters [87]. The curved switching surface was derived in the normalized domain to provide generality that is applicable to any combination of boost converter parameters. Under this boundary control scheme, the converter showed an excellent dynamic behavior, with no overshoot and time-optimal response for start-up and load disturbances and achieving the steady state in only one switching action.

DC-DC converters are commonly controlled using PWM, where switch control signals are determined based on sensing state variables, and by employing compensators using small-signal averaged models and frequency-domain techniques. Various large-signal-based approaches have been considered to improve transient responses and robustness of converters [83]–[87] but sliding mode control is able to characterize the system under both small- and large- signal conditions and provide output robust responses against uncertainties and disturbances.

The traditional SMC, usually requires that the switching surface, $s = 0$, be a combination of the output voltage and an inductor or capacitor current. In general, current sensing leads to increased noise sensitivity and increased cost. The second order sliding mode (SOSM), can solve this problem [88]. The surface in first-order SMC is a line, s = 0, in while in SOSM, it is a point, $s = \dot{s} = 0$. So, under SOSM control, a trajectory in the phase plane can reach the origin directly. The proposed digitally implemented controller can stabilize synchronous buck dc-dc converters without requiring current sensing or an integral term in the control loop. The method illustrates fast stability, fast transient responses, and robust operation in the presence of load disturbances and parameter uncertainties.

In addition to simple implementation, boundary control is also robust. Furthermore, transient performance and ripple specification can be adjusted with relative ease, and in special applications, current and voltage overshoots may be eliminated. These features are used in [97], to overcome the destabilizing effects introduced by constant-power-load and to drive the two-state buck converter system to a desired operating point. The hysteresis band in this paper prevents chattering and also hinder the closed-loop system from stalling. Table 3 summarizes the control schemes stated above.

B. SWITCHING STRATEGIES

1) PULSE-WIDTH MODULATION (PWM)

The output voltage control of the converter is one of the most significant problems in bidirectional DC-DC converters. A common strategy is that for the step-down mode of the converter (Buck) a PI controller is used to regulate the voltage. In the step-up (Boost) mode, another PI controller is introduced to control the current. Usually, the PI controller is used to differentiate between the modes of operations [98]. The proposed control structure implemented on SABER scheme dc-dc converter and achieves a good current tracking performance and avoids the damages caused by over-current. However, in order to achieve the objective of the control phase, it is necessary that instantaneous error between the reference and the measured control variable be calculated precisely. This scheme assures if a system operates only in the steady state, it will track the reference and reject the disturbance. Hence, in order to ensure the controller operates just at the steady state condition, the PI controller is replaced with a ramp of duty cycle from zero to steady value, to turn the output voltage off when it is lower than the reference value.

As mentioned before, though PWM is simple and easy to implement, it has poor dynamic performance. Therefore, in order to improve the performance of the different control schemes developed.

2) SINGLE PHASE SHIFT (SPS)

In phase shift control, the power switches can be chosen to switch at 0-50 percent of duty cycle and 180 degrees out of phase with each other. In fact, as shown in Fig. 15, this control scheme generates the signal to decide when the power switches should turn on and off. However, the amount of the phase shift decides the amount of the overlap between the diagonal switches, which in turn decides the amount of

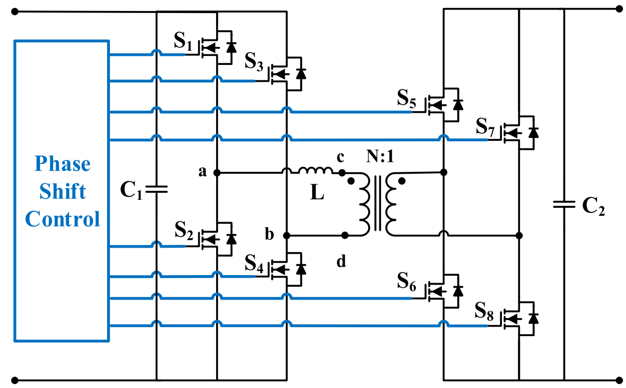

FIGURE 15. General phase shift control to trigger isolated bidirectional switches.

energy transferred. Thus, different types of phase shift have been proposed to produce the proper duty cycle and achieve the particular control objectives such as flexible power flow control and zero-voltage switching (ZVS) in isolated bidirectional converters. To maintain ZVS conditions under a wide input voltage range, the duty cycle has to be adjusted for both upper and lower switches, which may cause high input current ripples [99]. The designed controller is operated on an IBDC used in hybrid electric vehicle energy management application.

The single phase shift control considers only one duty cycle to trigger the switches. In this case, the phase shift is between the primary and the corresponding secondary side of the converter (See Fig. 17.a).

SPS is applicable to different isolated bidirectional converters such as dual active bridge, three port or hybrid converters [99]–[101]. For instance, in [100], the case study is a three-port bidirectional DC-DC converter with two current-fed ports interfacing with low voltage battery and ultra-capacitor in a fuel cell vehicle. The transferred power between every two ports is independent to the third port, so the duty cycle of each half-bridge can be tuned to control half-bridge DC voltage and achieve a wide ZVS range and reduces the converter peak current and root mean square (RMS) current. Although SPS is the most widely used control scheme in isolated converters, it is essentially an active-power-centered control algorithm and lacks the flexibility in power regulation, which brings additional stress to the devices used in the converter during steady-state operation. In addition, efficient operation of single phase shift control is only possible when the voltage conversion ratio is equal to one and the circuiting current becomes much greater and the efficiency is lowered when the voltage amplitudes of two sides of the transformer do not match. Hence, the SPS control can only operate under soft switching within a reduced range of operation. These drawbacks motivate researches to improve the concept of phase shift to overcome the issues.

3) PHASE-SHIFT PLUS PWM (PSP)

In order to minimize the size and the weight of the converters, the switching frequency needs to be increased.

TABLE 3. Summary of control schemes in bidirectional converters.

Control Schemes	Control Problems	Benefits	Limitations	Suggested applications
PID	-Controlling the power flow -Realizing the operation mode -Minimizing the switching time between two directions -Reducing dead time of switches -Protecting the elements from overcurrent	-Low cost -High reliability -High dynamic performance	-Low efficiency -Lack of robustness in presence of disturbance and uncertainty -Weakness in avoiding large transient between directions	Smart grid systems [57], electric vehicle [59], fuel cell [89], satellite applications [90].
Sliding Mode	-Considering external perturbations in large signal -Dealing with severe variations in load and line	-Reference tracking -Fast and finite-time response -Robustness against parameter variation and external perturbation -Ability to characterize the system under both small- and large- signal conditions	Accurate parameter and state information are needed	DC motor control [63], stand-alone dc networks and dc microgrid [64], energy storage applications [67], hybrid electric vehicle applications [91].
Dynamic Evolution	Minimizing the voltage drop even after an instantaneous change in the load current	-Reference tracking - High performance -No need to precise knowledge of the model parameters -Able to compensate the variation	The duty cycle calculation has a division component, making it difficult to implement in analog circuit form.	Interfacing ultra-capacitor energy storage to fuel cell system [72].
Model Predictive	-Controlling the power flow -Regulating the DC voltage and current	-Fast dynamic response -Reference tracking -Simple implementation thanks to powerful microprocessors	Limited to using a linear model of the converter inside the algorithm	DC distributed power system [73], battery application [74], and hybrid powertrain in tramway [92].
Fuzzy	-Minimizing power consumption from the grid -Attaining smooth performance of super-capacitor in charge/discharge -Minimizing control time	-Fast response -Robust response due to its adaptive characteristic -Applicability to nonlinear and inaccurate system with uncertainty, parameter variation and load disturbance	Sensitive to expert knowledge (ANFIS reduces the expert error)	PV powered lighting system [75], energy storage, elevator motor drive, braking energy [76], and fuel cell hybrid electric power systems [93].
Digital Control	-Achieving valley switching in flyback converter -Accurate small-signal modelling of DAB -Changing the power flow directions smoothly with start-up inrush current protection -improving the transient response's speed	-Reduces the capacitive switching losses without sensing HV side -high EMI immunity -Enhances the efficiency and charge/discharge speed -Higher flexibility than analog electronics -Fault monitoring -Ease of use -Improved reliability -Stability in hybrid digital adaptive controller under all operating conditions and arbitrary disturbances	-Difficult to implement the electronic configuration of nonlinear control law -Requiring great analog/digital processing effort (raster surface control can help to solve this issue)	Driving a capacitive incremental actuator [80], energy storage systems [94], hybrid electric vehicle [95]-[120], DC distribution system [82], [96], and power management [82].
Boundary Control	-Time optimal transient response -Switching surface without current sensing -Devising a normalized switching surface for any boost converter	-Global stability -Good large-signal operation -Fast dynamics	-Not optimized transient dynamic -Ideal time-optimal control is sensitive to parameter variations and accuracy of the model (proximate time-optimal control can help to solve this issue) -Large signal performance (second-order switching surface can solve this issue) -Current sensing in designing switching surface leads to increased noise sensitivity and increased cost (SOSM can solve this limitation)	Buck and boost converters [85]-[87].

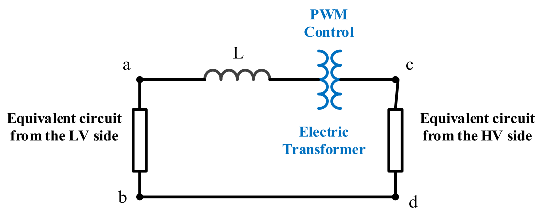

FIGURE 16. Phase-shift plus PWM.

However, increasing the frequency results in higher switching losses. Phase-shift ZVS technique can solve this problem since it can realize ZVS for all switches without any auxiliary switch. However, as can be seen in Fig. 15 and the equivalent circuit is shown in Fig. 16, when the amplitude of input voltage (V_{ab}) and output voltage (V_{cd}) are not matched, the current stresses and RMS currents of the converter become much higher and the transferred reactive power increases. This situation leads to higher current stresses of the switch devices and higher conduction losses, and hence, the converter cannot achieve ZVS in light-load condition. A PWM plus phase-shift (PPS) control is able to overcome this issue [102]. As shown in Fig. 16, the PWM control of duty cycles acts as an electric transformer between the equivalent input voltage and equivalent output voltage so that both positive and negative amplitudes of equivalent input voltage are equal to those of output voltage. Compared with PS control, PPS control can reduce the current stresses and RMS currents of the converter. So, the converter losses decrease and ZVS in larger load variations can be achieved.

The active clamping branch, PWM technology and selecting appropriate control parameters of this variable structure controller make the PPS control suitable to deal with high voltage spike and high circulating conduction losses in current-fed switches and can improve the steady and dynamic performance of the system [103], [104]. This technique can be applied to aircraft HVDC power supply and UPS system.

Peak current in isolated transformer causes core loss. Hence, in order to achieve more efficiency, limiting the current is a considering control problem [105]. Dual loop control is a suitable design to generate the switching commands by comparing the current generated by the outer voltage loop and the inner current loop. So, the output voltage would be an output state, the phase shift is the controllable input and the load current is the disturbance. To generate a reference current, the generated error should pass through a PI regulator and current limiter so as to limit the maximum current. This method is used in a battery energy storage system of an aircraft flight surfaces.

Although the isolation transformer can improve the electromagnetic interference (EMI), it can only reduce high-frequency EMI interruption from one side to the other, while EMI caused by its own side or environmental factors couldn't be avoided. Eliminating part of the sources could lead to shoot-through of bridge arms. To address this problem, a bivariate coordinated phase-shifting shoot-through control strategy based on two PI controllers is designed on a switched

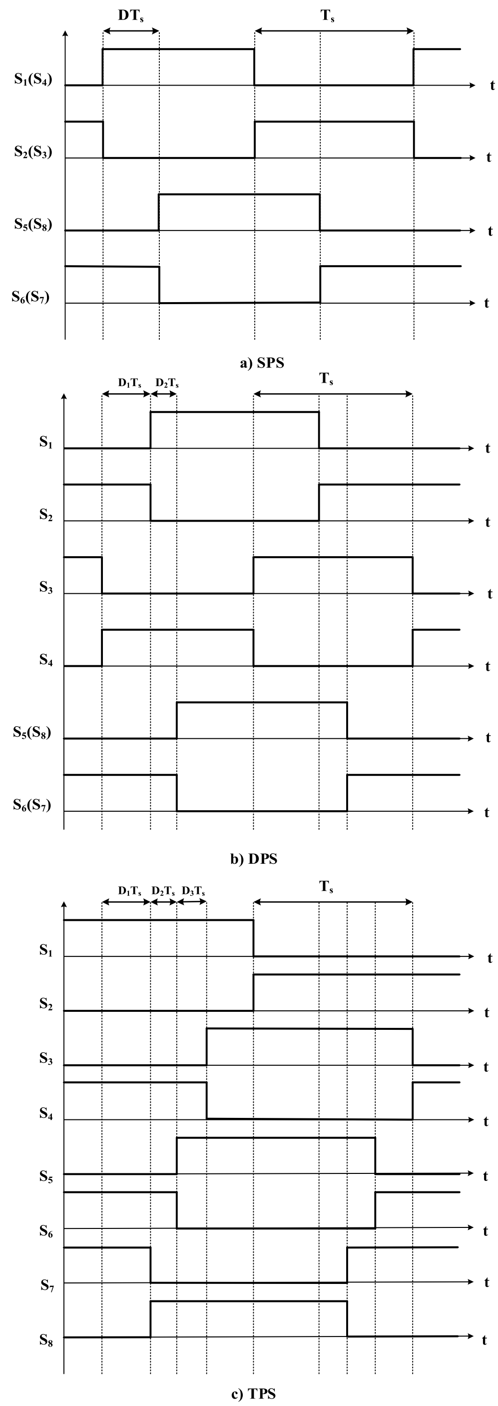

FIGURE 17. Generating the control signal to trigger the gate signal of power switches: (a) SPS (b) DPS and (c) TPS.

Z-source isolated BDC that the output voltage can be regulated by both the phase-shifting and shoot-through angle to provide a wider regulation range [106]. These advantages make this method suitable to be used in both low-power and high-power applications, such as battery energy storage system, dc motor driving system, UPS and auxiliary power supplies for hybrid electrical vehicles. To minimize conduction loss with PPS control, transformer's turn's ratio has to be obtained precisely which is difficult. But, even if the turn's ratio can be designed precisely and the reference of PWM control loop is given accurately, the slew rate of leakage inductance current can't be kept zero in facing with the load variation due to the existence of circuit elements that naturally are in variation. But, the development of the processing speed of DSP, makes it possible to solve this problem. Therefore, the high-frequency leakage inductance current can be sampled by a low-cost current transformer and the inner A/D converter of the DSP to avoid the voltage sensing of the clamp voltages by voltage sensors to become cost-effective. So in [107], a PPS-based controller is designed to keep the slew rate of the leakage inductance current zero during the power transfer stage in spite of the variations of turns-ratio mismatch, output power variations, and system parasitic parameters. This scheme is suitable for high voltage applications.

Once the voltages on the two sides of the converter are not matched, a high circulating current, high turn-off power loss and lack of soft switching occurs that will dramatically decrease the conversion efficiency. PWM control can be adapted to ensure that the voltage on the two sides of the converter is always matched. And also phase-shift control can regulate the power flows of the proposed bidirectional converter [108]. Regulating the duty cycle by the PI controller improve the soft-switching performance of the converter. The application of PPS control strategy can be extended to a wider group of bidirectional converter [109]. The experiment result shows that the proposed control technique is suitable for an energy storage system with a wide voltage range and high efficiency.

The combination of PWM and SPS provide useful advantages that can be seen in Table 4. But besides these benefits, researchers found that the main factor that causes the circulating current of the converter is the reactive power under SPS control, which is contributed to large peak current and large power loss. So, this fact triggered the development of single phase shift control method aiming at eliminating reactive power and increasing efficiency.

4) DUAL PHASE SHIFT (DPS)

In the power transmission process, there are time intervals that backflow (negative) power occurs. In SPS control, the power flow is dependent on the transformer's leakage inductor. With the increase of the backflow power, the forward power increases to compensate for the loss. Therefore, the circulating power and current stress will increase, which results in a great loss in power devices and magnetic components and consequently low efficiency in the converter. In order to decrease the backflow power, the concept of phase shift needs to be extended [110]. In this control scheme, not only there is an outer phase-shift ratio (D2), which is the phase shift between the primary and secondary voltages of the isolation transformer, but also the inner phase-shift ratio (D1) is proposed which is the phase-shift ratio between the driving signals in each side (See Fig. 17.b). The proposed scheme is used in power distribution micro-grid and in comparison with traditional SPS method, applying the extended phase shift, which also called dual phase shift (DPS), expands regulating range of transmission power and enhances regulating flexibility; reduces power-circulating flow, and thus reduces conduction losses and improves the system efficiency; reduces current stress, and thus reduces switching losses and prolongs the service life of devices; and also it is easy to implement.

The DPS control can be used to lower the inrush current in the starting process of the converter, which adds another degree of freedom to the system by adjusting the time sequence between the gate signals of diagonal semiconductor switches [111]. This method is useful in high voltage or power converters, where it is difficult to design a safe operation area. The dead-band effect is also easier to compensate in DPS control than in SPS control and with the same outer phase-shift ratio D2, the DPS control can offer wider power transmission range than the SPS control [112].

Renewable power sources are often varying with time, weather, and environment and they are unstable and discontinuous, which makes it difficult to predict the generated power range. In order to predict the dissipated power for each power component, DPS control can give a detailed switching characteristic analysis that analyzes the efficiency-optimized characteristic across the whole range [113], [114]. DPS can be combined with model predictive control, in order to improve the dynamic performance of the converter [115]. The combination demonstrates good behavior in eliminating reactive power, decreasing the steady state voltage ripple and dynamic performance.

The predominance, disadvantage, and application of DPS control are listed in table 4 [107]–[116]. Adding a degree of freedom to SPS, empowers the DPS to improve the converter performance, to eliminate the reactive power, to decrease the back-flow power and to enable the dissipated power prediction for each power component. Although some DPS-based algorithms are devised to optimize the current-stress or efficiency of the isolated converters [113], [114], they have suboptimal operation modes and finding the global optimal solution is still under investigation.

5) TRIPLE PHASE SHIFT (TPS)

As mentioned in the previous sections, the phase shift control is commonly used in the isolated bidirectional converters due to the easy-to-use feature. However, the single phase shift control shows difficulties in keeping high conversion efficiency over wide operating range as the ZVS range is limited and the circulating current of the inductance is high in such converters. The dual phase shift not only overcomes this issue but also is able to eliminate the reactive power and therefore minimize the converter conduction losses. However, the efficiency improvement using DPS control is not obvious in some operating zones as the phase-shift angles of the gate signals between the diagonal devices in two bridges are assigned equally and result in sub-optimal operating modes.

TABLE 4. Summary of switching strategies in bidirectional converters.

Switching Strategies	Control Problems	Benefits	Limitations	Suggested applications
PWM	Considering different operation modes of the converter	Simple implementation	-Poor dynamic performance -Limitation in regulating the range of voltage	High power applications [122], rural induction generator [123], machine drive [124].
Single Phase Shift (SPS)	-Controlling the power flow -Minimizing the circulation power loss caused by circulation current -Maximizing the derived power of multi-port converter	-High dynamic performance -Easy to use -Soft switching control -Small inertia -Achieving unified control - ZVS capability	-Backflow power -Low efficiency over wide operating range -Not effective in wide voltage-variation -Lack of flexibility in power regulation -Lack of ZVS realization in wide load range -Limited ZVS operation range and high current stress in non-unity voltage-conversion ratio -High circulating current and conduction loss in mismatched magnitudes of the input/output voltages -High inductor RMS current and hard switching in light loads -Bringing additional stress during steady-state operation	Hybrid electric vehicle energy management [99], fuel cell vehicle [100], PV application on a dc distribution system [125].
PWM + SPS	-Minimizing the size or weight -Reducing the EMI interruption -Matching the two sides of the converter voltage in all situations -Choosing proper duty cycle and corresponding phase-shift value -Eliminating the shoot-through of bridge arms -Zeroing the slew rate of leakage inductance current -Reducing the peak current in isolated transformer causes core loss -Reducing high voltage spike and high circulating conduction losses in current-fed switches	-Reduces circulating current -Reduces current stress -Reduces conduction losses -Expands ZVS range -Improves the efficiency -Enhances the reliability -Enhances the flexibility because of soft switching possibility	Restricts the input and output voltages to square waveforms with 50% duty ratio leads to high current and reactive power	Low-power and high-power applications, electric aircraft [105], high voltage applications [107], energy storage systems [108], photovoltaic battery [126].
Dual Phase Shift (DPS)	-Decreasing the back flow power -Improving the dynamic performance -Eliminating reactive power -Designing a current-stress-optimized switching strategy -Optimizing efficiency across the whole load range -Predicting the dissipated power for each power component	-Decreases peak current -Minimizes conduction loss - Increases power capability -Enhances efficiency -Limits high inrush current in the starting process In comparison with SPS, it has: -Wider power transmission range -More power transfer -Better regulating flexibility -Better dynamic and static performance -Better dead-band effect compensation	-Has suboptimal operating modes -Difficult to find global optimal efficiency	Micro grid power distribution [110]-[112], in high voltage conversion ratio and light load situations [113], power conversion application [127].
Triple Phase Shift (TPS)	-Reducing the current stress -Considering all operating modes -Stability analysis under possible arbitrary parameters change -Extending soft-switching operating range	-Enhances the performance by improving the ZVS range -Reduces the overall losses by introducing an extra control variable -More flexible than SPS and DPS, due to the existence of three degrees of freedom	No closed-form solution found for achieving the optimal control parameter in medium power level	Battery storage systems, fast charging application, traction transformer in electric railway locomotive, [128].

To address the problem of low efficiency of these converters in some applications such as light-load case, the triple phase-shift (TPS) control strategy has been used that includes three phase shifts [117]. The first is the phase shift between the primary and the corresponding secondary control signal; the second is the phase shift between the diagonal control signals in the primary power circuit, and the third is the phase shift between the diagonal control signals in the secondary power circuit (See Fig 17.c). Proper selection of operating modes and phase-shift group shows the efficiency improvement in a large load range. Triple phase shift adds an extra control variable to improve the ZVS range and reduces the overall loss that as a result improves the performance [118].

The TPS control operates three degrees of freedom that provide more flexibility than SPS and DPS control. However, no closed-form solution is found for the optimal control parameter at medium power levels. In order to derive the global minimum current stress and the optimal control parameters, an optimized TPS control scheme has been proposed that minimizes the current stress and achieves full soft-switching operation in the whole load range, minimum conduction and copper losses and enhancement of the efficiency in the converter [118].

When the parameter of the triple phase shift control scheme is arbitrarily altered, the stability analysis is inevitable. For this purpose, first a mathematical model should be developed for the bidirectional converter with triple phase-shift control, which is a nonlinear system. In order to make the system attain high efficiency in a large load range and improve the adaptability of the system to parameter changes, the triple phase-shift control method may be used [120]. As the DAB converter is separated into eight stages in one period, the stability analysis of this converter may be complicated. If a positive-definite Lyapunov function can be found for the bidirectional converter in a stage and its derivative is negative definite in this stage, the equilibrium point of the bidirectional converter is internally asymptotically stable in this stage. If the converter is stable in every stage and there is no instantaneous change at the interface of two stages, it will be stable during the entire working period.

As mentioned before, triple phase shift provides the possibility of extension of the soft-switching operating range by considering all operating mode in control design and is able to prove the stability of the converter under arbitrary parameters change. These advantages make it useful for applications like battery storage systems, fast charging applications, traction transformer in electric railway locomotive and etc. However, it has some limitations in finding the optimal control parameter to optimize the current stress, for instance, in the whole power range. The difference between SPS, DPS and TPS is in their duty cycles. SPS has a single duty cycle, DPS has two and TPS has three duty cycles. The triggering of power switches in phase shift control design is based on these duty cycles. Fig. 17 shows how to generate the required control signals in SPS, DPS and TPS to trigger the gate signal of power switches based on the defined duty cycles.

Table 4 shows a summary of what is stated in switching strategies used in bidirectional converters.

IV. CONCLUSION

Bidirectional DC-DC converters can be investigated from various perspectives. This paper presents a comprehensive review of these converters from the topological structure and the control schemes.

The fundamental bidirectional converters are non-isolated topologies, which are simply derived by replacing the unidirectional switches of the basic converter with a bidirectional switch. Galvanic isolation can bring an extra degree of freedom namely the transformer turn ratio to the voltage boost ability of the converter. In addition, it provides isolation between the input-output side and the possibility of introducing the multi-input versions of converters. The most popular bidirectional converter uses two full-bridge topologies in both sides of the transformer, which is known as DAB converter and is suitable for high power applications. From the circuit topology point of view, same as other DC-DC converters, the current research focus is to minimize the weight, volume, losses and cost, and to maximize the reliability and power density. Various techniques are utilized to reach these aims such as increasing the voltage boost ability of the converter, introducing multi-cell topologies, and using advanced solid-state semiconductors such as GaN. Furthermore, the wireless power transfer for the charger application from low power to high power ranges is another ground of research in the field.

This article also investigates the control schemes and switching strategies applied to both non-isolated and isolated topologies of bidirectional DC-DC converters. For the isolated topologies, the most useful switching strategy is designed based on the phase shift control. The useful characteristic of PWM such as simplicity of implementation has inspired the researchers to combine it with single phase shift control method to reduce the circulating current, current stress, conduction loss and expand ZVS range. Therefore, finding the optimal solution is under investigation for these methods with the augmentation of phase shift. The main ideas of control schemes and switching strategies used in bidirectional dc-dc converters are reviewed in this paper and current research focus are to solve bigger problems with these methods. For instance, works around industrial applications were very rare because of the presence of circulating current and the research focus is getting more popular in this area. Moreover, from the control point of view, designing a soft-switching control strategy with high reliability and efficiency is necessary. The trends in control design are going through the simplicity of control circuit to reduce the additional elements and variable frequency as well as the design of control strategies to achieve zero-voltage switching for all switches in all operation modes.

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