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A Review on Two-Stage Back End DC-DC Converters in On-Board Battery Charger for Electric Vehicle

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Abstract- Development in the area of Power Electronics leads to a drastic change from fuel-based conventional transportation to e-transportation. Due to the adverse environmental effects caused by the conventional transportation such as global warming, GHG emissions, depletion of fuel reserves etc... Electric vehicle technology becomes more popular as a remedial measure. Electric vehicles (EV) need a battery system to reserve the electric energy and utilized later to drive the electric motor. Thus a battery and its charging system play a vital role in EV. Supply from the utility is fed to the battery charger to make it compatible with battery for storage. Hence the performance of the battery charger is measured based on its efficiency, regulation and power quality in terms of power factor and THD (Total Harmonic Distortion). There are numerous configurations available for battery charging circuits. Battery chargers can be broadly classified into on-board charger (OBC) and off-board charger. In addition to the above mentioned factors, on-board charger integrated in EV must satisfy space factor in terms of size, weight and also the life span. To meet out these needs, OBC's can be further categorized into a single stage (AC-DC) converter and two-stage (AC-DC & DC-DC) converter. Single stage converter has certain limitations in achieving high efficiency, step-up capacity and a problem of increased stress on switches. Due to these limitations of single-stage converter, two-stage topology becomes more popular. Two-stage topology exists with front end AC-DC power factor correction stage and back end DC-DC regulating stage. Achieving high efficiency, power quality and regulation is essential for the OBC. In this paper, a brief review of various topologies of two stage back end DC-DC converter with isolated and non-isolated configurations as OBC for EV application is presented.

Keywords Dual Active Bridge, On-Board Charger, Power Factor Correction, Phase Shifted Full Bridge, Triple Active Bridge

1. Introduction

In recent years, the technology of electric transportation gains high interest over conventional fossil fuel-based transportation because of the major factors like emission of GHG which results in global warming, air pollution, and the deficiency of fossil fuels. These significant factors urge us to seek an alternate way of transportation and consequently, we stepped into a new technology called "Electric Vehicle" (EV's). Electric vehicles are energized by the integrated batteries for the propulsion. The Major portion of the Electric Vehicle is battery, followed by the battery charger. The Role of the battery charger is to charge the battery to its standards.

Various types of batteries used for EV's are Li-ion, Lead-acid, Ni-MH, Ni-Cd. Among which Lithium-ion (Li-ion) is most popular due to its high energy density, high specific energy, and power, high cycle durability, etc.

Battery chargers are basically classified as an on-board charger or off-board charger based on the type of power levels [1]-[6]:

- ✓ **Level 1 charging**: for up to 3-6 kW power, on-board charger, 1Φ 120 V / 230 V.
- ✓ **Level 2 charging**: (<20kW) power, 1Φ/3Φ 240V/400V, off-board charger.
- ✓ **Level 3 or DC fast charging**: (<50 kW) power, off-board charger.

Types of plug as per standards [7] - [9]:

- ➢ **Type 1** – 1Φ vehicle coupler reflecting SAEJ1772/2009 automotive plug specifications.
- ➢ **Type 2** – 1Φ and 3Φ vehicle coupler reflecting the VDE-AR-E 2623-2-2 plug specifications.
- ➢ **Type 3** – 1Φ and 3Φ vehicle coupler equipped with safety shutters reflecting the EV Plug Alliance proposal.
- ➢ **Type 4** – DC fast charge coupler - CHAdeMO.

In OBC, battery chargers are assessed based on the performance parameters such as its efficiency, regulation and power quality. Along with this, OBC's integrated in EV's must also assure reduced size, less weight and long lifetime [10] & [11]. OBC's can be broadly classified as single-stage (AC-DC) converter and two-stage (AC-DC and DC-DC) converter. Based on the power flow direction, it can be further classified as bidirectional and unidirectional converters [12] & [13].

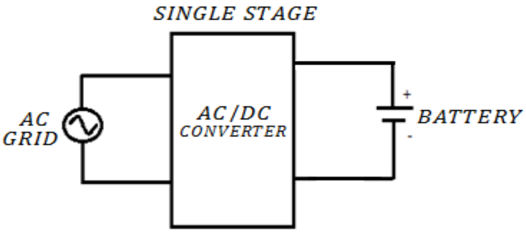

Fig.1. Single Stage On-Board Battery Charger

Shows the block diagram of Single Stage On-Board Battery Charger [14]. In single-stage conversion, there are certain restrictions in reaching high efficiency and voltage step-up capability. Also there is a drawback of high voltage stress on switches [15]. Due to these limitations, there is an increase in interest towards two-stage converter [16] & [17]. Two-stage converters consists of front end AC-DC converter as PFC (Power Factor Correction) stage [18]-[23] and inherently followed by a DC-DC converter as a regulating stage [24]-[26]. Fig. 2 shows the block diagram of Two-stage On-Board Battery Charger. There are many topologies available for DC-DC converter, which can be further categorized as Isolated and Non-isolated configurations.

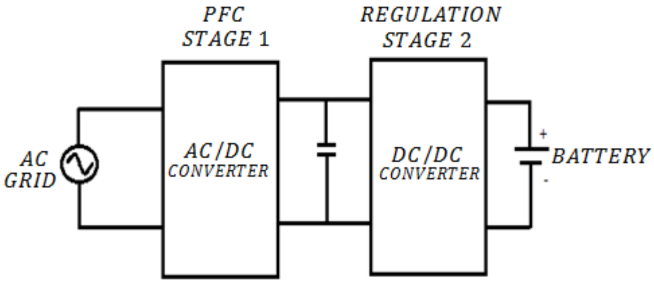

Fig.2. Two Stage On-Board Battery Charger

Fig. 3 shows the list of isolated and non-isolated configurations of DC-DC converter [27] & [28]. The following converters come under non-isolated configuration such as Buck, Boost, and Buck-Boost [27],[29] & [30]. Cuk and SEPIC [31]-[33] converters are derived from Buck-Boost. Types of isolated configurations are Half-bridge, Full-bridge, Flyback, Push-pull, and Forward converters [29] & [34]. Forward converters can be classified again as a single switch or double switch topology. Flyback converters are derived from Buck-Boost. Forward, Half-bridge and Full-bridge are derived from Buck [35].

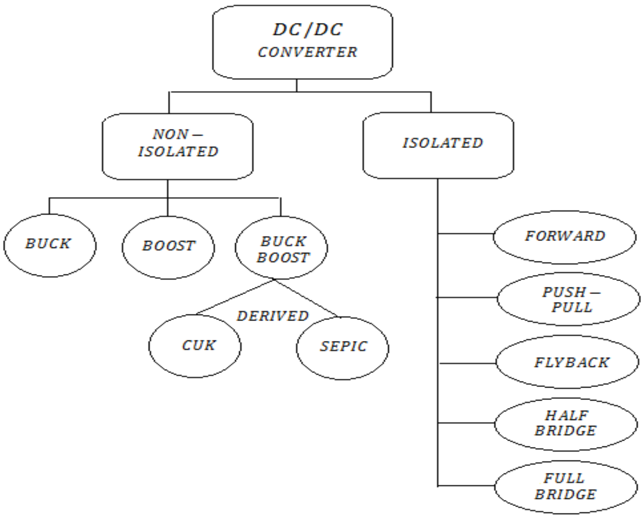

Fig. 3. Classification of isolated and non-isolated DC-DC converters

Concept of interleaving in converters [35],[36] possesses numerous advantages like cancellation of ripple in input and output currents to a larger degree, a better way of achieving higher bandwidth control, etc. For low output voltage power supplies, synchronous buck converter is an optimal topology [37].

Operating range of isolated DC-DC converters [38] is shown in fig. 4. With the universal input voltage range of (90-264) VAC:

- ➢ Flyback (for Load current <10A) and Forward (for Load current >10A) can be selected for an output power range of less than 150 W.

- For the output power in the range of 150-350W, two-switch Forward or Half-Bridge or Push-Pull can be chosen.
- Half-Bridge, Push-Pull is best suited for less than 500W output power.

With the input voltage of greater than 350V DC:

- Half-bridge is a suitable topology for an output power of <750W.
- For the output power in the range of 500-1000W, Full-Bridge configuration is well suited.

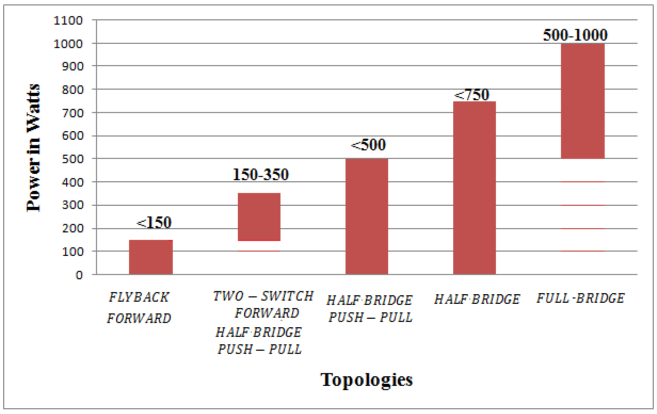

Fig. 4. Operating range of converters

It is inferred that for low power applications of <750W, Half bridge topology will be a suitable one and for high power applications in the range of >500W, Full bridge is best suited. Under isolated configurations, Half-bridge and Full-bridge topologies are widely used in practice. Similarly, Buck-Boost topolgy under non-isolated configurations is popularly used in practice. Hence, these topologies gains high interest over electric vehicle as an on-board battery charger.

In this paper, some of the isolated and non-isolated configurations implemented in two-stage back end DC-DC converter as on-board charger for EV is briefly reviewed.

2. Two stage back-end dc-dc converter topologies

2.1. Bidirectional Resonant Converter with Integrated Magnetics for On-Board Charger

In OBCs, space factor and conduction losses of switches are the identified issues. Space occupied by the resonant elements like L and C are considerable and thus it can be resolved by integrating the inductor element into the isolation transformer to improve the space factor as proposed in this paper [39]. The secondary issue is the conduction losses which can then be reduced by operating the second stage DC-DC converter as Active rectifier (or Synchronous rectifier). Active rectification is done by replacing diodes by active controlled switches like MOSFETs. Since MOSFETs have very low on-state resistance Rds, conduction losses are reduced in turn increases the overall efficiency. Fig. 5 shows the circuit diagram of the Bidirectional LLC resonant converter with Ls (series inductor) integrated into the transformer. The efficiency of this converter at charging is η=98.1% and during discharging η=97.2%

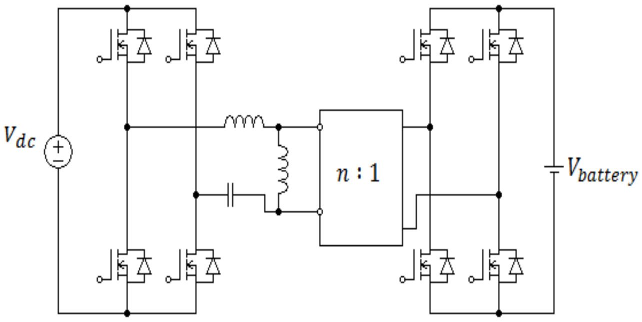

Fig. 5. Bidirectional LLC resonant converter with Ls (series inductor) integrated into transformer

2.2. Full-Bridge LLC Resonant Converter with Series-Parallel connected transformers

Drawbacks of single transformer configuration in isolated DC-DC converters are power density and problem of heat dissipation. To overcome these drawbacks, two transformers are used instead of one. This two transformer configuration also reduces transformer copper loss and diode conduction loss. Half-bridge LLC resonant converter is suitable only for low voltage and low power applications [40]-[43]. Hence, a Full bridge LLC resonant converter with a parallel-series connected transformer is proposed in [44]. But it suffers due to voltage imbalance and high voltage stress on the switches. Thus, a Full Bridge LLC resonant converter with a series-parallel connected transformer is proposed in this paper [45], where the primary winding is connected in series and the secondary winding is connected in parallel to ensure the voltage balance. This structure is more advantageous in reducing the copper loss of the transformer, conduction loss of rectifier diodes, current stress of rectifier diodes, and also improves the heat dissipation. Fig. 6 shows the circuit diagram of the Full Bridge LLC resonant converter with the series-parallel connected transformer. Efficiency of this converter at Vo = 420 V is η = 96.3%

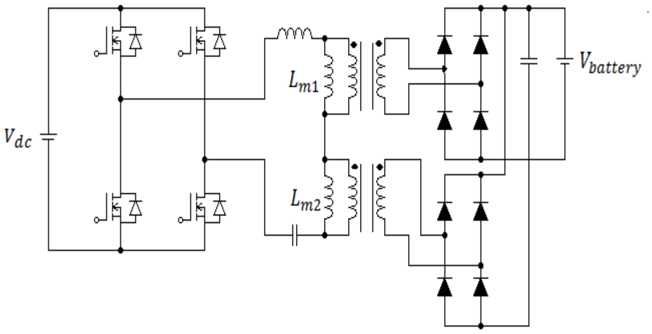

Fig. 6. Full Bridge LLC resonant converter with series parallel connected transformer

2.3 Phase Shifted Full-Bridge DC-DC Converter with High Efficiency and High Power Density using Centre-Tapped Clamp Circuit

The Most widely used on-board battery charger is a Phase Shifted Full Bridge converter (PSFB). But there are certain drawbacks in this PSFB [46] and they are:

i) Considerable conduction loss created by circulating current during the freewheeling period

ii) Secondary side suffers from over-voltage, this can be eliminated by RCD snubber even then there is a loss in the snubber circuit

iii) The Problem of reverse recovery, which can be mitigated by the usage of Schottky diodes applicable only for low voltage rating

iv)The requirement of the huge filter inductor

All the problems stated above can be resolved by introducing a centre-tapped clamp circuit in the phase-shifted full-bridge configuration as proposed in this paper [46] with diodes D1, D2, and capacitor Cc. [47] RCD snubber is now replaced by a CDD clamp. Fig. 7 shows the circuit diagram of Phase Shifted Full-Bridge DC-DC Converter with Centre-Tapped Clamp Circuit. Efficiency during CC (Constant Current) mode with Io =7.85A is η=97.3% and during CV (Constant Voltage) mode at Vo =420 V is η=98.3%

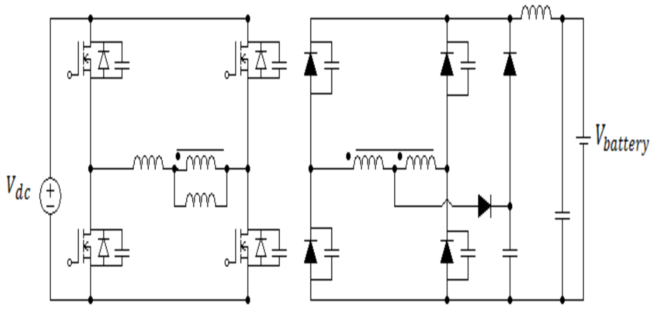

Fig. 7. Phase Shifted Full-Bridge DC-DC Converter with Centre-Tapped Clamp Circuit

2.4 Dual Active Bridge Topology

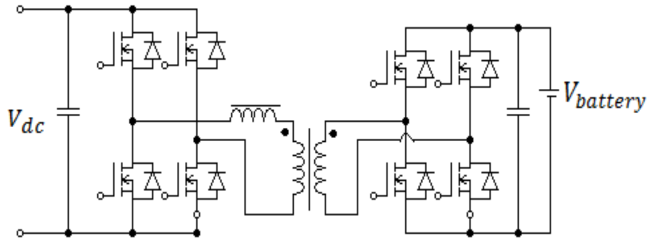

Fig. 8. Dual Active Bridge Topology

For high voltage applications, isolated type of bidirectional back end DC-DC converter is preferable which ensures galvanic isolation [48]-[50]. The well-known topology for this is, Dual Active Bridge (DAB) which comprises symmetric configuration, having less no. of passive elements, increased efficiency, and increased power density [51]. Phase shift modulation is the control strategy used in general for this DAB, but here a novel control strategy has been introduced in this paper [15]. During charging, pulse width modulation is done on the secondary side from the adjusted value of the duty cycle based on the error generated. Similarly, during discharging pulse width modulation is done on the primary side. Fig. 8 shows the circuit diagram of Dual Active Bridge topology. Efficiency during charging mode η=92.6% and during discharging mode efficiency η=92.2%

2.5 Non-regulating Half Bridge Series Resonant Converter

In two-stage AC-DC converter topologies, electrolytic capacitor as a dc-link becomes an essential component [52], [53]. Electrolytic capacitor results in low power density and also reduces the lifetime. Thus, electrolytic capacitors are replaced by thin-film capacitors. This can be done by choosing the sinusoidal charging method [54]-[56] in which the frequency of charging current is equal to 2 times of line frequency ripple leads to an increase in efficiency, less effect on battery capacity and thermal rise. Here the DC-DC converter is a non-regulating Series Resonant Converter [57]. Fig. 9 shows the circuit diagram of the Non-regulating Half-bridge SRC topology. Efficiency during charging η=95.7% and during discharging η=95.4% at 600W.

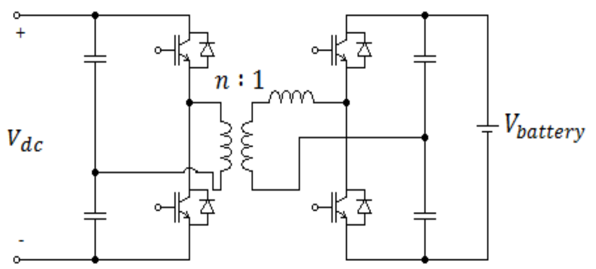

Fig. 9. Non-regulating Half bridge Series Resonant Converter

2.6 Bidirectional Switching Capacitor based Buck-Boost charger

In the earlier bidirectional two-stage battery charger topologies [58], [59], the back-end DC-DC stage can perform only buck operation in G2V mode. In other topologies [60]-[62] which consist of buck-boost configuration, there is no V2G mode of operation due to unidirectional nature. [63], [64] The above mentioned issues can be solved by this novel topology termed as Bidirectional switching capacitor-based buck-boost charger introduced in [65]. This new topology is efficient in controlling active and reactive power in both the modes of operation G2V and V2G. Voltage levels can be adjusted for both the directions based on SOC (State of Charge) of battery. Fig. 10 shows the circuit diagram of the DC-DC stage of Bidirectional Switching Capacitor based Buck-Boost charger. Input current THD = 7%

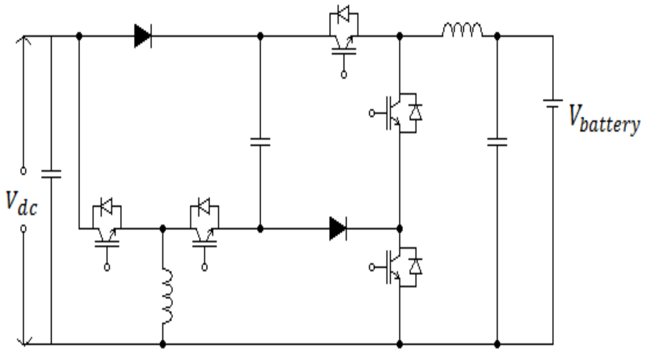

Fig. 10. Bidirectional Switching Capacitor based Buck-Boost charger

2.7 *Triple Active Bridge Topology*

The Objective of integrating OBC and APM (Auxiliary Power Module) is to shrink the size and weight. But there are some issues in integrating OBC and APM as follows:

i) In [66], integration is done by two different bidirectional switches to eliminate the additional charger, but efficiency decreases due to multiple stages.

ii) In [67], here integration is done with the aid of dual output DC-DC converter adapting pulse-frequency modulation. Since there is a restriction in topology, the simultaneous charging of two batteries (HV and LV) is not possible.

iii) In [68], integration is done here, by the DAB converter associated with the current doubler rectifier. It fails to manage power flow which leads to unregulated output at LV battery side.

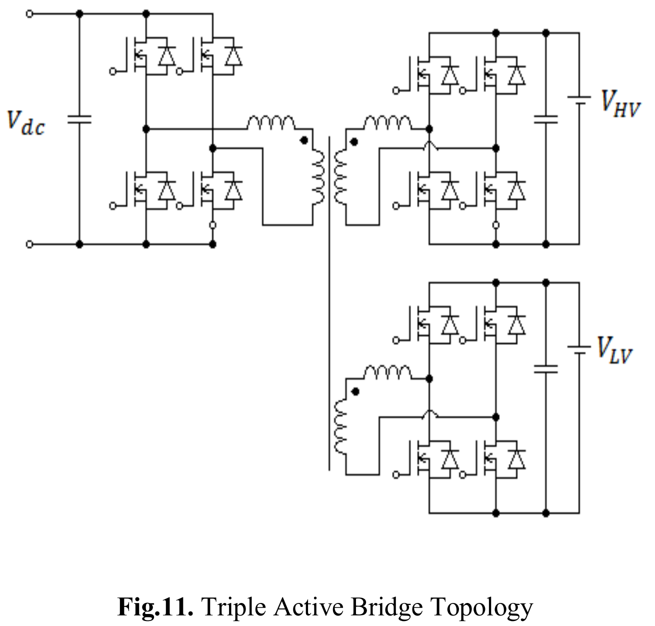

Fig.11. Triple Active Bridge Topology

All the issues stated above can be overcome by Triple Active Bridge (TAB) converter which is introduced in this paper [69]. Here [69], to resolve the issue of power flow management, control is implemented based on Generalized Harmonic Approximation (GHA). Simultaneous charging is achieved. Fig. 11 shows the circuit diagram of Triple Active Bridge Topology. Peak efficiency of TAB is 97.6%

2.8 *Bidirectional three-level (B3L) DC-DC Converter*

In this paper [70] bidirectional 3-level DC-DC converter is introduced which overcomes the drawbacks of conventional interleaved DC-DC converter. This [70] topology works at 3-level whereas conventional interleaved converter operates at 2-level. Voltage stress is reduced to half, since the voltage applied to each switch is only Vdc/2 when compared to conventional interleaved configuration. Bidirectional 3-level DC-DC converter works with output variable (inductor current) having frequency equal to twice of switching frequency. Value of current ripple in Bidirectional 3-level converter is 0.6A, which is very low when compared to interleaved converter of 2.4A. Fig.12 shows the circuit diagram of Bidirectional three-level (B3L) DC-DC Converter.

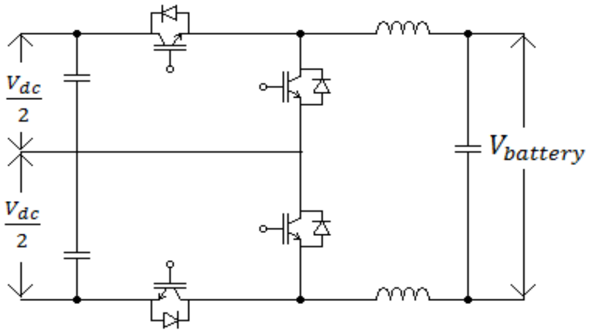

Fig.12. Bidirectional three-level (B3L) DC-DC Converter

3. Comparison of Topologies and Control Strategy

Table-I summarizes about the comparison of two-stage back-end DC-DC converter based on its efficiency, soft switching [71] and modes of operation addressed. Topology in section 2.5 with ZCS (Zero Current Switching) for both turn-on and turn-off addressed all the three modes of operation, but with lesser efficiency compared to the other topologies. Topologies in sections 2.1, 2.2 and 2.3 has high efficiency but limiting its application to only basic mode of operation G2V (Grid to Vehicle). Topology in section 2.7 with high efficiency is suitable for both V2G (Vehicle to Grid) and G2V applications. Topology in section 2.2 has inculcated both ZVS (Zero Voltage Switching) and ZCS for turn-on and turn-off of the switches respectively. Except topology in section 2.5 with ZCS, all the other above mentioned topologies has ZVS for eliminating the switching losses.

From the summary of Table-II, it is inferred that toplogies in sections 2.2 and 2.7 consists of more no. of components under isolated configuration which makes the circuit quite bulky and complex. For low power applications, topologies in sections 2.6 and 2.8 which falls under non-isolated configuration are preferrable. Topology in section 2.3 with CDD (Capacitor-Diode-Diode) clamping circuit is suitable for achieving high power density.

Control strategy adapted in all the above discussed topologies are summarized in Table-III. From that it is inferred, PWM (Pulse Width Modulation) with constant current (CC) and Constant Voltage (CV) mode is implemented widely due to its less control complexity and wide range of control.

4. Challenges and Future scope

- All the above discussed topologies are suitable for level 1 of charging. Work can be extended for level 2 of charging in EV.

- V2H mode of operation is addressed only in limited topologies of isolated configuration. Work can be extended to non-isolated configurations to perform dual functionality.

- PI current controller faces the difficulty of sine wave tracking under load fluctuations, this can be overcome by PR current controller [72], [73]. Thus the work can be extended to implement PR current controller to maintain power quality during V2G mode of operation.

Table. I Comparison of Topologies

Topologies	Efficiency (η)	Soft Switching	Modes Addressed
Bidirectional resonant converter with integrated magnetics	During charging 98.1% at Po =3KW During discharging 97.2% at 500W	ZVS (Zero Voltage Switching)	G2V (Grid to Vehicle)
Full-Bridge LLC Resonant Converter with Series-Parallel connected transformers	During charging 96.3% at Po =3.3KW	ZVS (Zero Voltage Switching) turn-on ZCS (Zero Current Switching) turn-off	Not addressed
Phase Shifted Full-Bridge DC-DC Converter with Centre-Tapped Clamp Circuit	During CC mode 97.3% with Io=7.85A During CV mode 98.3% with Vo=420V	ZVS (Zero Voltage Switching)	Not addressed
Dual Active Bridge	During charging 92.6% During discharging 92.2% at Po =3.3KW	ZVS (Zero Voltage Switching)	V2H (Vehicle to Home)
Non-regulating Half Bridge Series Resonant Converter	During charging 95.7% During discharging 95.4% at Po =600W	ZCS (Zero Current Switching) turn-on and turn-off	V2G (Vehicle to Grid) G2V (Grid to Vehicle) V2H (Vehicle to Home)
Bidirectional Switching Capacitor based Buck-Boost charger	-	-	V2G (Vehicle to Grid) G2V (Grid to Vehicle)
Triple Active Bridge Topology	During charging Peak efficiency = 97.6% During discharging Peak efficiency = 97.1% at PHV = 450W and PLV = 200W	ZVS (Zero Voltage Switching)	V2G (Vehicle to Grid) G2V (Grid to Vehicle)
Bidirectional three-level (B3L) DC-DC Converter	-	-	Not addressed

Table. II Comparison based on components count, resonating elements, clamp circuit

Topologies	No. of Switches	No. of Rectifier Diodes	Isolated configuration	Resonating Elements	Clamp Circuit
Bidirectional resonant converter with integrated magnetics	8	-	Yes	LLC	-
Full-Bridge LLC Resonant Converter with Series-Parallel connected transformers	4	8	Yes	LLC	-
Phase Shifted Full-Bridge DC-DC Converter with Centre-Tapped Clamp Circuit	4	4	Yes	LC	CDD
Dual Active Bridge	8	-	Yes	LC	-
Non-regulating Half Bridge Series Resonant Converter	4	-	Yes	LCC	-
Bidirectional Switching Capacitor based Buck-Boost charger	5	-	No	-	-
Triple Active Bridge Topology	12	-	Yes	LC	-
Bidirectional three-level (B3L) DC-DC Converter	4	-	No	-	-

Table. III Comparison of Control Strategy

Topologies	Control Strategy	Mode
Bidirectional resonant converter with integrated magnetics	In Charge mode – FM (Frequency Modulation In Discharge mode – Phase Shift Modulation	-
Full-Bridge LLC Resonant Converter with Series-Parallel connected transformers	PFM (Pulse Frequency Modulation)	CC-CV (Constant Current-Constant Voltage)
Phase Shifted Full-Bridge DC-DC Converter with Centre-Tapped Clamp Circuit	PWM (Pulse Width Modulation) with phase shift	CC-CV (Constant Current-Constant Voltage)
Dual Active Bridge	PWM (Pulse Width Modulation)	CC-CV (Constant Current-Constant Voltage)
Non-regulating Half Bridge Series Resonant Converter	Sinusoidal Charging	CC-CV (Constant Current-Constant Voltage)
Bidirectional Switching Capacitor based Buck-Boost charger	PWM (Pulse Width Modulation)	CC-CV (Constant Current-Constant Voltage)
Triple Active Bridge Topology	GHA (Generalized Harmonic Approximation)	-
Bidirectional three-level (B3L) DC-DC Converter	PWM (Pulse Width Modulation)	CC (Constant Current)

4. Conclusion

This paper briefly reviewed the topologies of back-end two-stage DC-DC converter in on-board battery charger for EV. Resonant converter with integrated magnetics provides a better solution for space factor where space occupied can be reduced by integrating resonating components. For low copper and conduction losses with improved efficiency, Full Bridge LLC resonant converter with series-parallel connected transformers topology can be a suitable one. The Phase shifted full-bridge DC-DC converter with centre tapped clamp circuit configuration overcomes the drawbacks of conventional PSFB such as conduction loss by circulating current, losses in the snubber circuit, reverse recovery problem and large filter inductor. DAB with its peculiar control strategy becomes prominent topology for high voltage applications with improved efficiency. Non-regulating Half-Bridge SRC topology attains high power density and a long lifetime by replacing electrolytic capacitors with the thin film capacitors. Bidirectional switching capacitor-based Buck-Boost charger operates in both the modes V2G and G2V with its simple buck-boost structure. Triple Active Bridge topology satisfies the objective of integrating OBC and APM, which reduces additional circuitry for auxiliary supply. Bidirectional 3-level DC-DC converter overwhelms the conventional interleaved converter which operates at 2-level and also reduces the voltage stress to half. All the above discussed topologies can be applied for level 1 of charging as on-board charger. Bidirectional 3-level (B3L) DC-DC converter topology is compatible for both on-board and off-board charging. Thus, it is inferred from the review that DC-DC converter topologies with isolated and non-isolated configurations as a back-end conversion in two-stage converter is gaining significant interest in on-board charger for EV application.

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