
Comparison and evaluation of different DC/DC topologies for plug-in hybrid electric vehicle chargers

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Abstract: The battery charging system is a critical part of a plug-in hybrid electric vehicle (PHEV). The efficiency, charging speed, and cost of such chargers are crucial to the commercialisation of PHEVs. In this paper, the advantages and drawbacks of four potential PHEV charger topologies were compared based on their operations through simulation and experiments. Their electrical stress, efficiency, cost, and the feasibility were discussed in detail. It was concluded that a full-bridge based PHEV charger is the most favourable choice among the four available topologies due to its power capability, soft switching capability, low electric stress, high efficiency, but slightly elevated cost.

Keywords: forward converter; flyback converter; half-bridge converter; full-bridge converter; DC-DC converter; battery charger; plug-in hybrid electric vehicle; PHEV; electric vehicle; fast charging.

Reference to this paper should be made as follows: Bai, H. and Mi, C. (2012) 'Comparison and evaluation of different DC/DC topologies for plug-in hybrid electric vehicle chargers', *Int. J. Power Electronics*, Vol. 4, No. 2, pp.119–133.

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1 Introduction

Plug-in hybrid electric vehicles (PHEVs) are usually driven in all-electric mode for the initial driving range by using the electrical energy stored in the on-board battery (Amjadi and Williamson, 2010; Electric Power Research Institute, 2007). Most of PHEVs are capable of 40 miles electric driving range. For a typical passenger car, the average energy consumption is approximately 150–300 Wh per mile (Thompson et al., 2009). To achieve 40 miles electric range, a battery that contains usable energy of 8 kWh is appropriate, e.g., using Lithium ion batteries (Anderson, 2009).

The battery on-board a PHEV needs to be charged from the grid through either an on-board or an off-board charger. In order to make sure that the vehicle is ready for use by the second morning, the battery must be fully charged within a reasonable amount of time, typically two to six hours. In addition, a PHEV charger must also be electrically isolated, maintain high efficiency, low cost, and easy to control.

In the past decades, various charging circuits have been developed targeting different applications (Kutkut et al., 1998), such as laptop computers, portable electronics, and uninterruptable power supplies (UPS), etc. As far as unidirectional charging system is concerned, chargers based on flyback and forward converters are typical examples for low power applications. Both topologies need only one active switch. However, flyback and forward converters undertake high voltage spikes when the excessive energy stored in the leakage inductance of the isolation transformer is exhausted at the turn-off moment (Zhao et al., 2002; Huber and Jovanovic, 1998; Wang, 2008). Therefore, at higher power operations, an auxiliary snubber circuit is indispensable. Regardless of the limitations, flyback/forward topologies are being used in PHEV charges.

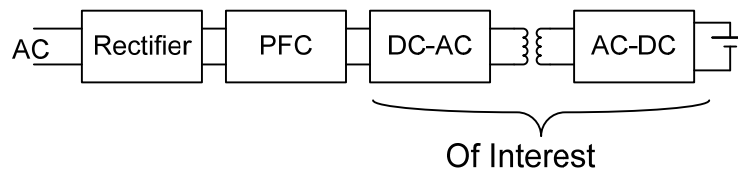
Chargers based on half-bridge and full-bridge unidirectional DC/DC converters are favourable alternatives to chargers based on flyback and forward converter (Zhang and Xu, 2007; Su and Tang, 2008). The magnetisation of the isolation transformer in a half-bridge converter is bidirectional therefore the demagnetising circuit is eliminated. The leakage inductance of the transformer is a key parameter for energy transfer. The operation of a full-bridge DC-DC converter is similar to a half-bridge converter (Wu et al., 2008; Zhang et al., 2006; Wu et al., 2007). The electrical stress of semiconductors in a half-bridge/full-bridge converter is significantly reduced. Soft-switching is easy to implement in half-bridge/full-bridge converters. The disadvantages of half-bridge/full-bridge converters are the increased number of semiconductor switches.

This paper will compare the operation, advantages/disadvantages in terms of electrical stress, cost, and power capability for the four potential charger topologies.

2 Operation of different charger topologies

Figure 1 shows the one feasible architecture of a PHEV charger. It consists of a front-end rectifier, a power factor correction (PFC) stage, and an isolated DC-DC stage. The grid electricity is converted to DC by a rectifier and a PFC. In this paper, we assume that the rectifier and PFC stage are common to all charger topologies involved. Therefore, the focus is on the isolated DC-DC stage. For this DC-DC stage, one of the typical examples is a buck or boost converter (if isolated, it will be a forward and flyback converter). Another way to realise the DC/DC is DC/AC/AC/DC, e.g., the half bridge or full bridge converter. We further assume that the DC-DC stage will have the same DC input from the PFC stage, and the same output voltage and power rating. In addition, only unidirectional chargers are of interest in this paper.

Figure 1 Basic PHEV charger architecture



2.1 Forward/flyback converters

Figures 2 and 3 show the circuit and operation of a forward and a flyback converter respectively, where R is the battery internal resistance; E is the battery internal voltage; and V_o is the output voltage across the battery (including battery internal voltage and voltage drop across the internal resistance). The operation of a forward converter is similar to that of a buck converter, as shown in Figure 2(b).

In the flyback converter shown in Figure 3(a), when D_1 conducts, the load voltage will be induced to the primary side. Therefore, in the off-state of S_1 , the voltage across S_1 is $V_{in} + V_o/n$, where n is the turns-ratio of the isolation transformer. It indicates that although there may not be necessary to have a filtering inductor in the flyback converter, the semiconductor switch will in fact undertake a higher voltage stress.

Figure 2 Forward converter (a) circuit topology (b) operation of a forward converter

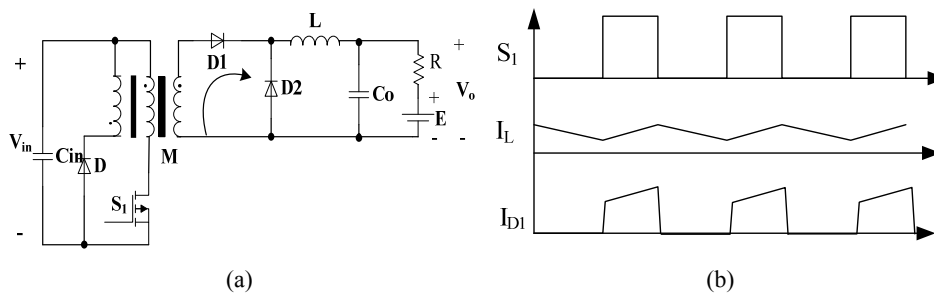
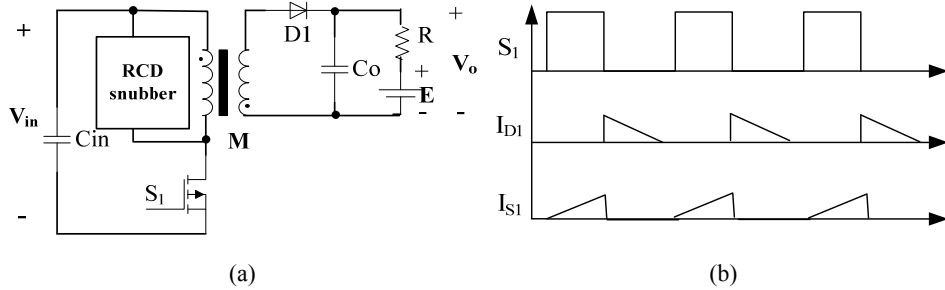


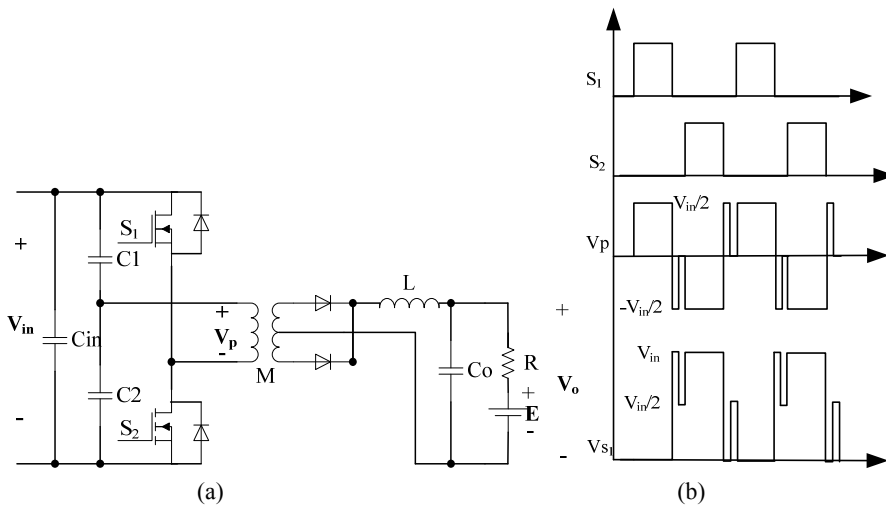
Figure 3 Flyback converters (a) circuit topology (b) operation of a flyback converter



2.2 Half-bridge DC-DC converter

Figure 4 shows a half-bridge DC-DC converter. Switches S_1 and S_2 are switched with their phase shifted by 180° . The leakage inductance of the transformer serves as the component for energy transfer. If the parasitic inductance of the commutating loop is negligible, the voltage spike across the semiconductors will not be of concern.

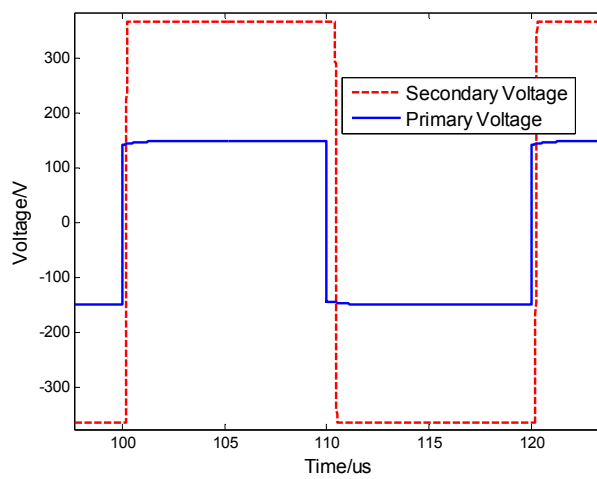
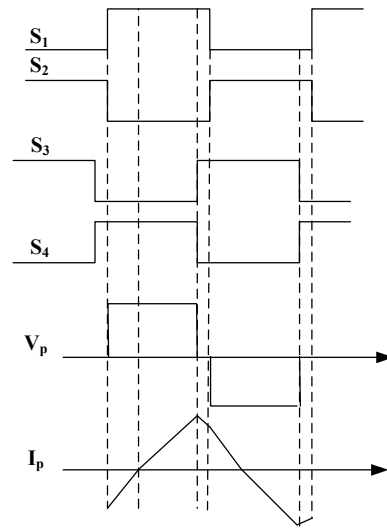
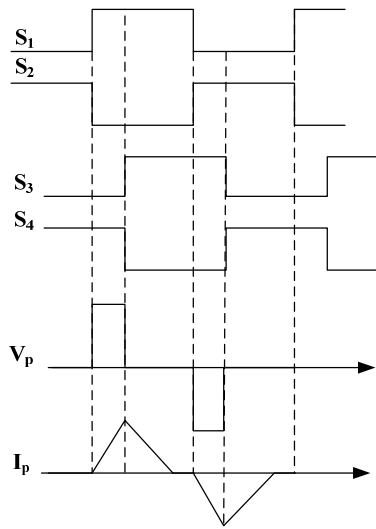
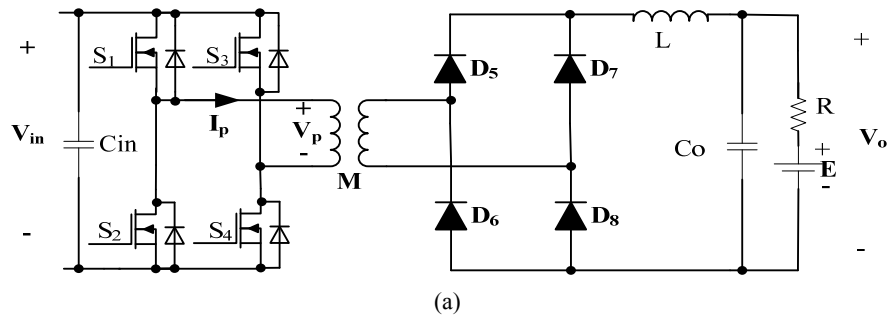
Figure 4 Half-bridge converter (a) circuit topology (b) operational modes



2.3 Full-bridge DC-DC converter

Figure 5 shows the circuit topology and operation of a full-bridge DC-DC converter. Compared to the half-bridge converter where only half of the DC voltage is imposed on the primary-side of the transformer in every switching cycle, the full-bridge converter utilises the whole DC-link voltage. Similar to a half-bridge converter, the leakage inductance of the transformer in a full-bridge converter does not contribute to any voltage spike across the switches. This leakage inductance should be designed appropriately for best performance (Bai et al., 2009).

Figure 5 Full-bridge converter (a) circuit topology (b) discontinuous mode operation (c) continuous mode operation (d) Primary and secondary voltage of the transformer (see online version for colours)



(d)

3 Comparison of different charging topologies

The comparisons studied in this paper are based on the same input and output parameters. The DC input to the isolated DC-DC stage is 400 V, and the battery nominal voltage is 365 V. The charger will have a maximum charging rate of 5 kW. The ripple of battery current is less than 2%. The passive components (inductor and capacitor) for each circuit topology are designed based on its circuit requirement. Simulation is performed to compare the stresses of devices used in the different topologies.

3.1 Voltage stress

Simulation shows that, without a snubber circuit, the voltage spike in forward and flyback circuits is excessive even though the leakage inductance of the transformer has been reduced to 2 μH . The voltage spike is mainly induced by the leakage inductance of the transformer windings instead of the excitation inductance. Therefore even though the auxiliary winding of the transformer is assembled, the snubber circuit is still indispensable. Such voltage-spike phenomenon will not occur in half-bridge and full-bridge systems. If a DC bus is laid out properly, the stray inductance of the commutating loop can be minimised to nH level, which leads to negligible voltage spikes across the semiconductors in half and full-bridge converters. Therefore, the semiconductors in half-bridge/full-bridge based PHEV chargers will have less voltage stress than those in forward and flyback converters.

3.2 Current stress

For chargers based on forward topology, the current peak in the primary side of the isolation transformer is directly determined by the filtering inductor L shown in Figure 2(a). For chargers based on flyback topologies, the magnetising inductance of the transformer helps smooth the current ripple. For the forward and flyback converters, the current flowing through the switches is nI_o plus ripple. If the inductance is sufficiently large, the current ripple can be neglected.

For half-bridge and full-bridge converters, the current through the switch is complicated. It is not only determined by the power and voltage output, but also the turns-ratio and leakage inductance of the isolation transformer (Bai et al., 2009). The optimised equivalent inductance of the optimised transformer is 30 μH .

Theoretically, since the primary voltage of the transformer of the half-bridge converter is only one half of the DC input (one half less than that of the forward/flyback or full-bridge converters), the switch current of half-bridge based charger is the largest in the four available topologies with the same input voltage and output power.

One advantage of the full-bridge based charger is the need of a much smaller filtering inductance, which can be in the μH level or could even be eliminated. In the simulation, without any output filtering inductor the peak current of the full-bridge converter is 60 A and that of a half-bridge charger is 100 A. Both are larger than that of the forward converter. When a 50 μH filtering inductor is added, the primary current is lowered to 40 A for full-bridge charger and the 90 A for the half-bridge charger.

In this simulation, the filtering inductance of the forward converter must be at the mH level otherwise a smooth constant charging current will not be possible. For the half-bridge and full-bridge chargers, this filtering inductance can be small but still

indispensable. The switch current will also increase when there is no filtering inductor, which indicates that the output capability will decrease without the output filtering inductor. When the inductance increases to 50 μH for the full-bridge converter, the primary current of the transformer will be significantly reduced and is competitive with the forward converter. The functionality of this filtering inductor will be addressed again in a later section.

3.3 Switching loss

Switching loss is another concern in determining which topology is the best choice for the application. For forward and flyback converters, all the semiconductors are hard-switched. The half and full-bridge converters are, however, naturally soft switched. Without additional soft-switching control, the efficiencies of the four topologies are compared for a 5 kW charger not including the rectifier and PFC circuit. The efficiencies are 71%, 76%, 83%, and 93% for the forward, flyback, half bridge, and full bridge converters, respectively. Although there is only one active switch in a forward or flyback converter, their efficiency is the lowest.

In order to decrease the voltage stress in forward and flyback converters, a snubber circuit is needed, which will bring extra loss to the system. For example, when the snubber circuit has a capacitance of 0.1 μF , at $V_{\text{in}} = 400 \text{ V}$, and switching frequency $f_s = 50 \text{ kHz}$, we can approximately calculate the extra power loss due to the snubber circuit is $CV_{\text{in}}^2f_s/2 = 200 \text{ W}$. The high loss is attributed to the high DC voltage and high switching frequency. When the switching frequency decreases to 5 kHz, the power loss caused by the snubber circuit will be reduced to 20 W. At this low frequency, however, the size of the transformer and other magnetic components will increase significantly. Therefore, from the switching loss point of view, the half-bridge and full-bridge converters, which do not need snubber circuits, are more suitable for the fast chargers in PHEVs. The efficiency of the half-bridge converter is lower than that of the full-bridge converter because the half-bridge converter experiences a higher current stress.

Zero voltage switching (ZVS) and zero current switching (ZCS) can be implemented to mitigate switching loss. However another auxiliary semiconductor will be needed to implement soft switching in forward and flyback converters (Wang, 2008), which will increase the system cost. For half-bridge and full-bridge converters, soft-switching control is easy to implement. The parasitic capacitance of semiconductor switches and leakage inductance of the transformer can construct a resonant circuit to realise ZVS and ZCS (Wu et al., 2008). Improvements on control algorithms can decrease switching loss which can be realised through complicated control software but will not bring additional cost in the hardware.

3.4 Cost

Compared to forward/flyback converters, full-bridge converters have the least electrical stress under the same input/output. It has the highest DC-voltage utilisation therefore smaller current stress than the half-bridge converter. In addition, it can easily realise soft switching and its efficiency is the highest among all four topologies. However this topology has the largest number of semiconductor switches. Therefore a cost comparison

needs to be addressed. Table 1 lists the main components needed by different charger topologies in the DC-DC stage.

For the active switches in the forward and flyback converters, they can be chosen as unidirectional one, i.e., no parallel diode existing inside the chip. For half-bridge/full-bridge converter, the parasitic diode is required to freewheel.

Table 1 Main components and price needed by different charger topologies in the DC-DC stage

	<i>Forward (unidirectional)</i>	<i>Flyback (unidirectional)</i>	<i>Half-bridge (unidirectional)</i>	<i>Full-bridge (unidirectional)</i>	<i>Full-bridge (bidirectional)</i>
*Active devices (560 V/52 A CoolMOS)	1 (\$5.9)	1 (\$5.9)	4 (\$5.9 * 8 = 47.2)	4 (\$5.9 * 4 = 23.6)	8 (\$5.9 * 4 + 5.9 * 4 * 2 = \$94.8)
Diodes (600 V/20 A)	2 (\$2.39*2)	1 (\$2.39)	2 (\$2.39 * 2)	4 (\$2.39 * 4)	--
Isolation transformer	*1 (\$100)	1 (\$100)	1 (\$100)	1 (\$100)	1 (\$100)
Filtering inductor	1 (\$50)	Dispensable	Dispensable	Dispensable	Dispensable
****Capacitor	2 (\$26.7 * 2 = \$53.4)	2 (\$26.7 * 2 = \$53.4)	4 (\$26.7 * 4 = \$106.8)	2 (\$26.7 * 2 = \$53.4)	2 (\$26.7 * 2 = \$53.4)
Snubber	1 set (\$10.3)	1 set (\$10.3)	0	0	0
Total price (\$)	(\$224.7)	(\$172.3)	(\$258.8)	(\$186.6)	(\$212.4)

Notes: *All the switches are 560 V/52 A CoolMOS. If other switches are selected, the cost will change. The diode is 600 V/20 A (average current) fast reverse recovery diode. All the prices are based on the quote for 5,000 pieces.

**The transformer price was not investigated. We assume all transformers have the similar price.

***For the forward-converter transformer, it needs another extra demagnetising winding therefore the price should be higher.

****500 V/100 μ F film capacitors are used for long life time and high temperature.

The prices of major components are obtained through a major electronic retailer, www.digikey.com for comparison purpose. The prices are quoted in US dollars. For example, the price of a 500 V/52 A MOSFET is \$5.9, and the fast reverse recovery diode is \$2.39. A full bridge will need four active switches while the forward/flyback topologies only need one active switch. Since the current is doubled in a half bridge converter, therefore, it will also need four MOSFETs (with two MOSFET in parallel for each switch) which will bring the cost of active switches the same as a full bridge converter. Therefore, compared to the half/full-bridge converter, the flyback converter can save cost on the switches. However, a forward or flyback converter needs another set of RCD snubber, whose capacitor and resistor need to be inductance-free and the diode needs to have fast recovery. A 500 V/0.1 μ F ceramic capacitor is \$1.66, a 5 Ω /50 W non-inductive resistor costs \$6.2, and a fast recovery diode costs \$2.39. Therefore, the additional snubber circuit reduces the savings of a flyback converter compared to the full-bridge converter. Meanwhile the filtering inductor at mH level for the forward

converter is also costly. Furthermore, a set of demagnetising circuit is required for the transformer in the flyback/forward converter. Therefore, the cost advantage of the flyback/forward converter is no longer attractive given the lower efficiencies and other disadvantages of the system, as shown in Table 1.

4 Power capability

4.1 Comparison of the power capability

Power capability is a key factor to determine the right topology for the application. For consistency, the following comparison is based on the same input and output voltage.

For the forward converter, the output voltage is clamped to the battery voltage. After each switching period, the inductor and transformer current should reset to the original value, otherwise the magnetic components will fall into saturation. If the battery is regarded as the ideal voltage source, for a forward converter the critical duty ratio of the switch is

$$D = \frac{V_2}{nV_1} \quad (1)$$

where V_2 is the battery voltage and L_1 is the smoothing inductance. A duty ratio larger than this value will induce a significantly large switch current until the system reaches a new electrical balance. For example, assume the voltage of a battery pack is 330 V, internal impedance is 0.5 Ω , $n = 1.5$ and the input voltage is 400 V. According to (1), the critical duty ratio is 0.55. If $D = 0.7$, the battery voltage is 420 V. Therefore, the voltage drop across the battery internal resistance is 90 V, which represents 180 A charging current and the switch current is $180 * 1.5 = 270$ A. If the current peak is 1.1 times of the average current, the MOSFET current is close to 300 A, which is far beyond the current capability of the MOSFET.

Ideally the maximum output power is

$$P = \frac{V_2^2 (nV_1 - V_2)}{2nV_1 f_s L_1} \quad (2)$$

For the flyback converter, that critical duty ratio of the switch is

$$D = \frac{V_2}{nV_1 + V_2} \quad (3)$$

and the maximum power is

$$P = \frac{(nV_1)^2}{2f_s L_1} \left(\frac{V_2}{nV_1 + V_2} \right)^2 \quad (4)$$

where L_1 is the excitation inductance of the transformer. The common aspect of forward and flyback converters are that in the charging process, the inductor current is always discontinuous. Any duty ratio larger than (1) or (3) will disturb the system balance and saturate the magnetic components.

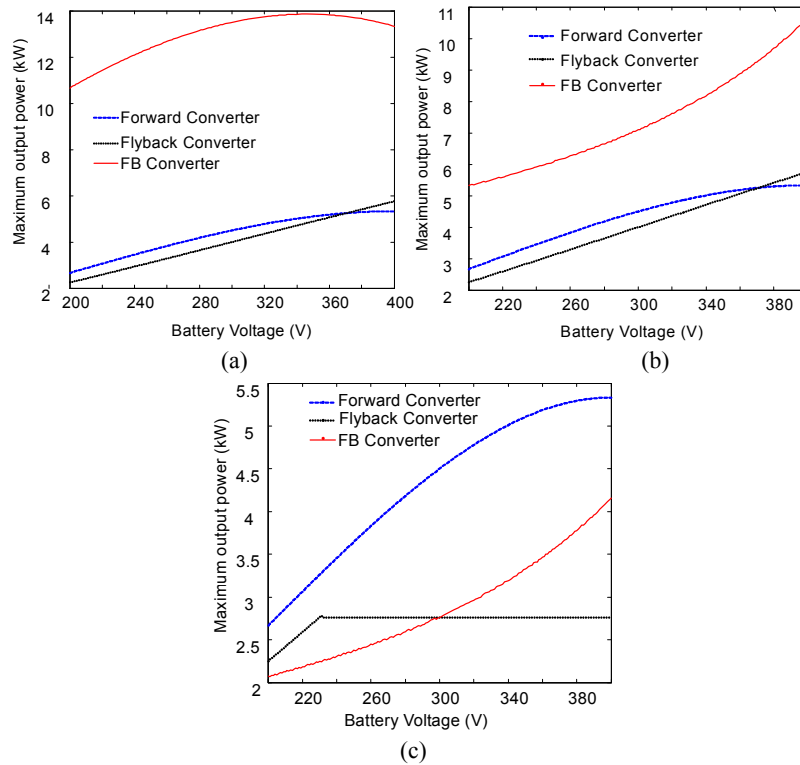
For the full-bridge converter, the operation mode is different, as shown in Figure 5. Due to the bidirectional magnetisation of the transformer, the duty ratio of the gate signals can reach 1. Therefore its maximum power is

$$P = \frac{(nV_1 - V_2)(nV_1 + V_2)}{8f_s L_s} \frac{V_2}{nV_1} \quad (5)$$

where L_s is the equivalent leakage inductance of the transformer. The operation of a half-bridge converter is the same as a full-bridge as long as the current limit of the switches is not concerned.

It can be seen that the maximum power output is related to the switching frequency, input/output voltage, and transformer turns-ratio. For a given transformer, the output of a full-bridge converter is the largest. As an example, when $V_1 = 400$ V, $n = 1.5$, $f_s = 50$ kHz, $L = 100$ μ H, $L_s = 25$ μ H, the maximum power of the different converters is shown in Figure 6(a). However, if the device rating is taken into account, then the output capability will also be limited by the switch ratings. The results are shown in Figure 6(b)–(c). Using switches with high current capability will enhance the advantage of a full-bridge converter. When lower-current-rating switches are chosen, the forward converter has the highest power capability.

Figure 6 Comparison of output capability (a) without the device current limit (b) device current limit = 80 A (c) device current limit = 30 A (see online version for colours)



For the forward/flyback converter, the snubber circuit is indispensable. The loss by this snubber is also considerable, as shown in the previous section. At the same output capability, the input power of a flyback converter is higher than that of a full-bridge converter.

4.2 Functionality of the smoothing inductor

The previous analysis is based on the assumption without the output filtering inductance. In the switching process, the primary and secondary voltage sources are connected through the leakage inductance of the transformer. In order to output sufficient power and maintain high efficiency, the leakage inductance of the transformer need to be designed appropriately (Bai et al., 2009).

For the power rating compared in this paper, the inductance value is in the mH level, which brings huge current peak as shown in Figure 7(a). Adding a filtering inductance between the output capacitance and rectifier will not only smooth the charging current but also help decrease the current ripple into the battery and further increase the maximum charging current, as shown in Figure 7(b). Compared to Figure 7(a), the switch current is decreased to one half with the same output power (5 kW). In Figure 7(c), the solid line shows the maximum charging current without filtering inductor, and the dashed line shows maximum charging current with 100 μ H inductance. The repetitive turn-off current of the switch is set to 70 A. A summary comparison of different PHEV charger topologies is listed as Table 2.

Figure 7 Maximum charging current at different battery voltage (a) charging current is 30 A, no filtering inductor (b) charging current is 30 A, $L = 100 \mu\text{H}$ (c) comparison of charging with and without filtering inductance (see online version for colours)

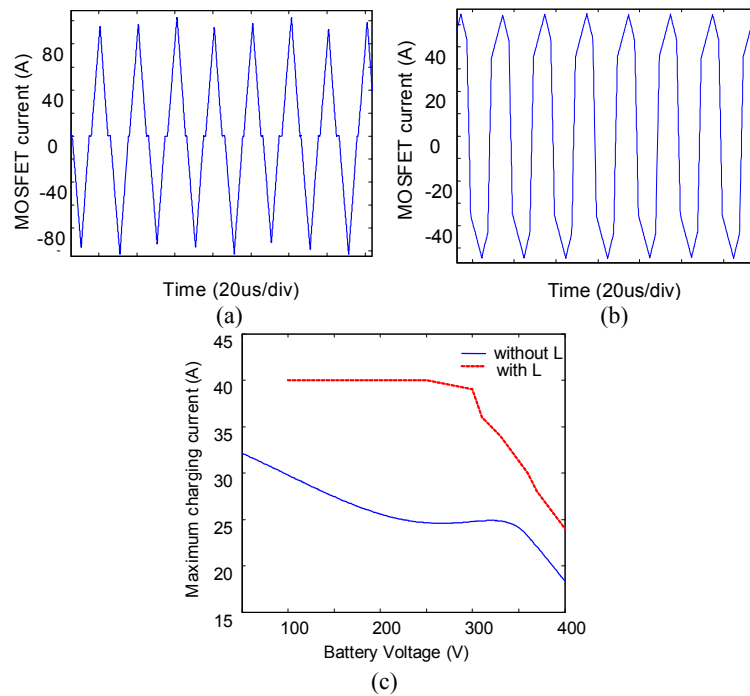


Table 2 Summary comparison of different PHEV charger topologies

	<i>Forward</i>	<i>Flyback</i>	<i>Half-bridge</i>	<i>Full-bridge</i>
Switch amount	Smallest	Smallest	Middle	Largest
Maximum current	Average	Average	Depend on f_s and	Depend on f_s and
Inductor	Largest	Dispensable	Dispensable	Dispensable
Voltage spikes	Higher	Highest	Small	Small
Biased magnetic	Frequently	Frequently	Somewhat	Seldom
Soft switching control	Hard	Hard	Easy	Easy
Requirement for snubber	High	High	Dispensable	Dispensable
Hard-switched loss	High	High	Lower	Lowest
Application	Low	Low power	High power	High power

Table 3 Efficiency comparison

	<i>Forward</i>	<i>Flyback</i>	<i>Full-bridge experimental</i>	<i>*Full-bridge simulated</i>
High voltage high current (hard switched)	-	-	90% $V_{in} = 150$ V, $P = 2.5$ kW	87% $V_{in} = 150$ V, $P = 2.5$ kW
Low voltage high current (hard switched)	~80% (Ye et al., 2007) $V_{in} = 12$ V, $I_o = 30$ A	~80% $V_{in} = 12$ V, $I_o = 30$ A	> 84% $V_{in} = 12$ V, $I_o = 30$ A	86% $V_{in} = 12$ V, $I = 30$ A
Low voltage high current (soft switched)	~90% (Lee et al., 2007) $V_o = 5$ V, $I_o = 20$ A	~90% (Zhang et al., 1998; Zhang and Yan, 2009) $V_o = 12.4$ V, $I_o = 20$ A	> 95% (Wu et al., 2006) $V_o = 50$ V, $I_o = 24$ A	93% $V_o = 50$ V, $I_o = 24$ A

Note: *Here the half-bridge converter is omitted since we believe its efficiency could be as high as the full-bridge converter.

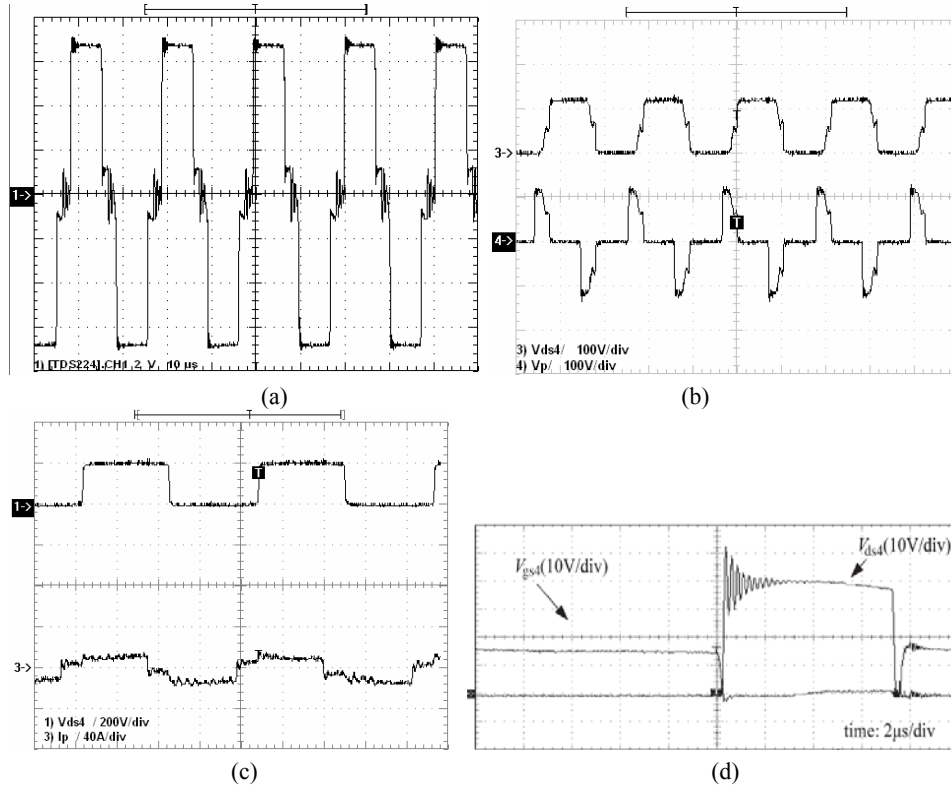
5 Experimental validation

In order to validate the conclusions, a full-bridge charger was developed. The charger has an input voltage of 110 VAC, DC bus voltage of 150 VDC, output voltage in the range of 250 V to 400 VDC, and maximum power of 5 kW. The charger uses MOSFETs rated at 500 V/52 A ($T_{on} = 27$ ns, $T_{off} = 18$ ns, $R_{internal} = 0.016$ Ω) with switching frequency of 50 kHz. The turn ratio of the transformer is $n = 3$, with equivalent leakage inductance of the secondary side of 30 μ H, primary resistance of 0.02 Ω , and secondary resistance of 0.13 Ω .

The test data, along with some other experimental data collected from literature are compared with simulation data in Table 3. The experimental results are consistent with the simulation results. In the low voltage and high current applications, the efficiency of a full-bridge converter is higher than a forward or flyback converter. In the high power and high voltage cases, a half-bridge and full-bridge converter are dominant. Up to now we still lack the detailed efficiency data of high-voltage forward and flyback converters. Most of the relevant applications are at several tens of volts and several hundred watts.

Figure 8(a) shows the hard-switched operation of the full-bridge converter at the rated voltage when phase shift is 75% and the battery voltage is 337 V. The input power is 2.1 kW and the output power is 1.9 kW. Therefore the efficiency is 90.5%, which is close to the above simulation and the data shown in the previous literatures.

Figure 8 Voltage and current stress (a) primary voltage when $P_o = 1.8$ kW (50 V/div, 10 us/div) (b) V_{ds} and V_p when $P_o = 1$ kW (c) V_{ds} and I_p when $P_{out} = 2$ kW (d) voltage spike with the forward-flyback topology (e) the prototype full-bridge DC/DC converter (see online version for colours)



(e)

In Figure 8(b)–(c), voltage and current waveforms are displayed. V_{ds} is the voltage drop across the single MOSFET, V_p is the primary voltage of the transformer, and I_p is the primary current. When the $V_{in} = 150$ VDC, the voltage spike on the single MOSFET is negligible as shown in Figure 8(b). The small voltage spike across the MOSFETs attributes to the compact DC-bus lay out in the prototype, where the multi-layer structured DC bus is adopted. The leakage inductance of the transformer does not induce any voltage peak. It is worthwhile to point out that the voltage distortion in Figure 8(b) is caused by the dead-band effect where the primary current of the MOSFETs is neutralised.

When the DC bus voltage is increased to 200 V and the output power is 2 kW, the primary current flowing through the MOSFET is less than 20 A, shown in Figure 8(c). Compared to the experimental waveforms of the voltage spike provided by Zhang et al. (1998) shown in Figure 8(d), all the electrical stress especially the voltage spike of the MOSFETs are negligible, which validates the above analysis in this paper.

6 Conclusions

In this paper, four different PHEV battery charger topologies, i.e., forward converter, flyback converter, half-bridge converter, and full-bridge converter, are compared and evaluated in terms of their operation, electric stress, power capability, cost and feasibility. With the same output and input, the full-bridge converter has the smallest current stress, the least voltage stress, and the highest efficiency. The full-bridge converter also has the highest output capability with the same switch ratings and the same input/output voltages. Soft switching is easy to implement in a full-bridge converter. Compared to the forward and flyback converter based chargers, the full-bridge based charger is the most favourable choice for high voltage applications. Experiments at $V_{in} = 150$ V, $V_o = 200$ V to 400 V, $P = 2.5$ kW shows the full bridge converter could reach 90% efficiency. Due to the lack of data for forward and flyback converters in the high voltage and high power application, simulation is pursued and showed that the efficiency at the same ratings is at least 10% lower than that of the full bridge converter.

In the design process, the PFC and a μ H-level smoothing inductor are the two key components to help decrease the current stress of MOSFETs. Simulation shows adding those two components can also help enhance the charging capability with the same device ratings.

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