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Review of multiport isolated bidirectional converter interfacing renewable and energy storage systems

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ABSTRACT

Multiport converters increasingly gain prominance in the recent past to interface renewable energy sources like photovoltaic cells, fuel cells with the load. Energy storage elements like battery and supercapacitors play an important role as an additional and alternate sources in systems with primary intermittent renewable energy sources. As these energy storage element's charging and discharging cycles are to be controlled, an isolated bidirectional converter topology with transformer is used. The galvanic isolation provided by the high frequency ac link transformers in partly isolated and fully isolated topologies makes these converters most preferrable in high power applications like electric vehicles. A comprehensive review is performed on various three port partly isolated topologies addressed by different research groups. The key contributions on soft switching for reducing switching losses and improving overall converter efficiency with help of resonant elements are discussed. In addition, control strategies for power flow control with enhanced soft switching of partly isolated converters are highlighted. A summary of converter topologies is provided considering power rating, device count, soft switching resonant elements and efficiency which gives an idea for selection of suitable topology for the desired system requirement.

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1. INTRODUCTION

Renewable sources such as Photovoltaic (PV), Fuel cell(FC) and Wind energy gains popularity in power generation due to the technology advancements and environmental concerns. In addition, integration of hybrid power sources are increasing in recent days. By nature, intermittency and unpredictablity of renewable sources and load highly demands inclusion of energy storage systems like battery, supercapacitors to meet the load requirement and also to improve the dynamic and steady state performance of the sources. Thus DC-DC converters are included to interface source, energy storing elements and load. Several unidirectional converters are proposed to realise DC-DC power conversion and to meet necessary voltage requirement of the load. In case of systems with energy storage, two individual unidirectional converters are used to control it's charging and discharging cycles. However, both charging and discharging capability can be implemented in same topology to lessen the count of power electronic components. Thus bidirectional DC-DC converter manages power flow between input source, energy storage elements and load in addition to voltage level conversion, control and increased lifetime of energy storage devices. Isolation between power circuits are preferrable for safety reasons and hence to achieve DC galvanic isolation, transformers are included in the topologies. Thus intense researches are being carried out in development of new power electronic circuit topologies that interfaces solar PV, battery or supercapacitors and load with controlled power flow between these ports [1–5].

The Bidirectional DC-DC converters (BDC) are operated in Boost mode (step up mode) and Buck mode (step-down mode) that controls power flow both in forward and reverse direction. The applications of such BDCs are extended in Electic Vehicles to charge and discharge the batteries. Dual Active Bridge (DAB) BDC topologies with a source port and a load port are derived with bidirectional power flow control [6–8]. However, only two ports are controlled which leads to development of three port converter topologies to integrate multi input and multi output ports with bidirectionality achieved in one or more ports. Based on the circuit configuration with or without galvanic isolation provided by the transformer, these converters are categorized into partly / fully isolated converters and non-isolated converters respectively.

The design and analysis of various multiport topologies integrating two or more sources are commonly found in literature. In this manuscript, a comprehensive review of three port partly isolated bidirectional converters in recent decades are given enhancing the researchers to develop many novel topologies for various applications. This paper gives an descriptive analysis of existing multiport bidirectional converters listing its enhanced features and key contributions compared with other topologies. The organization of this manuscript is as follows: An overview and importance of bidirectional converter topologies are discussed in section 2. Section 3 deals with various isolated topologies highlighting the topology features and limitations. A comparison of the topologies based on number of devices, soft switching elements, its efficiency are reported. In addition, the key contributions by the authors on achieving soft switching of devices and control techniques are also discussed followed with a brief summary in section 4.

2. OVERVIEW OF MULTIPORT BIDIRECTIONAL CONVERTERS (MP-BDC)

The traditional DC-DC converters involve two ports namely the source and load port. The power changeover between the two ports either unidirectionally (conventional converters) or bidirectionally (Bidirectional DC-DC Converter). Converters interfacing more than two ports are generally called multiport converters (MPC) in which the power conversion takes place between any two sources of the available sources. The primary source of the multiport converter is sized based on the average load power consumption for a particular application instead of the peak power. The primary source oversizing is avoided. In addition, the auxilliary storage serves the purpose of acting as a back up energy source in case of main source failure and also improves the system dynamics. [9, 10]

The input source port of the multiport converters is connected either to the renewable energy sources like photovoltaic system, fuel cells, wind energy or the energy storage systems like battery, supercapacitor or both [11]. The output load port is linked to DC load. The energy conversion could be unidirectional or bidirectional between any of these ports . The port voltage, current or power is regulated in each port for power flow control. The phase shifting technique is basically employed for power flow control. The inductors in addition to transformer windings act as energy transfer elements for power exchange.

As per the law of conservation of energy (power balance principle), in a system total power generated and total power consumed are equal. Neglecting system loss, the source power is equal to all the power sunk in the ports expressed as in (1) where P_x is positive for power sourcing from the port and negative for power sinking into the port [9].

$$\sum_{x=1}^{x=m+n} P_x = 0 \tag{1}$$

Depending upon the source port power levels compared with load port, the operating modes of three port converter are as follows [12]: Single Input - Dual Output (SI-DO) mode in which input renewable source supplies the load and surplus power from it charges the energy storage elements. In Dual Input - Single Output (DI-SO) mode, power from both source and energy storage supplies the load to meet the load demand. The converter functions in Single Input - Single Output (SI-SO) mode is similar to traditional two port DC-DC converter in the absence of renewable input power. The load is supplied only by the energy storage system. In case of motor load operating in regenerative braking mode, the braking power helps in charging the energy storage element representing bidirectional power flow in load port.

The renewable energy sources like photovoltaic cells, fuel cells, wind mills can be integrated to share the load with the help of power converters. As the renewable sources are intermittent by nature and load demands are unpredictable, energy storage systems like battery and supercapacitors are included as an additional component. Also, in applications like electric vehicles, the batteries and supercapacitors are the major input sources which are integrated to share the load. The conventional converters are being replaced with the multiport converters because of its compact design with better efficiency. As energy storage elements undergo charging and discharging cycle, the port that connects it should be bidirectional.

The multi-port bidirectional converters are categorized into (i) Non-isolated, (ii) Partly-isolated and (iii) fully isolated converter depending on the connection between source, load and storage ports. The non-isolated multi-port DC-DC converter shown in Figure 1(a) are derived from basic buck, boost and buck-boost converters. Due to the limitation of converter gain, the voltage conversion ratio can be extended by using coupled inductor. The circuit employs minimum power switches with no transformers for galvanic isolation and hence results in smaller size and higher power density. The partly-isolated and isolated multi-port bidirectional DC-DC converters employs a high frequency (HF) transformer to isolate source ports and load port galvanically avoiding shock hazards. In addition, the voltage conversion gain of the converter is increased by proper choice of transformer turns ratio. The galvanic transformers used in isolated and partly-isolated converters relatively limits power density and efficiency due its increase in overall size and magnetic losses respectively. The choice of modulation control strategies and power management systems helps in implementing these multi-port converters for the desired applications. A detailed review of various partly-isolated multi-port bidirectional DC-DC converters are discussed below.

2.1. Partly-isolated multi-port bidirectional DC-DC converter

In partly-isolated multi-port bidirectional DC-DC converters, the source ports and bidirectional energy storage ports will be connected directly and mostly, the load port will be galvanically isolated using transformers. In some cases, the bidirectional energy storage port and output ports will be connected without isolation and then interfaced to the source through a HF transformer. The general block diagram representing partly-isolated converters are given in Figure 1(b) and 1(c).

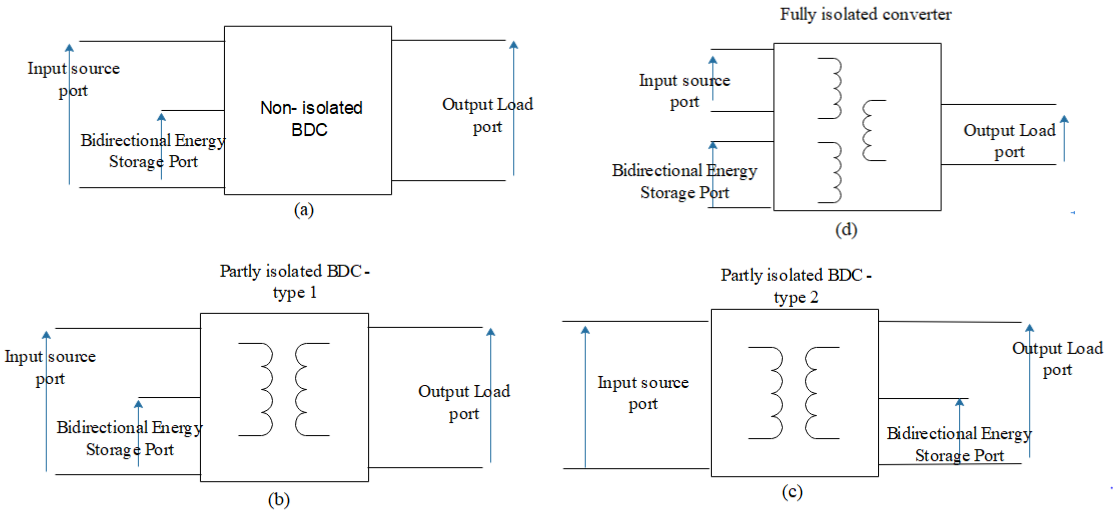

Figure 1. Structure of Multi-Port Converter (a) Non-Isolated Topology, (b) Fully Isolated Topology, (c) & (d) Partly-Isolated Topology Type 1, Type 2 respectively

A novel three port full bridge converter for renewable energy applications was proposed in [13] is given in Figure 2. It was actually derived from conventional full bridge topology. The topology comprises two bidirectional source ports and an isolated unidirectional load port without including any additional devices. A wide range of source voltage variation is allowed by the converter. The power relationship between PV and load makes the proposed converter to operate either in dual output mode (PV charging battery and feeding the load) or dual input mode (PV and battery supplying load) or SISO mode (battery discharged to feed load in the absence of PV source). Pulse Width Modulation strategy is implemented for smooth control of power flow with improved efficiency. The advantage of this topology is that power conversion is single stage with increased output voltage between the ports. The stored energy in the transformer leakage inductor is utilized to achieve Zero Voltage Switching (ZVS). However, only the primary side switches are soft switched and secondary side diodes are hard switched. In spite of minimized switching losses, increase in conduction losses results in reduced efficiency which can be overcome by half bridge topology by reducing device count.

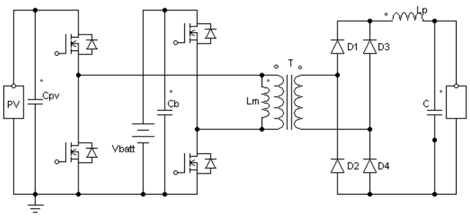

Figure 2. Full Bridge Three Port Converter [13]

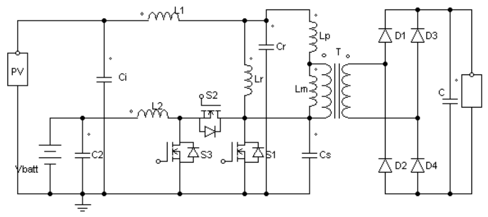

Figure 3. Three port isolated converter with LCL resonant tank [14]

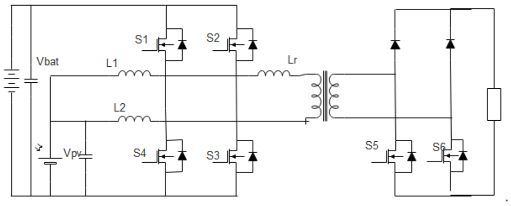

Figure 4. FB-TPC Topology with PWM-SSPS control [15]

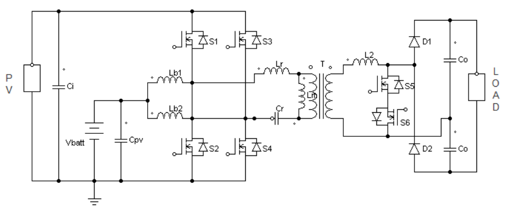

Figure 5. FB-TPC Topology with Voltage Doubler circuit [16]

The three port bidirectional DC-DC converter with two winding transformer integrating PV cells and Battery output load port is proposed in [14] and is shown in Figure 3. In order to realize Zero-Current Switching (ZCS) for the main switch S_1, resonant elements namely L-C-L (Inductor-Capacitor-Inductor) were included. The voltage stress in main switch S_1 and the current stress di/dt value are reduced as a result of soft switching achieved by L-C-L resonant tank. The PV and load ports are unidirectional and the energy storage battery port is bidirectional. When the generated solar power is in excess of load demand, the converter operates in buck mode and the surplus power charges the battery. In case of Ppv $<$ Pout, the converter works in boost mode to supply energy from charged battery to satisfy the load requirement. In the absence of solar energy, the battery completely contributes the load demand as the converter manages to operate in boost mode. It has been observed that the LCL component reduces the voltage stress and current stress by 45% and 91% respectively. However only the main switch S1 is soft switched and the remaining switches controlling battery bank are hard switched which results in overall increased losses. Also, the load port is unidirectional and hence this topology is not preferred for electric vehicle applications under regenerative braking mode.

The limitations of primary side phase shift control (PSPS) like limited soft switching range, high conduction losses and high current ripple are overcome by proposing a novel PWM - Secondary Side Phase Shift control (PWM-SSPS) as in [15, 17–19]. The proposed topology comprises of two bidirectional ports and an isolated port is given in Figure 4. Two interleaved Buck-Boost circuit integrated with Full Bridge converter to eliminate the circulating current so that conduction losses are reduced and hence resulting in improved efficiency in the range of 95% to 97%. A novel topology proposed in [16] as in Figure 5 has similar primary side converter circuit, but secondary side with voltage-doubler rectifier circuit. An organised approach for synthesizing three port converter is proposed using interleaving bidirectional converter and bridgeless boost rectifier. The analysis is carried out in both continuous and discontinuous conduction modes of converter operation. PWM modulation control is employed for primary side converter and phase shift control strategy for secondary side converter. The voltage stress and current ripple are highly reduced. ZVS is achieved for switches of both primary side and secondary side converters as result of PWM-SSPS technique. However, the selection of high frequency inductor L_f has a tradeoff between maximum output and efficiency for various load conditions.

Similar to the above presented converter, a topology integrating full bridge converter with two phase interleaved boost converter interfacing stand-alone PV system with energy storage battery is proposed in [20, 21]. A center tapped secondary side transformer is used with a limitation of unidirectional load port as in Figure 6. The minimum current ripple and better soft switching range are obtained with a trade-off in choice of inductor value with duty cycle maintained at 0.5. Only PWM control is implemented in the primary side converter circuit for maintaining the duty cycle to the prescribed value. However the limitation of center tapped circuit is overcome in [22] replacing with bridge type rectifier. The LLC resonant tank is included so that wide soft switching range, moderate circulating current and better power density can be obtained. In addition, the PWM and PFM modulation strategy is implemented. In Figure 7, the duty cycle D of S_1, S_3 (the upper switch pairs) given and switching frequency are the control variables for independent power flow of each port and tight load regulation of the output port. To achieve higher efficiency, the duty cycle and switching frequency are restricted to a relatively limited range. However, value of resonant elements are to be carefully chosen as it results in increased short circuit current and peak capacitor voltage of resonant elements.

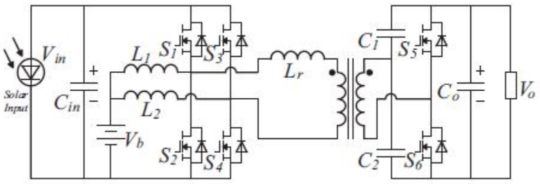

Figure 6. FB-TPC Topology with bidirectional output port [20]

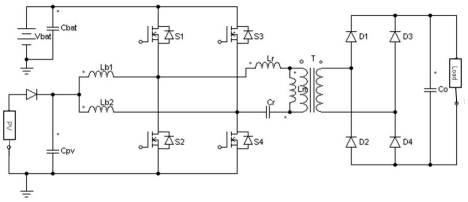

Figure 7. TPC integrated with interleaved boost converter and LLC tank [22]

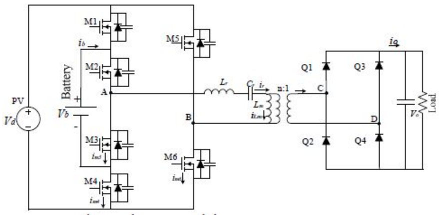

Figure 8. LLC-TPC using hybrid full bridge structure [23]

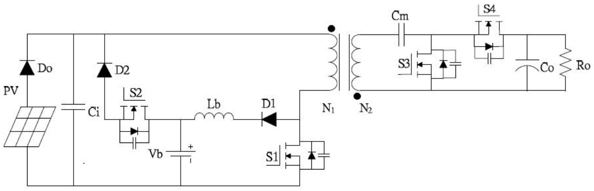

Figure 9. High efficiency novel three port isolated bidirectional converter [24]

The three port LLC resonant converter interfacing PV system, Battery with isolated output load port is proposed in [23]. In Figure 8, a hybrid full bridge system is shown with a bidirectional battery port stabilizing the source energy with load requirements. The battery charging and discharging is controlled by resonant current. The battery current direction remains same in a single switching period, hence increasing it's lifetime. Though the proposed topology has an advantage of reduced ripple current, switching device count is increased. A wide range of ZVS for switches of primary side converter and ZCS for switches of secondary side converter is achieved with the help of LLC resonant tank. However, the soft switching is diificult to achieve in devices which has low turn-off current. The inclusion of LLC resonant tank for the dual active bridge topologies is proposed in [25, 26] which gives the importance and operation of LLC resonant tank with multi level topology. In addition, PWAM control and Synchronous control startegies are implemented in addition to phase shift control strategy.

A novel isolated three port topology as shown in Figure 9 with improved boost flyback converter on the PV source side for stepping up the voltage level is proposed in [24]. The voltage stress on the transformer is reduced by a DC blocking capacitor on load port converter and current ripples in the battery are minimized by an auxiliary inductor on the battery port, thus improving the battery lifetime. Compared to full bridge topology, the number of devices are reduced which results in reduced cost and simple gate control. Despite the achievement of improved voltage gains in buck and boost modes of operation, soft switching of devices has not been addressed by the author which is very much essential to improve the overall converter efficiency.

An improved flyback-forward converter topology is proposed in [27] for standalone PV systems. PWM and phase shift control are used for better output regulation and to achieve MPPT in PV systems. In Figure 10, the main devices S_1 and S_2 are made to operate either in interleaved mode when PV supplies both load and battery or as an active clamp circuit when battery alone supplying load or as two buck-boost converters controlled independently in the absence of load. The switches S_3 and S_4 operates either in synchronous rectification mode or as flyback converter. A feedback loop design scheme is implemented for controlling the output voltage using phase shift method and PV voltage using PWM control. However converter efficiency could have been enhanced by introducing soft switching technique for all switching devices. Also the test results revealed that the ripple is comparatively higher in battery current which may degrade its lifecycle.

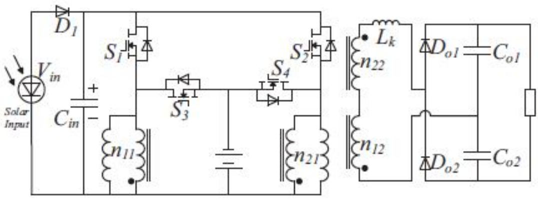

Figure 10. Three port converter with improved Flyback / Forward topology [27]

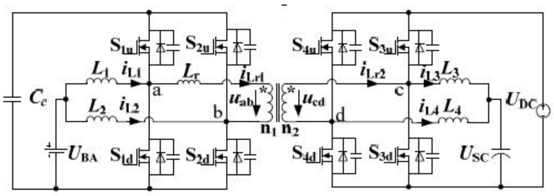

Figure 11. 3 + 1 Multi port bidirectional converter [28]

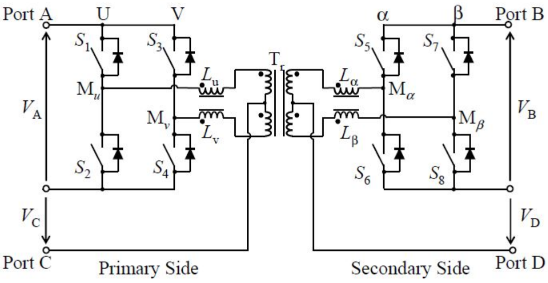

Figure 12. Multi-port DC-DC converter with coupled magnetic inductor [29]

A novel multi-port bidirectional DC-DC converter is proposed in [28] interfacing hybrid energy storage system (HESS) like battery and supercapacitor. The topology given in Figure 11 has two channel interleaving Buck/Boost on both primary side (battery) and secondary side with a high voltage port (DC bus) and low voltage port (Supercapacitor). In addition, filter capacitor on battery side forms an high voltage port without any input / output power and hence the proposed converter is named as 3+1 port Bidirectional converter. By extending ports, a novel "n+(n-2)" multi port converter can be obtained. ZVS for battery side switches is atained by maintaining duty cycle $D \leqslant 0.5$ and by proper choice of filter inductance on DC bus side. The proposed converter has been realized mainly for DC - micro grid system with energy storage systems. However, the experimental tests are being conducted ignoring fully charged or discharged state of battery which has to be addressed.

A multi-port bidirectional converter with two winding center tapped HF transformer as in Figure 12 is proposed in [29]. Two multi phase converter is integrated with an isolated DC-DC converter and the power flow is governed by proper choice of phase angle difference in full bridge and duty cycle. The impedance behavior of magnetic components like primary inductance, secondary inductance and transformer with respect to converter functioning have been addressed in detail. It has been found that the number of magnetic components and semiconducor switches are downsized compared to the prevailing converters. However, the converter efficiency could be improved by implementing soft switching for all devices with a penalty of including additional resonant elements.

The summary of partly isolated topologies considered for discussion are given in Table 1. The topologies could be either partly isolated with 2 winding transformer isolating all source ports and a load port or fully isolated with 3 winding transformer providing isolation for individual ports. The devices are soft switched by including resonant elements in the circuit and the resonant topologies (LCL, LLC, LC) are listed.

Table 1. Summary of partly isolated multi port topologies

Ref Paper	Topology	Input/Output ports their voltage levels	f_{sw}	Rating	Transformer connections	Resonant Elements	Device Count	Bi-directional Ports	Average η
[13]	FBTPC	PV - 38 to 76V, Battery - 26 to 38V,R_{load} - 42V, 180W	100kHz	180W	2 winding transformer n = 5:14	$L_m L_{lk} C_0$	4M, 4D	Battery port	94%
[14]	Partly isolated TPC	PV-22V, Battery-7.5V, R_{load}-50V, 25W	100-170kHz	100W	2 winding transformer n = 5:14	LCL	3M, 4D	Battery port	94.5%
[15]	FB-interleaved TPC	PV - 30 to 40V, Battery - 64 to 80V, R_{load} - 100V	100kHz	600W	2 winding transformer n = 6:8	$L_f L_1 L_2$	6M, 2D	Battery port	95 to 97%
[22]	FB-interleaved TPC	PV - 65 to 115V,500W Battery - 165 to 200V, R_{load} - 360V	74 - 100kHz	500W	2 winding transformer n = 25:45	$L_r L_m C_r$	4M, 4D	Battery port	94 to 96%
[23]	Hybrid FB-LLC interleaved TPC	Battery - 150V, R_{load} - 60 - 100V	100kHz	1kW	2 winding transformer n = 1:4	LCL	6M (4 +2), 4D	Battery port	–
[24]	TPC with improved boost flyback converter	PV - 20 to 26V,Battery - 24V, R_{load} - 200V	50kHz	500W	2 winding transformer n = 1:3	–	4M, 2D	Battery, load port	94.2 to 97.6%
[27]	Isolated TPC with improved flyback forward converter	Battery - 12V, R_{load} - 80V	20kHz	250W	2 winding transformer with coupled inductor	–	4M, 2D	Battery port	90 to 91.3%
[28]	Multi port converter with interleaving buck-boost	Battery - 40 to 56.4V, Supercapacitor - 150 to 300V R_{load} - 400V	20kHz	500W	2 winding transformer n = 1 : 3.1	$L_r C_r$	8M	Battery and supercapacitor port	–
[29]	Multi port converter with coupled inductor	Port A to D - 40V, 200V, 16V, 80V	40kHz	1.5kW	2 winding center tap, n = 1 : 5	-	8M	Port A and B	90 to 94%

*FB - Full Bridge, TPC - Threeport Converter, M - MOSFET, D - Diode

The power devices are soft switched to curtail the switching losses and enhance the efficiency [30]. Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS) either during turn on or turn off interval can be achieved by proper choice of resonant tank elements like inductor and capacitor. Different resonant tank configurations are developed like series or parallel LC tank, LLC tank, LCC tank. Also, the interleaved buck/boost converter circuitss are added to enhance better efficiency. The key contributions of soft switching techniques and elements in the considered topologies are listed in Table 2.

Table 2. Key contributions on soft switching range

Ref. Paper	Soft switched device	Key contributions
[13]	Turn on and turn off ZVS of all switches	Leakage inductance, filter inductance and output capacitors along with magnetising inductance are used to accomplish ZVS of the switches.
[14]	ZCS of switch S_1 in LCL converter	To achieve soft switching, the optimal range for Q factor is 1.5 to 5 and selected value is 3.7 for nominal load with allowable current ripple of 5$\%$. MPPT algorithm with frequency modulation method is realized for soft switching of the device S_1 by fixing its on time.
[15]	ZVS of primary side switches	high frequency inductor L_f, inductor current L_1, L_2, input output power and dead time has to be properly designed
[22]	ZVS - primary side switches (MOSFETs) turn-on and ZCS - secondary side diodes over full operating range	ZVS is related to resonant current I_{lr} and boost inductor currents I_{b1} and I_{b2} with condition f_n (normalized switching frequency) = 1, and D = D_{min} and the the range for ZVS could be improved by proper design of leakage inductance L_{lk}
[23]	ZVS on primary side MOSFET and ZCS on secondary side rectifier diodes	ZVS of lower device (M6) in leg B is difficult but still achieveable based on the design value of magnetizing inductor and parasitic capacitance value in addition to the switching interval dead time.
[28]	ZVS on primary side MOSFETs	Soft switching achieved for phase shift angle ranging from 0.5*π to -0.5*π with duty cycle = 0.5, with a condition of $i_{min} \leq i_{Lr2}$(min) and $i_{max} \geq i_{Lr2}$(max) for ZVS of all DC bus side switches for full load range.

2.2. Control strategy

The output voltage gain and power regulation between the ports are achieved by control variables like duty ratio, phase shift angle and switching frequency. Review on the control strategies using pulse width modulation and phase shift techniques are discussed as follows.

A three port topology interfacing battery and supercapacitor with load is discussed in [31] which is derived from [32]. The dynamic performance of battery is improved because of the supercapacitor sharing the load during sudden changes. The bidirectional power flow between the ports is achieved in addition to soft switching of main devices by employing phase shift control strategy. This technique has also been discussed in [33–37], However the solution for high current stress and limited soft switching range under light load conditions are not addressed.

Pulse width modulation with phase shift control (PWMPS) technique in [38] helps to vanquish the drawbacks of conventional phase shift control technique. However, the phase shift control results in higher current stress in switches and narrow limited ZVS range for mismatch in the input and output voltage amplitudes. The abovesaid limitations are subdued by PWMPS technique. The advantages are reduced current stress, conduction losses, switching losses of semiconductors with a wider ZVS range. Similar PWMPS control technique to Dual Active Bridge topology is implemented as in [39]. The reactive power algorithm for optimizing the reactive and average output power is developed to investigate in detail so that the reactive power is considerably reduced compared to PS technique.

An asymmetrical duty cycle control is proposed in [40] in which the duty cycle is varied for the input side bridge devices and is fixed to a value of 0.5 for the load side bridge switches. This control technique helps in achieving wide ZVS range, reduced peak and rms current, improved efficiency due to reduced rms losses. The isolated topology with LCLC resonant tank is proposed in [41] which discuss in detail the role of resonant tank in achieving high efficiency of 96.9 $\%$. The notable contributions by the authors on control strategy for various topologies are listed in Table 3.

Table 3. Key contributions on control strategy

Ref. Paper	control strategy	Key contributions
[13]	Pulse Width Modulation (PWM)	duty cycle of switching devices are determined based on minimizing L_m of the transformer
[15, 19]	PWM and Secondary side phase shift control	Phase shift angle in the range of (0 - 90)°; freewheeling stage circulating currents are eliminated; the rectifier voltage stresses are also suppressed
[22]	PWM and PFM	f_s and duty cycle are controlled with D=0.5 and inductor ratio m for gain characteristics. For minimizing input current ripple, design values are duty cycle D = 0.5, phase shift = π
[23]	Phase shift control	Fundamental Harmonic Approximation method to determine voltage gain by maintaining condition of D1 +D2 = 0.5
[28]	Phase shift control	phase shift angle is fixed to π

3. CONCLUSION

The intention of this paper is to provide a detailed review of the multi-port partial isolated bidirectional DC-DC converter topologies. The present trend in interfacing renewable source with energy storage system shows clearly an increasing demand for high performance DC-DC converters with bidirectional power transfer capability. The details of existing multi-port converter topologies interfacing renewable photovoltaic source, energy storing battery, supercapacitor and load are discussed. The charging and discharging of batteries, supercapacitors are controlled by implementing phase shift or pulse width modulated control techniques. Based on the discussions in this paper, it is clear that galvanic isolation by transformer in both partly isolated and fully isolated three port converter topologies are preferred for bidirectional power flow control of energy storage elements with higher power ratings.The soft switching of the power devices are achieved by including LC, LLC resonant tank elements and thus improving the overall converter efficiency as the switching losses are minimised. The key contributions by various authors on achieving zero voltage switching during turn on or turn off and contributions in implementing control strategy for power flow control are listed. This paper clearly exhibits the scope for developing novel bidirectional DC-DC converter topologies with additional input renewable source ports or hybrid energy storing systems.

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