Green University
GUBJSE: ISSN: 2409-0476

A Review of High Efficiency Non-isolated DC-DC Power Converters for Electric Vehicle Charging Application

Ratil H. Ashique

Abstract— The electric vehicle (EV) charging systems employ dc-dc power converters as EV chargers. Currently, the expected high penetration of electric vehicle (EV) demands for the integration of the renewable energy sources (RES) into the electric vehicle charging system as a promising solution to cut down the load on the electrical grid. These systems interface with RES by implementing dc-dc power converters. Moreover, with the advent of high-power dc charging, the charging efficiency is largely dependent on the performance of the power converters. Hence, to improve the charging, the soft switching dc-dc converters are implemented to maintain low switching losses and to achieve high-efficiency operation. This paper reviews the non-isolated, soft switching dc-dc power converters for EV charging application. For this purpose, different types of soft switching topologies, namely the snubber, the series resonant, the shunt resonant and the pulse frequency modulated converters are investigated. The advantages and the disadvantages associated with these converters are highlighted. Furthermore, to perform a comparative evaluation, the topologies are simulated in a standard simulation platform. Consequently, the relative standing of the converters depending on several parameters, i.e. the component count, the output voltage and current ripple, the soft switching range, and the power losses are established. Finally, based on these results, the optimum applicability of the converters in the EV charging application is determined.

Index Terms— Electric Vehicle Charging, DC-DC Power Converters, Soft Switching, Resonant Converters

I. INTRODUCTION

THE switched mode dc-dc power converter is an inseparable component of the renewable energy system. It has been used primarily to convert the dc power (from one level to another) from photovoltaic [1-4][5][6], wind [6], fuel cell [7, 8, 9], wave, ocean thermal and thermoelectric systems [10, 11, 12]. Looking into the future, there are debates on the possible replacement of ac distribution system by dc, within of the smart grid infrastructure. Another industry that requires significant dc-dc conversion is automotive [10]. In particular, the electric vehicles (EV) require dc-dc power converters to charge its lithium-ion batteries and the ultra-capacitors [13, 14]. The charger is also used to charge the lead acid batteries in the energy storage unit (ESU) [15, 16].

Recently, there has been an interest in integrating the energy source (RES) into the EV charging system. The main advantages of having such system are to reduce the burden on the electrical grid system. Also, it is to be noted that dc fast chargers normally draw large current in relatively short period of time. In addition, large growth of EV, requires grid upgrading. With the continuous downward trend in the price of the PV modules, the integration of PV as RES is becoming more attractive—as evident from numerous recent publications [9, 14-17]. A PV system is easy to set-up and is almost maintenance free [18]. This prospect is further enhanced by the improvement in power conversion technologies and installation practices [19-21]. The typical architecture of a renewable energy source (RES)-grid integrated dc charger is shown in Fig. 1 (a) and (b) for ac and dc bus system respectively. As can be seen, the dc-dc converters (highlighted by the yellow boxes in Figs. 1 (a) and 1 (b)) facilitate the integration of renewable energy systems, the ESU as well as operate as a main component of the dc charger. Hence, it is highly desired that the power converters maintain a very low loss profile in these power conversion processes.

The conventional hard-switched pulse width modulated (PWM) dc-dc converter exhibits considerable losses due to the switching and conduction of the power semiconductor switches. As the converter is generally operated at the high switching frequency (75-250 kHz), the situation gets worse and the switching losses (turn-on and turn-off) become dominant in the converter loss profile. To alleviate the problem, soft switching techniques are introduced to modify the voltage and current trajectories at the turning on/off instants of the switches. One approach is to apply the zero-voltage switching (ZVS), whereby the current is turned on

---

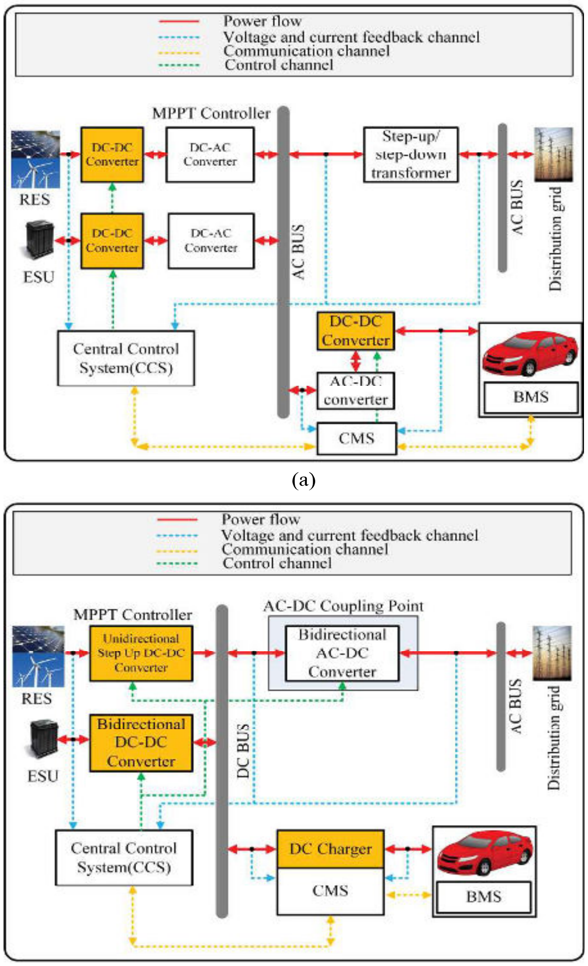
This paper was received on 6th May 2020, revised on 28th August 2020 and accepted on 13th October 2020.

Ratil H Ashique is with the Department of EEE, Green University of Bangladesh, Dhaka, Bangladesh. E-mail: *ratil@eee.green.edu.bd.*

while the voltage across the switch is deliberately forced to be at zero. Alternatively, the switch voltage can be made to turn off, while the current through the switch is forced to zero, i.e. the zero-current switching (ZCS). Furthermore, it is also possible to simultaneously make the voltage and current at the transition to be zero; such operation is referred to as the zero voltage zero current switching (ZVZCS). Since the inception of the idea in the late sixties, the soft switching techniques are widely applied to the non-isolated (as well as the isolated) dc-dc converters to improve the efficiency. Moreover, these techniques suppress the EMI by eliminating large variations of *di*/*dt* and *dv*/*dt*. Hence, the soft switching converters are highly deserved for high-performance EV charging systems. However, the soft switching range (i.e. the ability of the circuit to maintain its soft switching condition) varies significantly depending on the factors such as the input voltage, the switching frequency, the loading and obviously the type of soft switching technique itself. Consequently, these factors immensely influence the EV charging performance. Besides, to prevent damage to the battery in the charging process, the charging voltage and current from the converter must be ripple free. On the other hand, the V2G concept requires that the power converters incorporate the bi-directional feature.

There are review papers that comprehensively investigate the soft switching topics [22, 23]. In other review papers, various aspects of EV charging are covered including the PV-grid integrated charging schemes and associated challenges [9, 24, 25], the architecture and control for dc fast charging [26], economic and environmental impact of EV charging [27], V2G and optimization issues [28] etc. However, it appears that no review paper is written evaluating the soft switching converters to probe into their pros and cons as potential EV chargers despite the fact that a large number of power converters are reported [2, 9, 13, 29-69]. As the literature on this topic is large and diverse, it would be beneficial to systematically gather, organize, update and evaluate various high-efficiency soft switching power converters and evaluate them for EV charging application. Hence, in this paper, a classification is presented based on the architecture of the circuit, (i.e. the snubber, the series and shunt resonant and the pulse frequency modulated converters) and suggested for the optimum application environment based on simulation results.

The paper is arranged in the following manner. In Section 2, the EV charging system standards are introduced. In Section 3, the categorization of the soft switching converters is discussed. Section 4 provides general comments on the merits and demerits of the soft switching converters discussed earlier. Finally, Section 5 attempts to make a comparative evaluation to demonstrate the relative standing of the soft switching converters from the perspectives of the component count, the output voltage, and current ripple, the soft switching range or the switching loss, and the power consumption characteristics. Eventually, the best application environment is determined for each converter type. To probe further, an exhaustive reference list is provided. It is envisaged that this review work would be helpful for the reader to keep track with the research trend in this topic.



(a)

(b)

Fig. 1. The typical architecture of a renewable energy source (RES)-grid integrated dc charger with (a) ac bus (b) dc bus

II. THE CHARGING STANDARDS

It is evident that charging infrastructures are extremely important for large scale and widespread adoption of EV. There are two basic types of the EV charger: the ac and dc chargers [70]. In addition, the state-of-the-art standards for the EV battery charging are: the IEC, CHAdeMO, and SAE. Moreover, the Tesla has devised its own charging standard for its EV fleet.

Another very important parameter is the charging time. The later depends on three factors, i) the size of the battery pack, ii) the power rating of the charger, and iii) the number of connected EV to the charger at a particular instant. The ac Level 1 represents an on-board charging system from conventional 120 V ac outlets. Resultantly, it requires no additional setup and can be used conveniently at home. However, due to the size, weight, and thermal limitations, the Level 1 charging current is very low, thus extending the charging time. On the other hand, the majority of the public charging stations in the US and elsewhere are the ac Level 2—powered by a 240 V ac outlet. As opposed to Level 1, it demands for a dedicated setup at charging sites due to high voltage and power rating. The ac Level 3 represents higher power ratings as compared to Level 2 and 1. The system ensures fast and convenient charging for EV owners. However, only very small number of such systems are implemented. Alternatively, the dc fast chargers have very high-power rating to charge the large EV battery packs for modern PHEV and BEV. Resultantly, the charging time can be reduced significantly. The dc fast charger is the most the widespread commercial high-power charging systems.

The system is offered by the IEC CHAdeMO, SAE J1772 Combo and Tesla-S supercharger. The CHAdeMO is a conductive type dc fast charger that allows up to 200 A charging at 50 kW. The Controller Area Network (CAN) protocol is used to establish secure communication between electric vehicle management system (EVMS) and charge controller. On the other hand, the CHAdeMO supports vehicle to grid (V2G) or vehicle to home (V2H) applications allowing bidirectional power flow. The SAE J1772 Combo 1 and 2 specifies the physical, electrical and functional requirements to support the ac and dc fast charging. The Combo 1 (IEC Type 1) is very common in the US, while Combo 2 (IEC Type 2) is popular in Europe. These systems use the power line communication (PLC) standard IEEE P1901 protocol to establish communication between EV, electric vehicle supply equipment (EVSE), and other smart grid equipment. The Tesla 135 kW Supercharger is a dedicated dc fast charging utility for Tesla-S series, all-wheel drive (AWD) and Tesla-X vehicles. It is standardized and installed only by Tesla itself**.**

III. HIGH-EFFICIENCY SOFT SWITCHING CONVERTERS

The soft switching converters can be classified into four major configurations, i.e. the snubber, the series resonant, the shunted resonant and the pulse frequency modulated converters as shown in Fig. 2. Each division can be further subdivided according to the specific construction of the circuit. A self-explanatory TABLE I provides the basic characteristics of these converters. In the rest of this section, some of the technological aspects of each type of soft switching converter are explained.

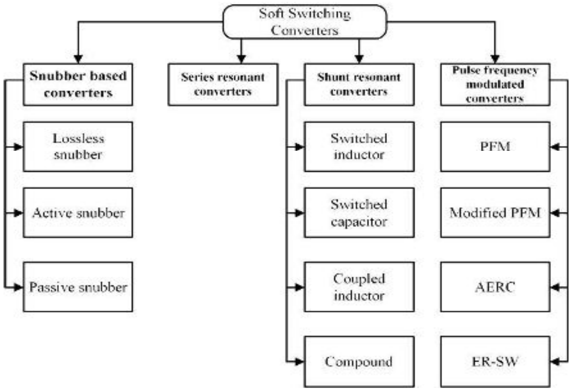


Fig. 2. The classification of soft switching converters

A. Snubber based converters

1) Simple snubber converters

This topology is the simplest and has the lowest device count. In its basic form, a snubber capacitor is placed across the power switch—restricting the sharp transition of the voltage across the switch at the turn off period.

TABLE I. Characteristics of the soft switching converters

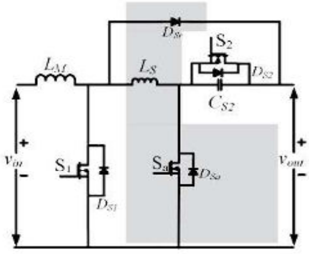
Soft switching converters	
Snubber networks-based converters **Generic architecture**	
Simple lossless snubber	Simple structure with a single snubber capacitor across the main switch
Active snubber	Extra active and passive components added to the simple snubber configuration to improve soft switching
Passive snubber	Extra passive components added to the simple snubber configuration to improve soft switching
Series resonant converters **Generic architecture**	
Single or multiple resonant inductors and capacitors in series on the power flow path to execute soft switching turn on and turn off of the main switches	
Shunt resonant converters **Generic architecture**	
Switched capacitor	Shunted auxiliary networks across the main switch with switched capacitor to trigger the resonance for soft commutation
Switched inductor	Shunted auxiliary networks across the main switch with switched inductor to trigger the resonance for soft commutation
Coupled inductor	Shunted auxiliary network across the main switch with resonant inductor coupled to the main inductor
Compound	A logical combination of switched inductor, switched capacitor and coupled inductor formation shunted across the power switch to trigger resonance for soft commutation
Pulse frequency modulated (PFM) converters Generic architecture	
Basic PFM	Resonant inductor connected in series while resonant capacitor is shunted across the main switch to execute soft commutation

Modified PFM	Extra set of components added to the basic PFM converter for increasing the soft switching range
AER	Shunted switched resonant capacitor added to the basic PFM converter to improve soft switching performance
ER-SW	Resonant capacitor with bypass power switch shunted across the main switch added to the AER converter to execute soft commutation

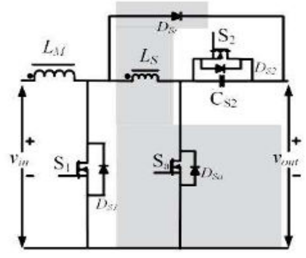
However, at the turn on, the capacitor discharges through the body diode to emulate zero voltage across the switch. To serve this purpose, the main inductor is expected to turn on the body diode as soon as the rectifier switch is turned off. The soft switching operation is largely affected by the switch voltage and current. Hence, to maintain high-efficiency charging (i.e. by keeping the switching losses lower), these converters should be employed in low voltage and low current charging applications.

2) *Active snubber converters*

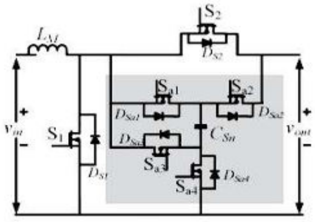
In active snubber-based converters, active components are included in the simple snubber converters as reported in [5-10]. Examples of three active snubber converters are shown in Figs. 3 (a) to (c). As evident, a number of active and passive components are added to execute soft switching of the main switches, i.e. S_1 and S_2. In many of these converters, the shunted snubber capacitor across the main switch (as prevail in simple snubber converters) is no longer required and replaced by an auxiliary switch (e.g. S_a in Figs. 3 (a) and (b)) with an anti-parallel diode. Consequently, the soft switching performance of the converter is largely improved as compared to the simple snubber counterpart. This, in return, makes these converters suitable for high power charging applications.



(a)



(b)



(c)

Fig. 3. Active snubber network (a) with parallel switch [6] (b) parallel switch and coupled inductor [7] (c) with three auxiliary switches [8]

3) *Passive snubber converters*

In passive snubber converters, no active components are used in the auxiliary network [11-14]. This eliminates additional losses that would otherwise be incurred by the active auxiliary devices. The passive snubber converters in Figs. 4 (a) to (d) composed of diodes (i.e. D_{r1}, D_{r2}, D_{r3}, D_{r4}), snubber inductors (i.e. L_r) on the charging path of the main inductor and snubber capacitors (i.e. C_r, C_{r1}, C_{r2}) shunted across the switches. A large number of diodes (i.e. D_{r1}, D_{r2}, D_{r3}, D_{r4}) are required to control the charging and discharging of snubber capacitors, as can be noted in Figs. 4 (a), (b), (c) and (d). This additional passive circuitry improves the soft switching operation and helps to achieve soft commutation for longer operating range. However, in general, the device losses in the passive circuitry are higher than the active snubber counterpart.

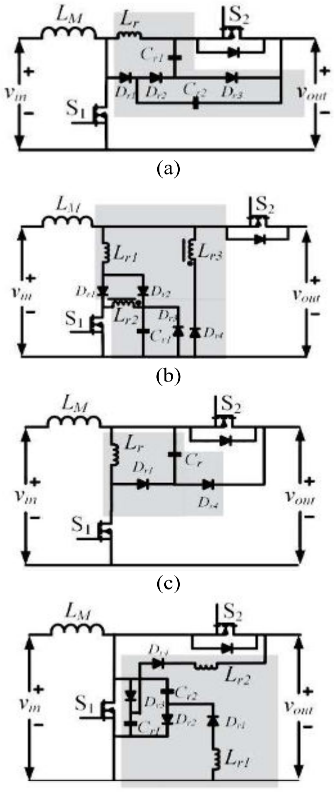


Fig. 4. Passive snubber network (a) with three diodes and two capacitors [23] (b) in LLC formation [44] (c) in LC formation [31] (d) in LCL formation [28]

B. Series resonant converters

Series resonant converters [22] comprises of resonant inductors and resonant capacitors connected in series [13, 50, 66] in the charging path of the main inductor. The resonance between the inductors and the capacitors—which are precisely positioned in the power flow path, produces zero voltage crossings across the main switches. The switches are then simply turned on and turned off at the appropriate moment. Despite its simplicity, the high conduction loss is induced in the resonance components as they remain energized for the whole switching period. This limits its usage to only low current charging applications.

C. Shunt resonant converters

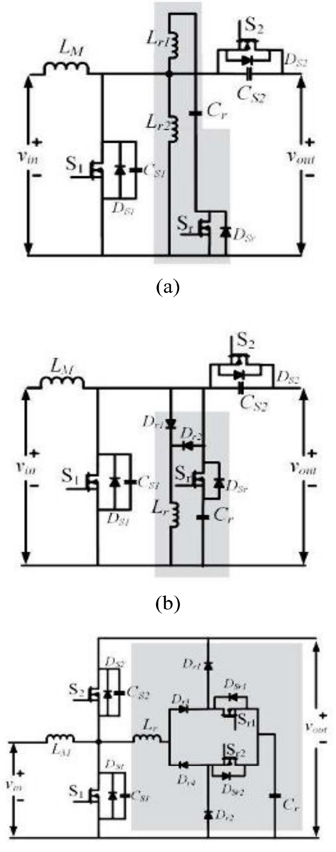
The shunt resonant converters are also known as zero voltage transition (ZVT), zero current transition (ZCT) or ZVT-ZCT converters. These soft switching converters comprise of one or multiple resonant inductors, resonant capacitors, and low power switches. In contrast to series resonant converters, the ZVT/ZCT network is shunted across the main switch and operates independently of the power circuit. That is, the resonance is turned on (to provide the ZVS or the ZCS condition) only when necessary. Thus, the power loss is reduced by eliminating the unnecessary circulation of energy in the resonance components. It also improves EMI performance of the converter. A large number of non-isolated ZVT/ZCT topologies are reported in [15-18] [19-25] [26-29].

1) Switched-capacitor resonant converters

The switched-capacitor resonant converters are demonstrated in [15, 18]. A generic pattern of the soft switching formations is done by the switched resonant capacitor. As in Figs. 5 (a) and (b), prior to turning on the resonant switch (i.e. S$_r$), the anti-parallel diode (D$_{Sr}$) remains turned on until energy is transferred to or from the resonant inductor (i.e. L_r in Fig. 5 (a) or L_{r1}, L_{r2} in Fig. 5 (b)). Consequently, the resonant capacitor (i.e. C_r) prevails either in fully charged or discharged state until the auxiliary switch is turned on. Turning on the auxiliary switch triggers the resonance and subsequent soft transition of the power switches (i.e. S$_1$ or S$_2$). Due to the position of the switched capacitor, the input voltage is restricted by the voltage rating of the capacitor. Hence, low voltage charging is recommended.

2) Switched-inductor resonant converters

In switched inductor converters, the resonant inductor is switched to trigger the resonance. As evident from Fig. 6, the converter may include multiple resonant inductors (i.e. L_{r1}, L_{r2}, L_{r3} or L_{r4}) as shown in Figs. 6 (a), (b) and (d) in addition to the auxiliary diodes (i.e. D$_r$, D$_{r1}$ or D$_{r2}$) and switches (i.e. S$_r$) to provide the ZVS mode switching. However, regardless of the structure, a switched inductor is generic to trigger the circulation of energy in the converter. Mutually coupled switched resonant inductors as shown in Fig. 6 (d) are also found in this category. Switched inductor based soft switching converters are reported in [19-25].

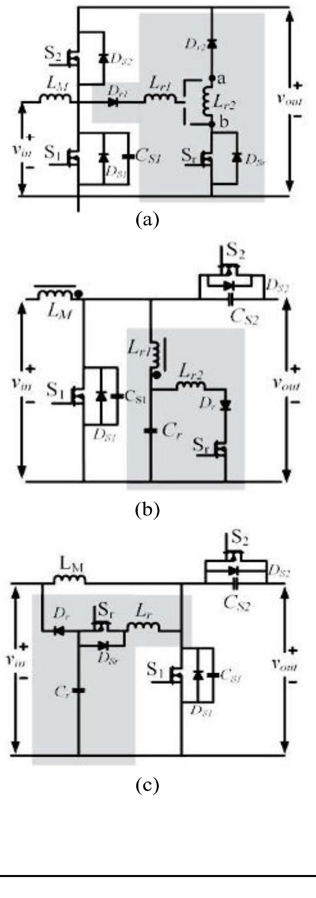


(a)

(b)

(c)

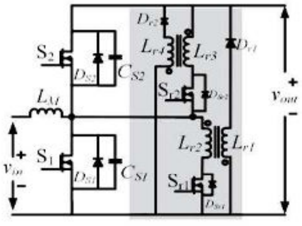
Fig. 5. Switched capacitor network (a) in LLC formation (b) in LC formation (c) in LC formation and with two switches [33]



(a)

(b)

(c)

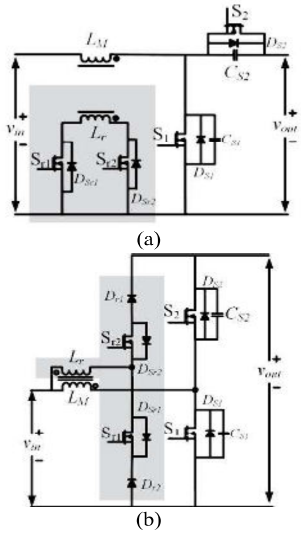


(d)

Fig. 6. Switched inductor network (a) with diode [58] (b) in coupled formation (c) in LC formation [25] (d) in double coupled formation [39]

3) *Coupled-inductor resonant converters*

The coupled inductor resonant converters are discussed in [17, 29]. In its generic formation, an auxiliary inductor is directly coupled to the main inductor and energizes the auxiliary network to trigger the resonance. The current through the main inductor is precisely determined by the coupling direction. The converter may include multiple low power auxiliary switches (i.e. S_{r1}, S_{r2}) and resonant capacitors (i.e. C_{s1}, C_{s2}) as depicted in Figs. 7 (a) and (b).



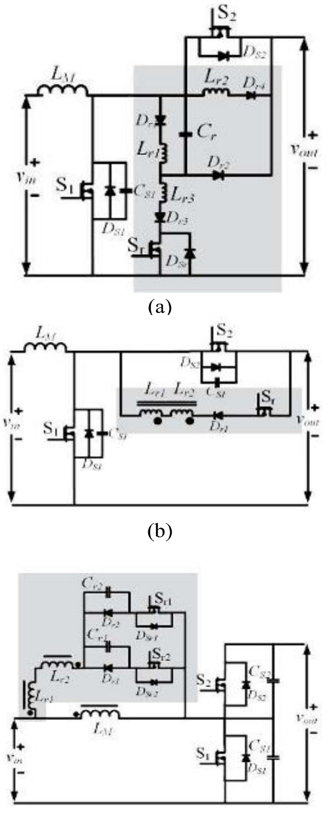
(a)

(b)

Fig. 7. Coupled inductor network (a) with two switches [57] (b) with two switches and two diodes [34]

4) *Compound resonant converters*

The converters in [26-28] are a combination of multiple shunted resonant networks to achieve soft commutation of the power switches. As evident from Fig. 8 (a), the compound resonant converters incorporate both a switched inductor and a switched capacitor network. In Fig. 8 (c), a switched inductor is coupled to the main inductor. Compound resonant converters are capable of widening the soft switching range, nevertheless, at the cost of the large component count and high control complexity. Besides, due to large number of active and passive components, the induced switching and the conduction losses are significant. Eventually, these converters are more appropriate in medium power charging applications.



(a)

(b)

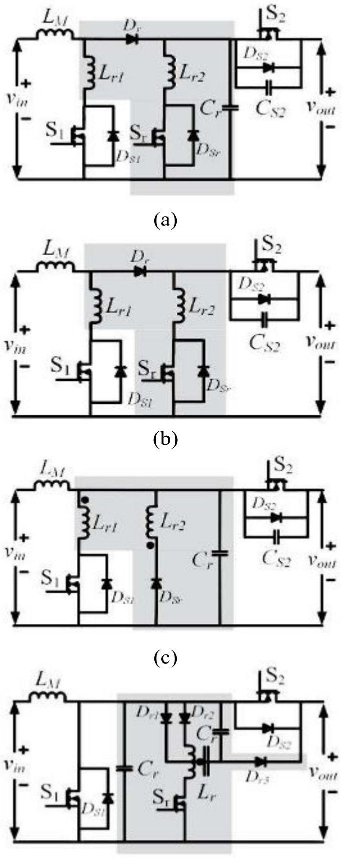
(c)

Fig. 8. Compound network (a) with switched inductor and switched capacitor formation [16] (b) with switched inductor [51] (c) with switched inductor and switched capacitors [47]

D. *Pulse frequency modulated (PFM) converters*

1) *PFM resonant converters*

Pulse frequency modulated or otherwise known as the ZCS-PFM resonant converters are implemented in two or three terminal formats. A number of modified PFM converters in two terminal formats are demonstrated in Figs. 9 (a) to 9 (d). In the basic PFM, at least one resonant inductor (e.g. L_{r1} in Fig. 10 (a)) is connected in series with the main switch (i.e. S_1) while at least one resonant capacitor (e.g. C_r in Fig. 9 (a)) is shunted across the same switch. Additional leg of passive components, as depicted in Figs. 9 (a), 9 (b), 9 (d), may be included for enhancing the soft switching operation in a wider load variation. Besides, it can be deduced that resonant components in PFM converters are not purely shunted across the main switch and encompass components on the power flow path. These induce additional device loss and degrade the output current ripple. A number of converter topologies implementing ZCS-PFM are reported in [30-32]. Modified PFM resonant converters with additional passive components in diverse formats are proposed in [16, 33, 34]. In general, as ZCS mode of soft switching is applied, these converters are particularly appropriate for low current charging applications.



(a)

(b)

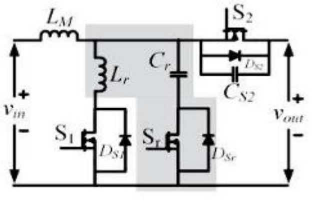
(c)

(d)

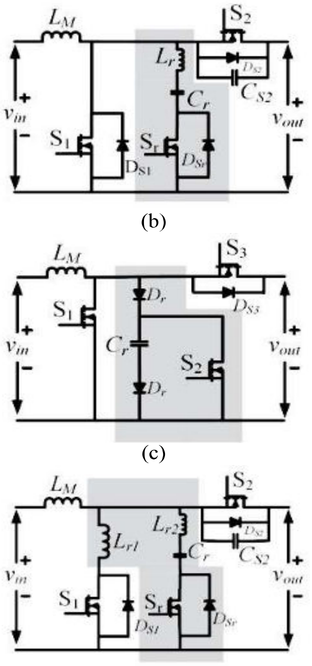
Fig. 9. PFM network (a) with active parallel LLC formation [52] (b) with LL configuration [20] (c) with passive LLC formation [17] (d) with active LCC formation [19]

2) *Active edge resonant (AER) converters*

Active edge resonant converters are modified versions of PFM resonant converters. In general, switched resonant capacitor C_r or an additional switched capacitor is included in AER converters. This is shown in Figs. 10 (a) to 10 (e). The AER converters can be extended further to four or five terminal versions. Active clamping of the auxiliary switches is executable by adding clamping diodes. The operation of the converter remains similar to the PFM converters except that additional switches and capacitors are included. Generally, in return, this improves the soft turn off operation. AER based converters are reported in [35-40]. Switched capacitor-based AER network otherwise called edge resonant switched capacitor (ER-SW) converter is reported in [41]. The ER-SW switching converter is demonstrated in Fig. 10 (c). An isolated type AER converter is also proposed in [42].



(a)



(b)

(c)

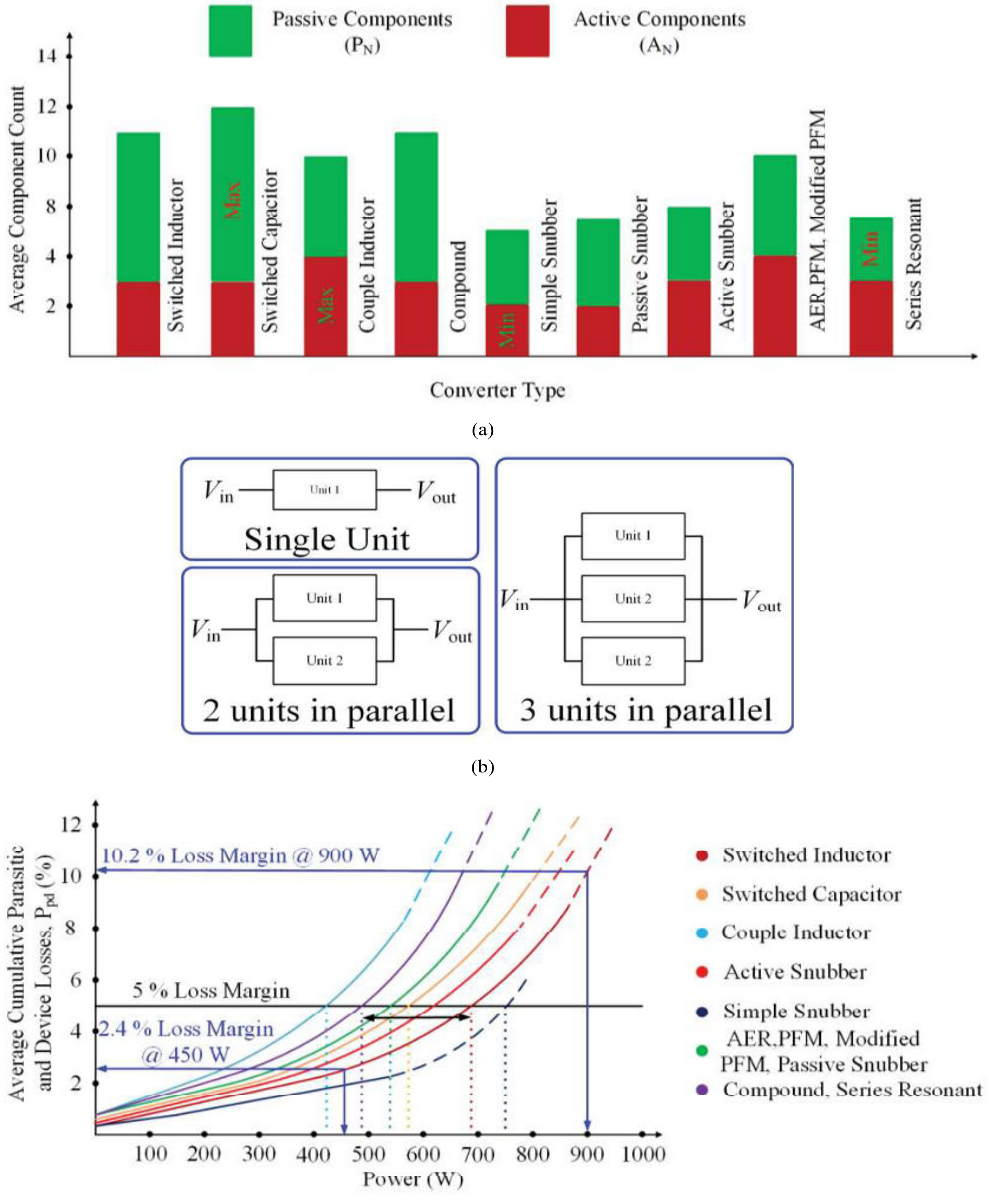
(d)

Fig.10. AER network (a) with parallel LC [42] (b) with series LC [59] (c) single capacitor and diodes [43] (d) with LLC series network [59]

IV. GENERAL COMMENTS ON THE SOFT SWITCHING CONVERTERS AS EV CHARGERS

A. *Snubber converters*

Simple lossless snubber-based converters require only a capacitor across the main switch; it has a very compact structure with simple control and low power loss. However, the soft turn on operation of the main switch is extremely vulnerable to the input voltage and the switching frequency. The soft turn off is also largely affected by the load current. Additionally, the soft turn on of the rectifier switch or diode is not achievable. Thus, this snubber is preferable in low voltage and low switching frequency EV charging applications. On the other hand, the active snubber is superior as the ZVS turn on and turn off of both the power switches is ensured and high-power charging application is possible. For the passive snubber, the reliability is lower as the charging and discharging of the passive elements are quasi-controllable, thus giving rise to residual charges. Furthermore, it barely provides the ZVS (which is dependent on the input voltage) at turn on for the main switch. However, the ZVS turn off of the main switches is easily achievable. Hence, passive snubber converters are more preferable in low voltage charging applications.



(a)

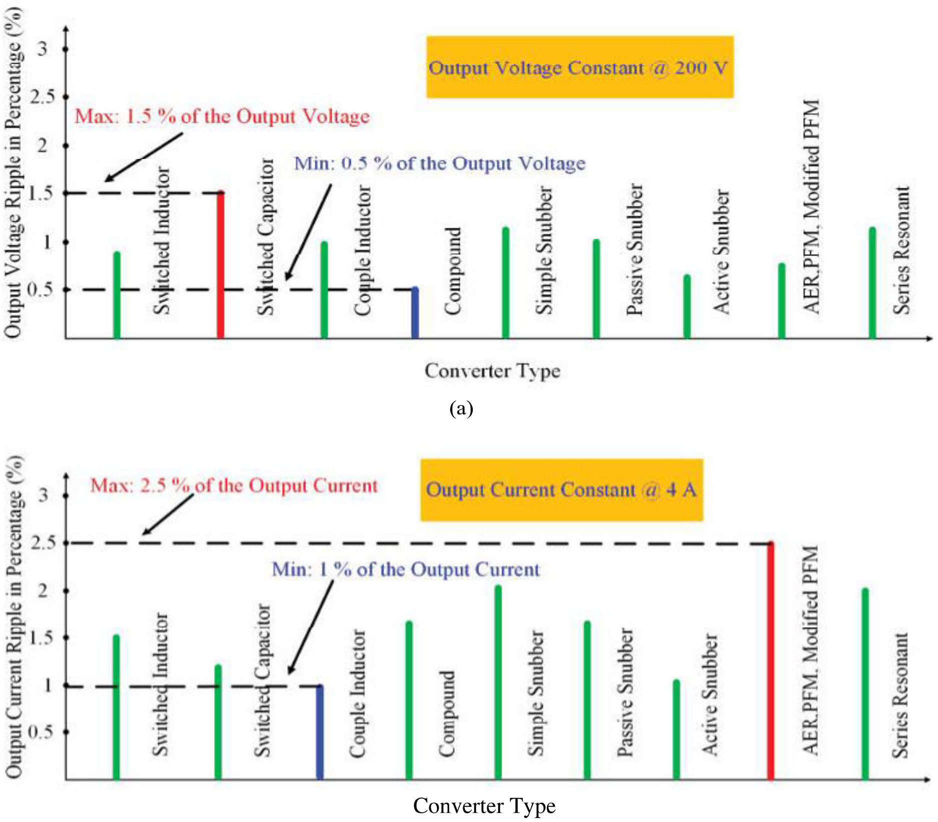
(b)

(c)

Fig. 11. (a) Average number of active and passive components (b) parallel operation of multiple converters (c) Average cumulative losses

B. Series resonant converters

The series resonant converters support the ZVS or the ZCS for multiple switches simultaneously. In addition, it eliminates the need for snubber capacitance across the main switches. However, the resonant components lie on the main power flow path and the resonance is perpetual regardless of the switching state. Thus, the required voltage and current ratings of the resonant components are higher. Besides, the stored energy in the resonant inductor depends on the load voltage and current. These factors increase the conduction loss in the circuit. Additionally, to achieve low output voltage distortion, the switching frequency should be selected close to the resonance frequency. Besides, as the resonance is not explicitly controllable, the EMI problem can increase. Consequently, the series resonant converters are preferred in fixed switching frequency and low current (i.e. low power) converters.



(a)

(b)

Fig. 12. (a) Output voltage ripple in percentage (b) output current ripple in percentage

C. *Shunt resonant converters*

The shunt resonant converters overcome the drawbacks associated with other converters while offering more flexible soft switching transition [43, 44]. As noted, for the series resonant converters, the energy stored in the resonant inductor depends on the load current and voltage—hence the reduced soft switching range. In the shunt resonant converters, this problem is partially removed by introducing the resonant networks shunted across the main switch. Consequently, the circulating energy in the auxiliary network is precisely controlled, resulting in lower conduction losses. In addition, the switching stress on the power switches is also reduced. Many of the converters (e.g. [15, 18]) compensate for diode reverse recovery loss and thus increase the soft switching range and boost the efficiency. Despite these advantages, the shunted resonant converters exhibit a high component count. Additionally, in most of the cases, the auxiliary switches are not soft commutated, which contributes to the increase in the switching losses. Besides, for high power applications, the magnetic circuits in the resonant converters become larger and hence higher magnetic loss is observed. Many compound resonant converters [27] provide the ZVT-ZCT simultaneously, but at the cost of increased component count. In summary, shunt resonant converters are well applicable in high power (i.e. high voltage and high current) EV charging applications.

D. *Pulse frequency modulated (PFM) converters*

The PFM and AER converters primarily apply the ZCS. They exhibit relatively simple structure and offer modest soft switching operating range. However, the voltage surge and current ringing at turn off are observed due to the interaction among the parasitic capacitance of the main switches and the resonant inductor [45]. These can be reduced by installing active clamping diodes across the switches. Additionally, as the resonant capacitor remains discharged for most of the switching period, smoother turn off transition can be achieved. In general, the PFM and the AER converters have low switch count. However, since the resonant current is not fully independent of the load current, the soft commutation is affected by load variations. Hence, these converters are suitable for high power but preferably at low current charging applications.

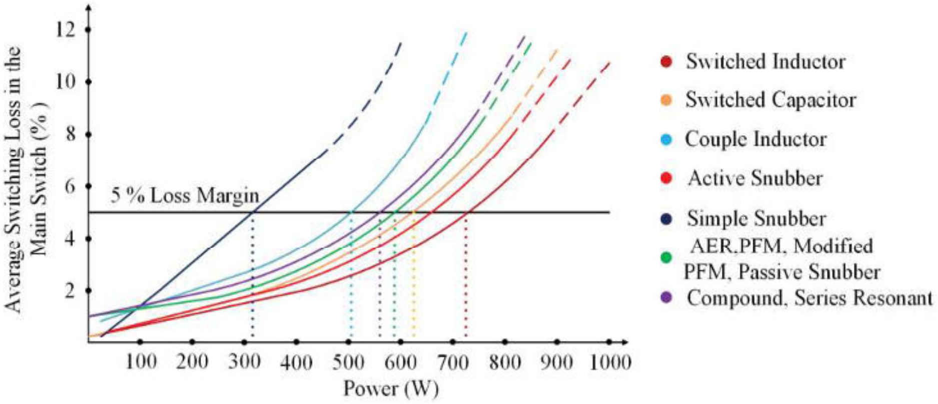
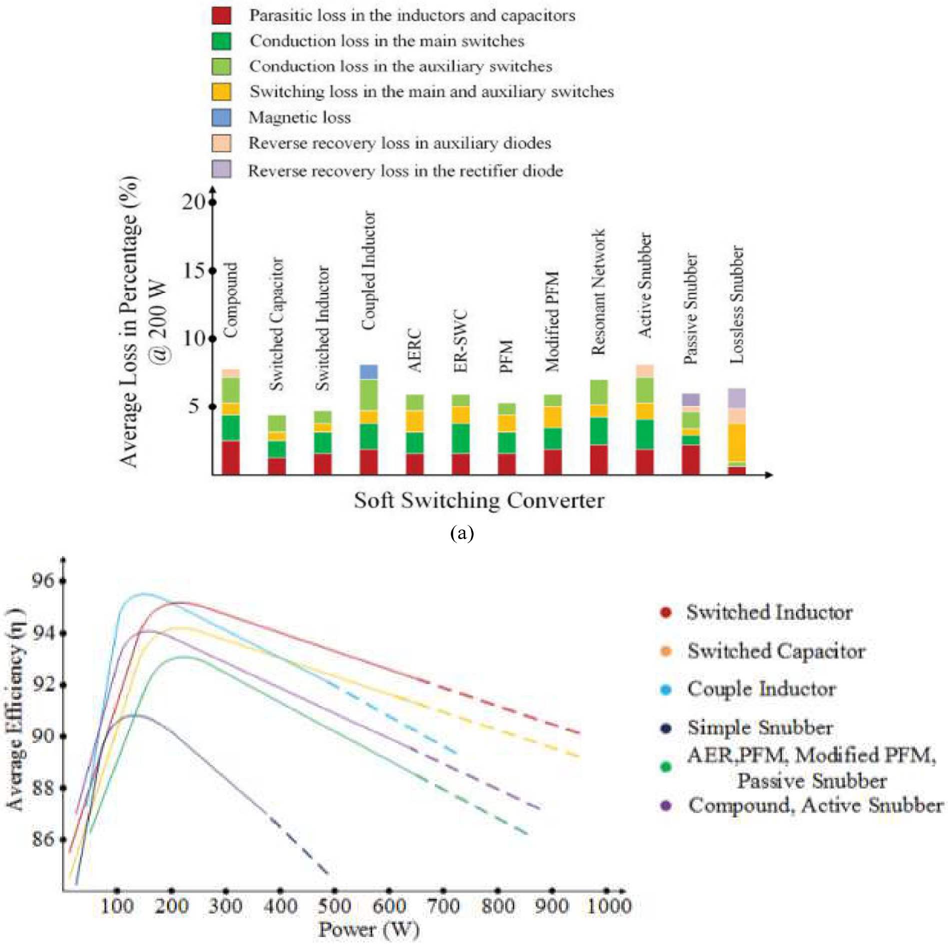


Fig. 13. Average switching loss in the main switch



(a)

(b)

Fig. 14. (a) Average loss in percentage (b) Average efficiency

V. COMPARATIVE EVALUATION

In this section, a brief evaluation of the various soft switching converters is given. The main aspects to be compared are the component count, the output voltage and current ripple, the soft switching range or the switching losses and the power dissipation. The soft switching converters under each category are simulated using the ORCAD PSpice Designer[2] environment. For a fair benchmarking, the converters are built using similar active and passive devices. The key results are plotted in Fig. 11 to Fig. 14, while the summary of the performance is given in TABLE II. The applicability in EV charging is demonstrated in Fig. 12. A brief discussion to compare the salient features of each switching converter follows.

A. Component count

The A_N and P_N provides an average of the total number of active and passive components respectively for each converter type. The A_N refers to the total number of active components, while P_N is the total number of passive components in the original converter circuit. A higher A_N or P_N indicates higher component count. Besides, A_N gives an approximate idea of the control complexity of the converter as the number of gate drivers and the PWM switching signal also increases with the increase in A_N. The bar chart in Fig. 11 (a) demonstrates A_N and P_N for each converter type. As obvious from Fig. 11 (a), the shunt resonant converters and the PFM converters have higher component count as compared to the snubber-based converters. The P_N has a maximum value of 9 for switched capacitor resonant converters and a minimum value of 4 for series resonant converters. On the other hand, A_N has a maximum value of 4 for coupled inductor and PFM converters and a minimum value of 2 for simple snubber converters. In general, it can be observed that the snubber-based converters and the series resonant converters have low A_N and P_N. However, despite high component count, certain compound resonant converters [27, 46] exhibit true ZVZCS switching capability which improves the soft switching range [47-51].

1) Parallel operation of multiple converters

The active and passive components in the converter give rise to parasitic and device losses. The greater the values of A_N and P_N, the greater the losses. Additionally, these losses increase exponentially with the increase in power. Hence, larger efficiency drop is induced. However, this efficiency drops or losses can be compensated by using parallel units of converters at high power. This is shown in Fig. 11 (b). In Fig. 11 (c), the average cumulative parasitic and device loss (P_{pd}) is formulated against the input power. As obvious, if the converters are operated in between 500 W to 700 W on average, a consistent 5 % loss margin in terms of parasitic and device losses can be maintained for all converter type. However, to operate at a higher power (i.e. > 700 W), the P_{pd} would increase exponentially. To alleviate this problem, two converters in parallel can be employed to maintain low P_{pd}. For example, if a single coupled inductor converter unit is operated at 900 W, the P_{pd} would be 10.2 % of the input power. On the other hand, two converter units in parallel each operated at 450 W can give rise to cumulative P_{pd} less than 5 %. This is marked by the blue lines in Fig. 11 (c).

B. The output voltage and current ripple

The output voltage and current ripple has significant impact on the battery life of the electric vehicle. High ripple current can degrade the battery life while high voltage ripple can elongate the charging time and damage the battery. Hence, the current and voltage ripple has to be minimum to avoid any significant damage to the EV battery pack. The voltage and current ripple of the soft switching converters is demonstrated in Figs. 12 (a) and (b) respectively under similar operating conditions. In Fig. 12 (a), the output voltage is kept constant at 200 V. As obvious, the switched capacitor resonant converters exhibit highest ripple voltage of 1.5 % and the compound resonant converters render lowest ripple voltage of 0.5 % of the output voltage. On the other hand, the output current is kept constant at 4 A in Fig. 12 (b) while the current ripple is measured. It can be observed that the PFM converters exhibit highest ripple current of 2.5 % while the coupled inductor resonant converters exhibit the lowest ripple current of 1 % of the output current. Consequently, the converters that exhibit high ripple voltage are more appropriate for low voltage charging application while the high ripple current converters are more appropriate for low current charging applications.

C. The soft switching techniques

The soft switching converters can be also distinguished by the type of soft switching technique used. As mentioned earlier, the technique influences the power loss in the soft-switching topology. The snubber and series resonant converters are designed for the ZVS, while the ZVT and ZCT shunt resonant converters mostly apply the ZVS and the ZCS, respectively. Besides, certain compound resonant converters are of the ZVZCS type. On the other hand, the majority of PFM converters apply the ZCS mode of soft switching. TABLE II summarizes the technique used for various types of soft switching configurations as recorded in literature.

D. The soft switching range

The soft switching range is defined as the operating window, within which the soft switching feature is available. The window can be limited to the input voltage, loading (output current/voltage) and switching frequency of the converter. The estimation of the exact range for a specific soft switching converter is not straightforward as it varies according the factors mentioned above. Despite these difficulties, a general sense of the range can be understood by simulating the converter by varying 1) the input voltages from 20 V to 200 V, 2) the load from 20 W to 800 W and 3) switching frequency from 20 kHz to 150 kHz. The

---

[2] ORCAD PSpice Designer is the trademark of Cadence Design Systems, Inc.

converters that provide the widest soft switching range demonstrate consistently low switching losses over the entire operating range. On the same note, converters that demonstrate high switching losses over the entire operating range provide low soft switching range of operation. In Fig.13, the average switching loss in the main switch of the converters is measured. As obvious, if a maximum of 5 % loss is sustained in the main switch, the switched inductor and switched capacitor converters can provide consistent low switching losses up to 620 W and 750 W respectively. On the lower end, the simple snubber converter can provide up to 320 W for the same loss margin. Similarly, the coupled inductor, the compound and the series resonant converters can provide up to 550 W for the same loss margin. This is shown by the dotted lines in Fig. 13.

E. The power consumption

The power consumption of the converters originate from several sources: 1) the parasitic losses in the passive components, i.e. the inductors and capacitors 2) the on-state and switching losses in the main and auxiliary switches (if not soft switched), 3) the reverse recovery loss in the main and auxiliary diodes and 4) the conduction and core losses induced in the magnetic circuits. These losses are not uniform; they vary with the load and switching frequency. To investigate the losses profile, the converter is independently analyzed for different type of losses. Furthermore, for consistency, the converters are simulated at the same switching frequency (i.e. 100 kHz), the input voltage (i.e. 80 V) and loading condition (i.e. 200 W). The breakdown of the total average losses for each converter type is depicted in Fig. 14 (a).

As obvious from Fig. 14 (a), the shunt resonant converters exhibit the lowest loss profiles (i.e. 5% on average). This is because the shunted networks are turned off for the most part of the switching period and activated only at the switching instants. However, the compound resonant converters demonstrate higher device loss, despite the fact it also belongs to the shunt resonant category. This is due to a large number of components that they possess. For the series resonant converters, the conduction loss is significant due to the perpetual resonance throughout the switching period. For the simple lossless snubber, the turn on loss and the reverse recovery loss (RRL) of the rectifier diode are noteworthy. On the other hand, the conduction losses in the auxiliary diodes and the residual charge in the passive components are significant contributors to the loss profiles for the passive snubber converters.

The RRL of the rectifier diode in a conventional boost/buck converter is significant because it contributes to about 0.2%-2% efficiency drop (depending on the switching frequency, loading, and type of the device). The reverse recovery loss minimization technique is integrated into many of the soft switching converters [9] [6] [15, 17, 18, 29] to compensate for the forced commutated diode operation while this feature is absent in many converters [12, 13] [11]. Yet for some other converters [12, 13], the loss is very low and has almost zero impact on the converter loss profile.

From another perspective as depicted in Fig. 14 (b), the shunt resonant converters provide high efficiency (>90%) consistently at the high-power region (i.e.≈1000W). On the contrary, the efficiency of simple snubber converters drops to below 90 % over 250 W margins. Similarly, the compound, PFM, active snubber, and passive snubber converters can maintain 90 % efficiency up to 600 W on average.

F. Preferred applicability in EV charging

Based on the results described in Section 5.1 to 5.4, the converters characteristics are tabulated in TABLE II. The applicability in EV charging is evaluated accordingly as shown in Fig. 15.

As demonstrated in Fig. 14 (b), the soft switching feature in simple snubber converters are highly vulnerable to lose at load variations. On top of that, the sharp degradation in the efficiency profile of these converters demonstrates that overall loss increases exponentially with power. Besides, the high ripple voltage and current are notable. Hence, these converters should be implemented for low power charging to maintain high efficiency. Besides, the high voltage and current ripple are notable. In contrary, the low switching loss and the efficiency profile of the active snubber converters demonstrate their ability to maintain high efficiency at high power region. This is further supported by the low voltage and current ripple of these converters. Eventually, these issues make them appropriate for high-voltage high-current charging applications. As discussed earlier, to maintain the ZVS turn on condition, the passive snubber converter should be operated at low voltage. Because of incorporating a large number of components, the compound resonant converters should not be operated at high power to avoid large degradation in efficiency in terms of device losses. On the other hand, the switched inductor and switched capacitor resonant converters maintain high-efficiency profile which makes them suitable for high power charging applications. However, due to large voltage ripple induced in switched capacitor resonant converters, it is recommended to use them in low-voltage charging applications to avoid any possible degradation in the battery life. Similarly, the soft switching converters that apply the ZCS scheme (i.e. the PFM resonant converters) should be employed in the low current charging application. This is because the ZCS becomes vulnerable at high load current. On top of that, the current ripple can be minimized if the load current is low. Eventually, this would help to reduce the on-state device loss as well as ensures ZCS operation for wide load variations.

TABLE II. Overview of the converter performances

Converter Type	Soft Switching technique	Component Count	Output Voltage Ripple	Output Current Ripple	Switching Loss	Overall Loss	Average Efficiency
Switched Capacitor	ZVS	10-12	1.5	1.25	1.2	4	>90
Switched Inductor	ZVS	9-11	0.9	1.5	1	4.2	>90
Coupled Inductor	ZVS	8-10	1	1	1.8	6	>85
Compound Resonant	ZVZCS	9-11	0.5	1.75	1.9	5	>90
PFM/ Modified PFM/AER	ZCS	8-10	0.8	2.5	1.8	4	>90
Series Resonant	ZVS	5-7	1.3	2.25	1.9	4.5	>90
Active Snubber	ZVS	6-8	0.75	1.25	1.6	5	>85
Passive Snubber	ZVS	5-7	1	1.75	1.8	4	>90
Simple snubber	ZVS	3-5	1.1	2.1	2.4	7	>85

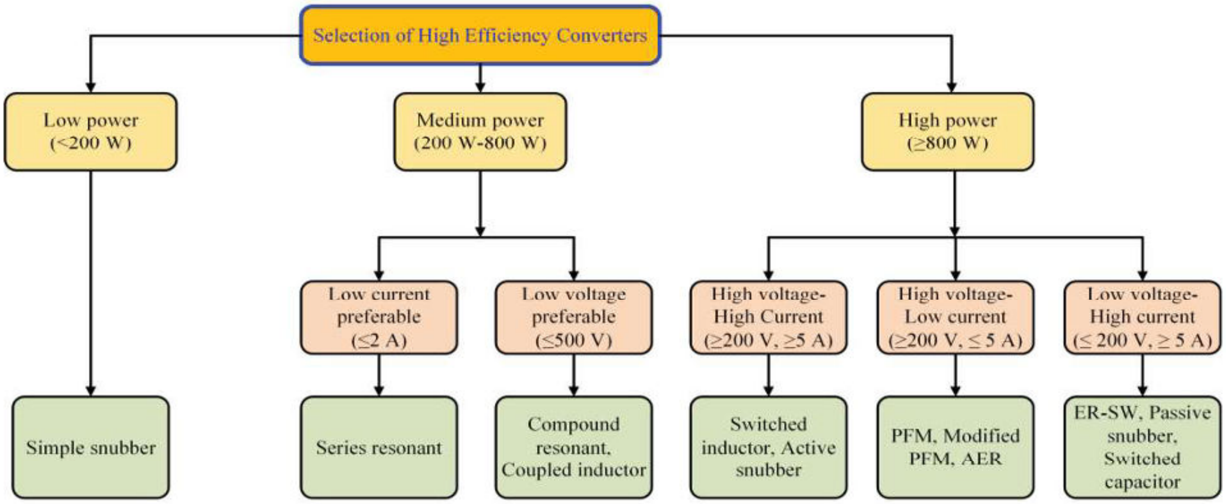


Fig. 15. The optimum applicability of dc-dc converters in EV charging

VI. CONCLUSION

In this paper, a review of the non-isolated soft switching dc-dc converters for EV charging application is presented. The soft switching converters are classified according to their structure and similarities in the soft switching operation; i.e. the snubber, the series resonant, the shunt resonant and the pulse frequency modulated converters followed by a short description. The merits and demerits of the soft switching converters and their applicability as EV chargers are discussed. Finally, a performance comparison is formulated, focusing on some of the most fundamental characteristics of each converter type, namely the component count, the output voltage and current ripple, the soft switching range of operation and the power loss. All these parameters play a vital role in determining the true effectiveness of the soft switching converters in various EV charging applications. For example, it is found that the shunt resonant converters, in general, have a low power loss, while PFM converters maintain a very low device count. However, due to high current ripple, the PFM converters are more appropriate for low current charging. On the other hand, despite low switching loss profile, the compound resonant converters have high device count. Hence, to maintain a low device loss profile, these converters should not be employed in high power charging applications. The active snubber converters and the switched inductor resonant converters have low output voltage and current ripple and maintain low switching and device losses. This enables them to employ in high power (e.g. high voltage and high current) EV charging applications. On the other end, due to high switching loss and high output voltage and current ripple, the simple snubber configuration is mostly appropriate for low power charging applications. The series resonant converters are mostly applicable for medium power charging applications as they would induce high ripple current at high power charging. The overall characteristics of the soft switching converters and their applicability in EV charging are tabulated for easier understanding of the readers.

References

[1] H. Mehrjerdi and R. Hemmati, "Stochastic model for electric vehicle charging station integrated with wind energy," *Sustainable Energy Technologies and Assessments,* vol. 37, p. 100577, 2020/02/01/ 2020.

[2] M. A. Quddus, M. Kabli, and M. Marufuzzaman, "Modeling electric vehicle charging station expansion with an integration of renewable energy and Vehicle-to-Grid sources," *Transportation Research Part E: Logistics and Transportation Review,* vol. 128, pp. 251-279, 2019/08/01/ 2019.

[3] L. Luo, W. Gu, Z. Wu, and S. Zhou, "Joint planning of distributed generation and electric vehicle charging stations considering real-time charging navigation," *Applied Energy,* vol. 242, pp. 1274-1284, 2019/05/15/ 2019.

[4] M. Muratori, "Impact of uncoordinated plug-in electric vehicle charging on residential power demand," *Nature Energy,* vol. 3, no. 3, pp. 193-201, 2018/03/01 2018.

[5] J. Y. Zhu and D. Daohong, "Zero-voltage- and zero-current-switched PWM DC-DC converters using active snubber," *Industry Applications, IEEE Transactions on,* vol. 35, no. 6, pp. 1406-1412, 1999.

[6] M. M. Jovanovic and J. Yungtaek, "A novel active snubber for high-power boost converters," *IEEE Transactions on Power Electronics,* vol. 15, no. 2, pp. 278-284, 2000.

[7] C. Tantisukarom, V. Tarateeraseth, W. Khan-ngern, and S. Nitta, "An efficiency improvement of the active snubber boost converter for low power," in *Power Electronics Specialists Conference, 2002. pesc 02. 2002 IEEE 33rd Annual*, 2002, vol. 2, pp. 437-440 vol.2.

[8] K. Zhuge and M. Kazerani, "A novel capacitor-switched active snubber for single-module and interleaved two-module bidirectional buck-boost converter topologies," in *Industrial Electronics Society, IECON 2014 - 40th Annual Conference of the IEEE*, 2014, pp. 1097-1103.

[9] B. Ivanovic and Z. Stojiljkovic, "A novel active soft switching snubber designed for boost converter," *IEEE Transactions on Power Electronics,* vol. 19, no. 3, pp. 658-665, 2004.

[10] W. Chao-Cheng and Y. Chung-Ming, "New ZVT-PWM DC/DC converters using active snubber," *IEEE Transactions on Aerospace and Electronic Systems,* vol. 39, no. 1, pp. 164-175, 2003.

[11] T. Ching-Jung and C.-L. Chen, "A passive lossless snubber cell for nonisolated PWM DC/DC converters," *Industrial Electronics, IEEE Transactions on,* vol. 45, no. 4, pp. 593-601, 1998.

[12] M. Mohammadi, E. Adib, and M. R. Yazdani, "Family of Soft-Switching Single-Switch PWM Converters With Lossless Passive Snubber," *IEEE Transactions on Industrial Electronics,* vol. 62, no. 6, pp. 3473-3481, 2015.

[13] B. T. Irving and M. M. Jovanovic, "Analysis, design, and performance evaluation of flying-capacitor passive lossless snubber applied to PFC boost converter," in *Applied Power Electronics Conference and Exposition, 2002. APEC 2002. Seventeenth Annual IEEE*, 2002, vol. 1, pp. 503-508 vol.1.

[14] K. Fujiwara and H. Nomura, "A novel lossless passive snubber for soft-switching boost-type converters," *IEEE Transactions on Power Electronics,* vol. 14, no. 6, pp. 1065-1069, 1999.

[15] S. Dusmez, A. Khaligh, and A. Hasanzadeh, "A Zero-Voltage-Transition Bidirectional DC/DC Converter," *Industrial Electronics, IEEE Transactions on,* vol. 62, no. 5, pp. 3152-3162, 2015.

[16] H. Bodur and A. F. Bakan, "A new ZVT-ZCT-PWM DC-DC converter," *Power Electronics, IEEE Transactions on,* vol. 19, no. 3, pp. 676-684, 2004.

[17] L. Jiang, C. C. Mi, S. Li, M. Zhang, X. Zhang, and C. Yin, "A Novel Soft-Switching Bidirectional DC–DC Converter With Coupled Inductors," *Industry Applications, IEEE Transactions on,* vol. 49, no. 6, pp. 2730-2740, 2013.

[18] Y. Jae-Won and D. Hyun-Lark, "Soft-Switching Bidirectional DC-DC Converter Using a Lossless Active Snubber," *IEEE Transactions on Circuits and Systems I: Regular Papers,* vol. 61, no. 5, pp. 1588-1596, 2014.

[19] N. Lakshminarasamma and V. Ramanarayanan, "A Family of Auxiliary Switch ZVS-PWM DC–DC Converters With Coupled Inductor," *Power Electronics, IEEE Transactions on,* vol. 22, no. 5, pp. 2008-2017, 2007.

[20] A. Mirzaei, A. Jusoh, and Z. Salam, "Design and implementation of high efficiency non-isolated bidirectional zero voltage transition pulse width modulated DC–DC converters," *Energy,* vol. 47, no. 1, pp. 358-369, 11// 2012.

[21] R. H. Ashique, Z. Salam, and M. J. A. Aziz, "A high power density soft switching bidirectional converter using unified resonant circuit," in *Energy Conversion (CENCON), 2015 IEEE Conference on*, 2015, pp. 165-170.

[22] G. Hua, C. S. Leu, and F. C. Lee, "Novel zero-voltage-transition PWM converters," in *Power Electronics Specialists Conference, 1992. PESC '92 Record., 23rd Annual IEEE*, 1992, pp. 55-61 vol.1.

[23] T. Ching-Jung and C.-L. Chen, "Novel ZVT-PWM converters with active snubbers," *Power Electronics, IEEE Transactions on,* vol. 13, no. 5, pp. 861-869, 1998.

[24] C. M. de Oliveira Stein and H. L. Hey, "A true ZCZVT commutation cell for PWM converters," *Power Electronics, IEEE Transactions on,* vol. 15, no. 1, pp. 185-193, 2000.

[25] M. L. da Silva Martins and H. L. Hey, "Self-commutated auxiliary circuit ZVT PWM converters," *Power Electronics, IEEE Transactions on,* vol. 19, no. 6, pp. 1435-1445, 2004.

[26] M. Pavlovsky, G. Guidi, and A. Kawamura, "Buck/boost DC–DC converter topology with soft switching in the whole operating region," *Power Electronics, IEEE Transactions on,* vol. 29, no. 2, pp. 851-862, 2014.

[27] B. Akin, "An Improved ZVT–ZCT PWM DC-DC Boost Converter With Increased Efficiency," *Power Electronics, IEEE Transactions on,* vol. 29, no. 4, pp. 1919-1926, 2014.

[28] S. Urgun, "Zero-voltage transition–zero-current transition pulsewidth modulation DC-DC buck converter with zero-voltage switching & zero-current switching auxiliary circuit," *Power Electronics, IET,* vol. 5, no. 5, pp. 627-634, 2012.

[29] M. R. Mohammadi and H. Farzanehfard, "A New Family of Zero-Voltage-Transition Nonisolated Bidirectional Converters With Simple Auxiliary Circuit," *IEEE Transactions on Industrial Electronics,* vol. 63, no. 3, pp. 1519-1527, 2016.

[30] F. T. Wakabayashi, M. J. Bonato, and C. A. Canesin, "A new family of zero-current-switching PWM converter," in *Power Electronics Specialists Conference, 1999. PESC 99. 30th Annual IEEE*, 1999, vol. 1, pp. 451-456 vol.1.

[31] C. A. Canesin and I. Barbi, "Novel zero-current-switching PWM converters," *Industrial Electronics, IEEE Transactions on,* vol. 44, no. 3, pp. 372-381, 1997.

[32] L. T. S. Sobrinho, R. A. Kitamura, and C. A. Canesin, "Novel zero-current-switching PWM step down Sepic converter," in *Power Electronic Drives and Energy Systems for Industrial Growth, 1998. Proceedings. 1998*

International Conference on, 1998, vol. 2, pp. 717-722 Vol. 2.

[33] J. Doo-Yong, J. Young-Hyok, P. Sang-Hoon, J. Yong-Chae, and W. Chung-Yuen, "Interleaved Soft-Switching Boost Converter for Photovoltaic Power-Generation System," *Power Electronics, IEEE Transactions on,* vol. 26, no. 4, pp. 1137-1145, 2011.

[34] M. R. Amini and H. Farzanehfard, "Novel Family of PWM Soft-Single-Switched DC-DC Converters With Coupled Inductors," *Industrial Electronics, IEEE Transactions on,* vol. 56, no. 6, pp. 2108-2114, 2009.

[35] T. Mishima and M. Nakaoka, "A Practical ZCS-PWM Boost DC-DC Converter With Clamping Diode-Assisted Active Edge-Resonant Cell and Its Extended Topologies," *Industrial Electronics, IEEE Transactions on,* vol. 60, no. 6, pp. 2225-2236, 2013.

[36] T. Mishima and M. Nakaoka, "A new family of soft switching PWM non-isolated DC-DC converters with Active auxiliary Edge-Resonant Cell," in *Power Electronics Conference (IPEC), 2010 International*, 2010, pp. 2804-2809.

[37] K. F. A. Sayed, T. Mishima, H. Sugimura, M. Sang-Pil, K. Soon-Kurl, and M. Nakaoka, "Interleaved ZCS boost DC-DC converters with coupled inductor using active edge resonant switch blocks for PV interface," in *Electrical Machines and Systems, 2009. ICEMS 2009. International Conference on*, 2009, pp. 1-7.

[38] K. Ogura, S. Chandhaket, T. Ahmed, and M. Nakaoka, "Boost chopper-fed ZVS-PWM DC-DC converter with parasitic oscillation surge suppression-based auxiliary edge resonant snubber," in *Telecommunications Energy Conference, 2003. INTELEC '03. The 25th International*, 2003, pp. 20-26.

[39] R. C. Fuentes and H. L. Hey, "An improved ZCS-PWM commutation cell for IGBT's application," *Power Electronics, IEEE Transactions on,* vol. 14, no. 5, pp. 939-948, 1999.

[40] M. Hengchun, F. C. Y. Lee, Z. Xunwei, H. Dai, M. Cosan, and D. Boroyevich, "Improved zero-current transition converters for high-power applications," *Industry Applications, IEEE Transactions on,* vol. 33, no. 5, pp. 1220-1232, 1997.

[41] T. Mishima, Y. Takeuchi, and M. Nakaoka, "Analysis, Design, and Performance Evaluations of an Edge-Resonant Switched Capacitor Cell-Assisted Soft-Switching PWM Boost DC–DC Converter and Its Interleaved Topology," *Power Electronics, IEEE Transactions on,* vol. 28, no. 7, pp. 3363-3378, 2013.

[42] M. M. Jovanovic and J. Yungtack, "A new, soft-switched boost converter with isolated active snubber," *IEEE Transactions on Industry Applications,* vol. 35, no. 2, pp. 496-502, 1999.

[43] R. L. Steigerwald, "A review of soft-switching techniques in high performance DC power supplies," in *Industrial Electronics, Control, and Instrumentation, 1995., Proceedings of the 1995 IEEE IECON 21st International Conference on*, 1995, vol. 1, pp. 1-7 vol.1.

[44] G. Hua and F. C. Lee, "Soft-switching techniques in PWM converters," *IEEE Transactions on Industrial Electronics,* vol. 42, no. 6, pp. 595-603, 1995.

[45] T. Mishima, S. Miyake, and M. Nakaoka, "Practical evaluations of ZCS-PWM boost DC-DC converter with active edge-resonant cell using Si-IGBT/SiC-SBD hybrid power devices," in *Power Electronics, Machines and Drives (PEMD 2010), 5th IET International Conference on*, 2010, pp. 1-6.

[46] R. H. Ashique and Z. Salam, "A Family of True Zero Voltage Zero Current Switching (ZVZCS) Non-isolated Bidirectional DC-DC Converter with Wide Soft Switching Range," *IEEE Transactions on Industrial Electronics,* vol. PP, no. 99, pp. 1-1, 2017.

[47] R. H. Ashique, Z. Salam and J. Ahmed, "An adaptive P&O MPPT using a sectionalized piece-wise linear P-V curve," 2015 IEEE Conference on Energy Conversion (CENCON), Johor Bahru, 2015, pp. 474-479, 2015.

[48] R. H. Ashique, Z. Salam and M. J. A. Aziz, "A high power density soft switching bidirectional converter using unified resonant circuit," 2015 IEEE Conference on Energy Conversion (CENCON), Johor Bahru, 2015, pp. 165-170, 2015.

[49] R. H. Ashique, Z. Salam and M. J. A. Aziz, "A high gain soft switching non-isolated bidirectional DC-DC converter," 2016 IEEE International Conference on Power and Energy (PECon), Melaka, 2016, pp. 417-422, 2016.

[50] R. H. Ashique and Z. Salam, "A High-Gain, High-Efficiency Nonisolated Bidirectional DC–DC Converter With Sustained ZVS Operation," in IEEE Transactions on Industrial Electronics, vol. 65, no. 10, pp. 7829-7840, Oct. 2018, doi: 10.1109/TIE.2018.2802457.

[51] R. H. Ashique, Z. Salam, M. J. Bin Abdul Aziz, and A. R. Bhatti, "Integrated photovoltaic-grid dc fast charging system for electric vehicle: A review of the architecture and control," *Renewable and Sustainable Energy Reviews,* vol. 69, pp. 1243-1257, 2017/03/01/ 2017.

Dr. Ratil H. Ashique received B.Sc. degree in Electrical and Electronic engineering from Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh, in 2011. He completed Ph.D. from Universiti Teknologi Malaysia (UTM), Skudai, Johor, Malaysia in 2018. His PhD research project was titled as 'Design, Development and Construction of Power Converter for Photovoltaic Based Charging Station for Electric Vehicle' funded by the Ministry of Science, Technology and Innovation (MOSTI) under the Malaysia Science Fund Grant. In 2017, he also received UTM International Doctoral Fellowship. Later, he worked as a post-doctoral research associate at The University of Sheffield, one of the leading research universities in UK from April 2018 to April 2020. The multidisciplinary project was titled as 'FPeT based Power Supply Design' and was sponsored by the prestigious British Engineering and Physical Sciences Research Council (EPSRC). His research contributions are published in top-tier ISI and SCOPUS indexed journals and conferences demonstrating a high impact (Combined Impact Factor: 39.118, JCR @ Clarivate Analytics 2019) standing and 200+ Google scholar citations. He is also a member of IEEE and a member of the advisory panel for the Nan Yang Academy of Sciences in Singapore for power electronics and e-mobility research. He is an active reviewer for IEEE TIE, TPE and Access journals. He also served as a technical committee member and a member of the editorial board for recognized international conference and journals respectively. His research interests include *design of application specific high efficiency/high gain power converters, controller design for PFC with integrated active filters, active filters for input current shaping, soft switching implementation in medium and high power converters, modelling of class E/D ZVS/ZCS resonant converters, design of very low voltage and ultra-high current multiphase converters, EMI suppression circuits, electric vehicle charging systems: architecture ,control and integration of renewables* etc.