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OVERVIEW OF BATTERY CHARGER TOPOLOGIES IN PLUG-IN ELECTRIC AND HYBRID ELECTRIC VEHICLES

Omer Turksoy[1,*], Unal Yilmaz[2], Ahmet Teke[3]
[1]Department of Electrical and Electronics Engineering, Iskenderun Technical University, 31200 İskenderun/Hatay
[2]Department of Electrical and Electronics Engineering, Harran University, 63000 Şanlıurfa, Turkey
[3]Department of Electrical and Electronics Engineering, Cukurova University, 01330 Sarıçam/Adana, Turkey
Corresponding author: Omer Turksoy, e-mail: omer.turksoy@iste.edu.tr

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ABSTRACT

In this study, an overview of battery charger topologies are presented for plug-in electric and hybrid electric vehicles. Battery chargers are designed in two forms, on-board and off-board, with unidirectional and bidirectional power flow options. Unidirectional and bidirectional options are determined according to the place of use. Circuit structure and control of the unidirectional charger is easier than bidirectional. Bidirectional chargers have a structure that allows the power in the battery to be transferred to the network when the vehicle is not in use and the network needs it. Bidirectional chargers will become a big part of the smart grid, which is often not so common today but will become inevitable in the future. This paper aims to determine the most suitable battery charger topology for energy saving by comparing the efficiency, cost and other aspects of charger topologies developed for plug-in electric and hybrid electric vehicles.

1. INTRODUCTION

Rapid depletion of fossil fuels and increased CO_2 emissions drive the people to more efficient and more environmentally friendly plug-in electric (PEVs) and hybrid electric vehicles (PHEVs) technologies [1-4]. PHEVs are improved version of the existing conventional hybrid electric vehicle including the battery can be connected to the network which are to be charged. PEVs have not yet become widespread due charging stations are not everywhere yet. Once PEVs technology becomes widespread, the use of PHEVs will decrease [5].

One of the most important issues affecting the development and spread of electric vehicles (EVs) are battery chargers. Battery chargers are a kind of power converter that supplies power from the network to the battery pack. The charger usually creates a non-linear load in the power system. This causes problems such as weak power factor and excessive total harmonic distortion in the network. A well-designed battery charger aims not only to charge the battery pack with high efficiency but also to meet the international standards such as IEEE 1547 [6].

Battery chargers are designed in two forms such as off-board and on-board, with unidirectional and bidirectional power flow types. The comparisons of on-board vs. off-board battery charger features are given in Table 1.

Table 1. The comparison of on-board vs. off-board battery chargers [7]

On Board Battery Charger	Off-Board Battery Charger
Generally lower KW charging	Generally higher KW charging
Battery management system is managed by on-board rectifier	Battery management system is more complicate
Less concern about battery heating	Battery heat must be controlled
Add weights to vehicle	Removes weight from vehicle
Level 1 and Level 2 charger	Level 3 charger
Slow and semi-fast charging	Fast charging

Table 2. Power Levels of EV Battery charger [8,14]

Power level types	**Level 1**	**Level 2**	**Level 3**
Grid Voltage	120 V_{AC} (US) 230 V_{AC} (EU)	240 V_{AC} (US) 400 V_{AC} (EU)	208-600 V_{AC} or V_{DC}
Power range	≤3.7kW	3.7-22kW	>50kW
Approximately charging time	11-36 hours	1-6 hours	0.2-1 hours
Charger topology	On-board	On-board	Off-board
Grid supply type	1-phase	1-phase or 3-phase	3-phase
Charging type	Slow charge	Semi-fast charge	Fast charge
Battery capacity	15-50kW	15-50kW	15-50kW

Unidirectional charger is a power converter with simple control structure that supplies power from the network to the battery pack in one direction. A unidirectional charger is a good choice because it reduces equipment, simplifies interconnection problems, and allows the battery to last longer [8-10]. Bidirectional battery chargers are power converters that charge the battery pack from the network and transmit this power to the grid when the network needs it [11]. The bidirectional battery charger assures higher flexibility for the grid due to control the EVs battery pack energy to increase the sustainability and reliability of the grid [12-13].

Battery chargers are available in three different power levels according to their power intervals and according to charging times and usage areas as given in Table 2 [8, 14]. Level 1 and Level 2 battery chargers are designed as on-board. Level 1 EV chargers offer slow charging and in this charger topology, EVs are connected to the grid via household outlets installed in home. Level 2 is a power level used both in private and public areas. It is known as semi-fast charging. Today, many researchers are concentrating on Level 2 chargers. Level 3 is usually the power level offered at charging stations for commercial purposes. It is also known as fast charging [8]. This paper organized as follows: In section 2, on-board and off-board battery charger topologies will be given in specific way.

2. BATTERY CHARGERS TOPOLOGIES

Battery chargers are one of the most important obstacles to the widespread deployment of EVs. The characteristic of the battery charger affects the battery life and charge time. The designed battery charger should be of high efficiency, low cost and minimal pressure on the network [8]. High power factor correction is required and the power dissipated in the switching elements must be minimized.

A general structure of the on-board and off-board battery charger configuration is given in Fig. 1. Off-board and on-board battery chargers can be designed as single-stage and two-stage. Some researcher has focused on single stage battery charger [15-16]. However, as the power level increases, the number of component used in the single stage charger is insufficient. This is why two-stage chargers are more suitable for high powers [17].

A general two-stage EV battery charger has two main stages. The first stage carries out the AC DC conversion with power factor correction (PFC). The second stage is DC-DC converter which is convert the output DC voltage level of AC-DC PFC converter to the battery DC voltage level. [16-17].

Main parts of EV charger; AC-DC PFC converter and DC-DC converter will be given in subsections.

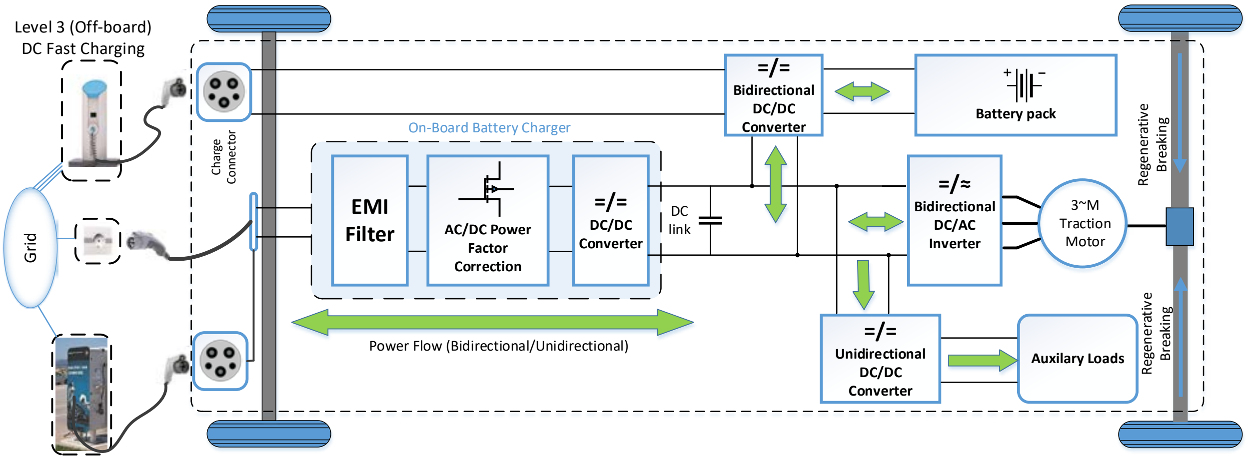

Fig 2. General structure of battery charger topology in EVs [7]

2.1. AC/DC Power Factor Correction

The choice of the most suitable AC/DC PFC topology is important to correspond the requirements of implementation of current harmonics injections, regulation of output voltage and unity power factor. Along with proper PFC topology, power losses are also reduced [18].

A variety of AC/DC PFC circuit has been evolved for implementation of PFC. The conventional PFC topology is boost PFC [19]. This topology includes a diode bridge that rectify the ac input voltage to DC. There is a boost PFC circuit after this circuit. The circuit diagram of this topology is given in Fig. 2. In this topology, very high ripple occurs at the output capacitor current, there is a difference between dc output current and the diode current. At the high power levels, the diode bridge heats up and power losses increase, and the efficiency drops greatly. Therefore, this converter is suitable for powers below 1 kW.

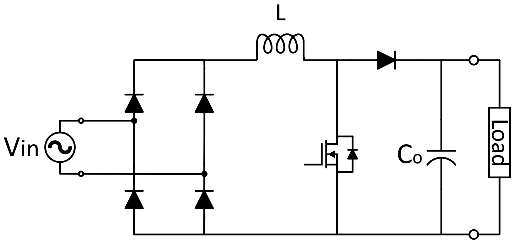

Fig 2. Circuit topology of conventional boost PFC

The second topology is bridgeless boost PFC topology which is avoids the use of the rectifier input bridge, however maintains the classical boost PFC topology, is illustrated in Fig. 3.

This topology solves the problem of efficiency drop due to heat losses but increases EMI due to the ınductor used at the inlet [19-20].

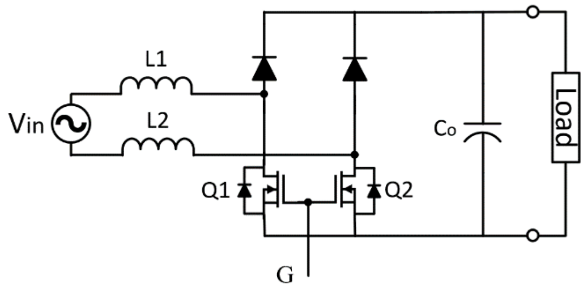

Fig. 3. Circuit topology of bridgeless boost PFC

The third topology is interleaved boost PFC topology which is consists of two boost PFC in parallel, is illustrated in Fig. 4. This topology decreases the EMI but heat management problem is still remaining [19,21].

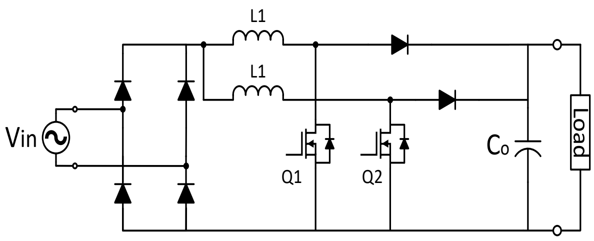

Fig. 4. Circuit topology of interleaved boost PFC

The other topology is bridgeless interleaved boost PFC topology, which is solve the heat management problem and EMI problem, is illustrated in Fig. 5. It is an attractive solution for power levels above 3.5kW [19,22].

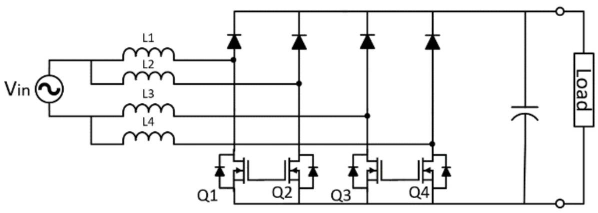

Fig. 5. Circuit topology of bridgeless interleaved boost PFC

2.2. DC/DC Converters

DC-DC converters designed for charger of EVs are divided into two groups, which are isolated and Non-isolated; the subgroups divide into two groups, which are unidirectional and bi-directional DC-DC converter.

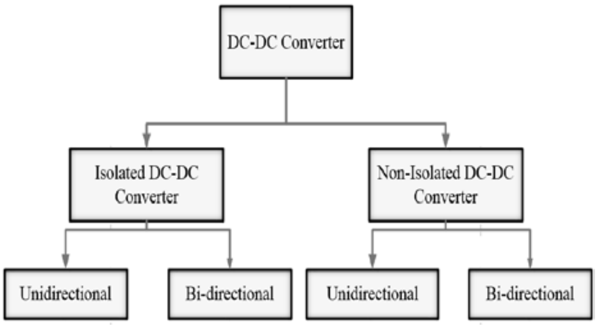

Fig. 5. DC-DC Converter Topologies

2.2.1. Non-isolated DC-DC Converter

The main advantages of non-isolated converters are that they have low cost, low active component number, high efficiency. But they are used for low power desired system and the big disadvantage is that in the electrical connection between source and load no protection for any high electrical voltage current and etc. occurs on the input side [23-24].

a. Unidirectional DC-DC Converter

The voltage of many batteries for EVs ranges from 100-400 V, so the most popular dc-dc topology is unidirectional buck converter in order to reduce the voltage from the DC-link to the voltage level of the battery. Unidirectional buck-boost converters are also used topology due to their capability to step-up and step-down the output voltage. In addition, interleaving technique can be applied on these topologies [24].

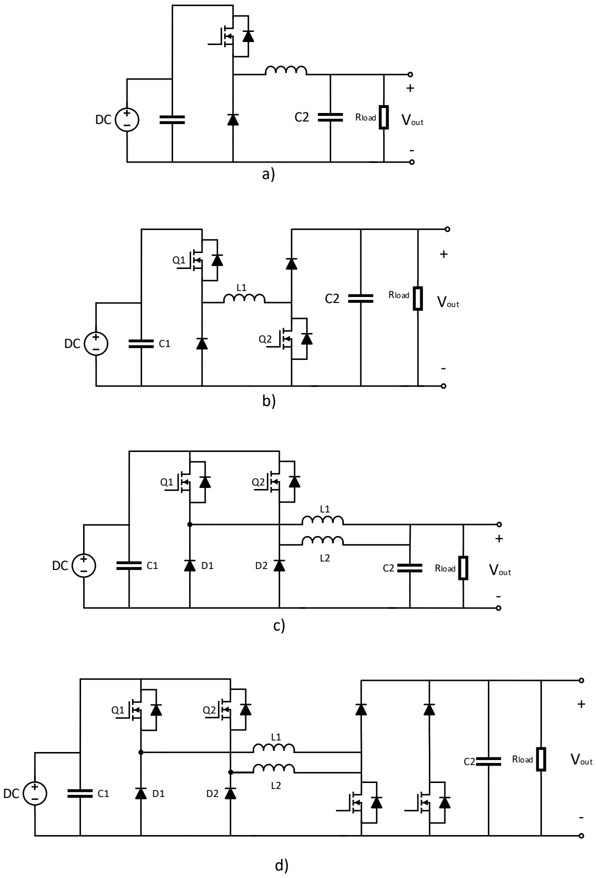

Fig. 6. Unidirectional DC-DC converters (a)Buck Converter, (b) Interleaved Buck Converter, (c) Buck-boost Converter (d) Interleaved Buck-boost converter

a. Bi-directional DC-DC Converters

In vehicle-to-grid (V2G) systems, electric vehicles energy storage systems are in interact with grid by providing a large number of potential benefits. In V2G systems, bidirectional converters play very important role. The features like being reliable, having efficiently conversion, cost effective, safety, having light weight, having small size, producing low harmonics are crucial for bi-directional dc-dc converters to achieve V2G. Bi-directional dc-dc converters in literature are summarized in Fig. 7 [8,25].

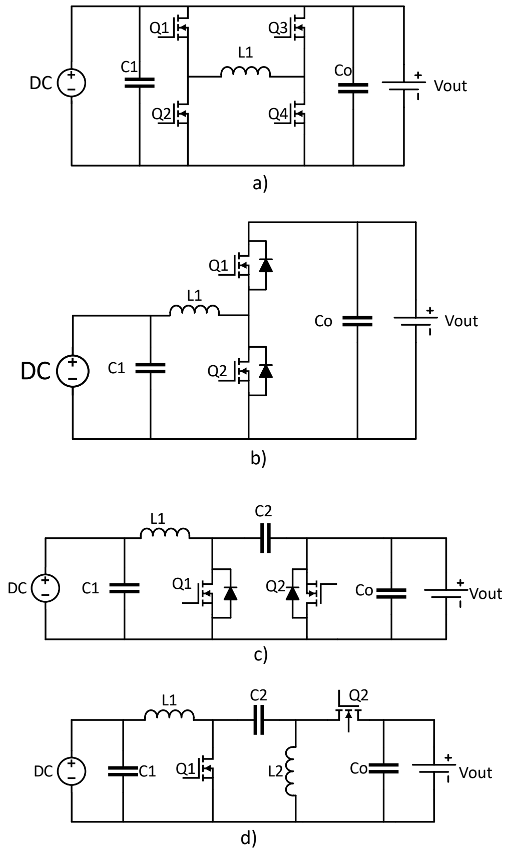

Fig. 7. Bi-directional dc-dc Converter topologies (a) buck-boost converter (b) half-bridge (c) Cuk Converter (d) Sepic Converter

2.2.2. Isolated DC-DC Converters

The isolated dc-dc converters have large size, there are more active components compared to non-isolated converters, switching losses is higher, they have less efficiency in low power applications. But isolated dc-dc converters have higher efficiency at high power applications, the transformer provide protection between load and source, and also the turn ratio of transformer facilities regulating load voltage [26].

a. Unidirectional

Unidirectional dc-dc converters are used electric vehicle charge system in grid to vehicle the most popular topologies are given in Fig. 8. Flyback topology has a simple structure. It can be performed with a single switch. Also, this topology does not require an output inductor in addition to the transformer. Due to these features, it is easy and low cost to implement

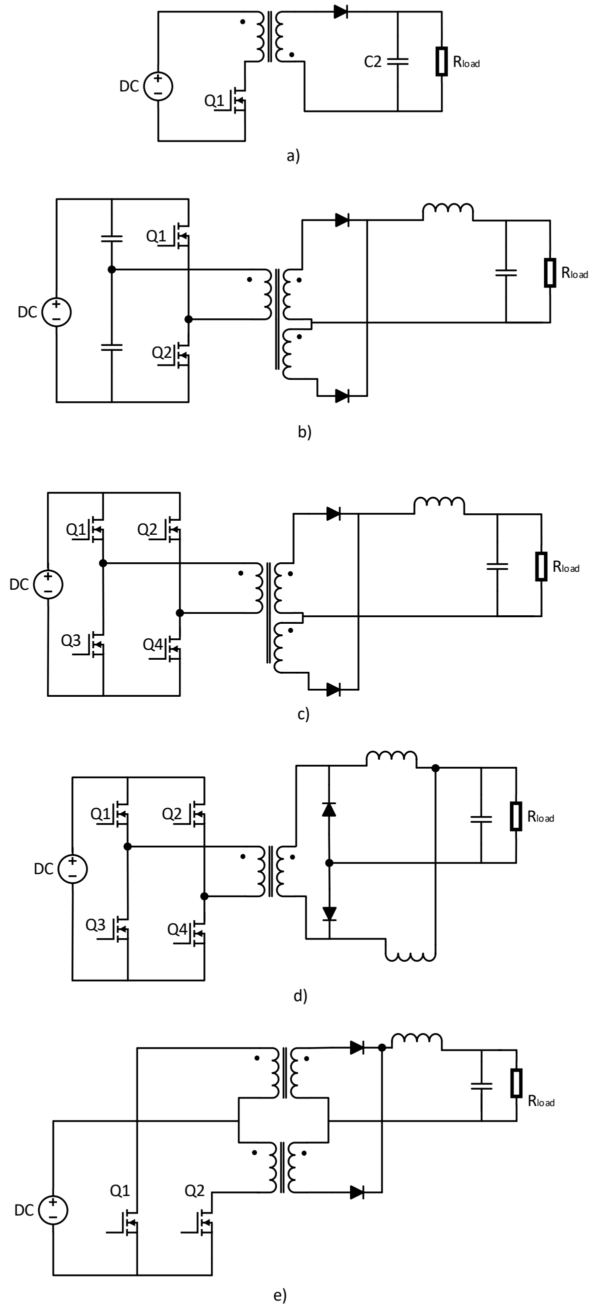

Fig. 8. Unidirectional dc-dc Converter topologies (a) Flyback Converter (b) half-bridge (c) Full bridge (d) Full-Bridge phase shift (e) push-pull Converter

this topology. The flyback topology has some drawbacks such as poor transformer utilization, and usage of extra capacitors, which are needed at both the input and the output side due to the high current ripples. Push-pull topology is an attractive solution for applications where high power density is desired because the transformer core is fully usable, however the peak voltage stress of primary switches is very high during the off state. The full-bridge topology used for higher power applications with higher Efficiency than half bridge converter. The disadvantage of the full-bridge topology is that the more primary switches cause to be more complex to control and also it is costly. Phase-shifted full-bridge, converters are useful for high input voltage and high power applications, the control methodology is different, zero voltage transition on primary switch, ZVT is beneficial at high input voltage applications. Disadvantage of this topology is higher conduction losses in the primary part during the freewheeling time [27].

b. Bidirectional

The bi-directional dc-dc converters were designed to provide voltage and frequency regulation of absorbed excess electricity from vehicle to the grid, during high demand periods. The bi-directional dc-dc converters allow two directional power flow, in charging mode grid to vehicle (G2V) and in discharging mode vehicle to grid (V2G). The most popular topology for bi directional isolated dc-dc converter in literature is shown in the Fig. 9 [28-29].

The comparison of all DC-DC converter topologies are given in below Table 3.

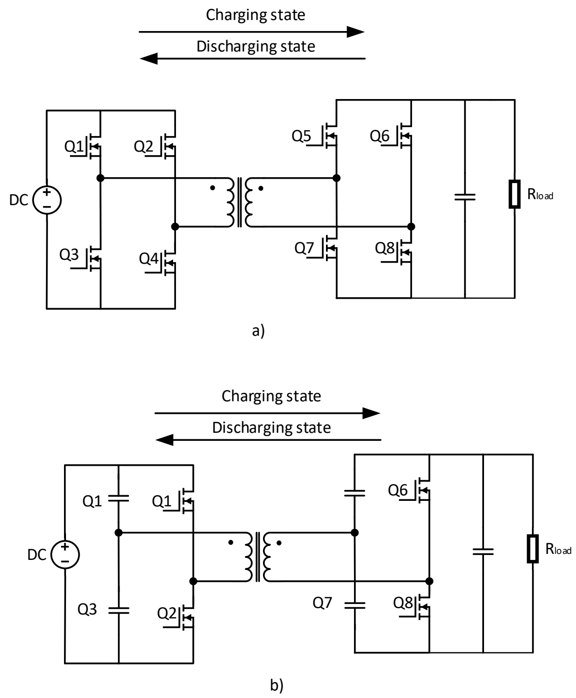

Fig. 9. Bidirectional Dc-Dc Converter Topologies (a) Bi-Directional Full-bridge Converter (b) Bi-Directional Half-bridge converter.

Table 2. The comparisons of DC DC converters

	Converter Types	Optimal Power demand	Efficiency	Number of component	Voltage stress	Cost
Unidirectional Non-Isolated DC DC Converters	Buck Converter	Low (<500 W)	medium	5	high	low
	Interleaved Buck	Low (<500 W)	high	8	low	medium
	Buck-Boost	Low (<1KW)	medium	7	medium	medium
	Interleaved Buck-boost	Low (<1KW)	high	12	low	high
Bi directional Non Isolated DC DC Converters	Buck-boost Converter	Low (<1KW)	medium	7	medium	medium
	Sepic converter	Low (<1KW)	medium	7	high	medium
	Cuk converter	Low (<1KW)	medium	6	high	medium
	Half bridge Converter	Low (<1KW)	high	5	medium	Low
Uni directional Isolated DC DC Converters	Flyback	Low (<500W)	high	4	high	low
	Half Bridge	Low (<1KW)	high	7	high	medium
	Full bridge	High (1KW<)	medium	9	medium	high
	Push pull	High (1KW<)	medium	8	high	high
	Full bridge phase shift	High (1KW<)	high	10	low	High
Bidirectional Isolated DC DC Converters	Half bridge	Low (<1KW)	medium	6	high	low
	Full bridge	High (1KW<)	medium	10	low	high

3. CONCLUSIONS

In this study, an overview of battery charger topologies has been presented for energy saving of plug-in electric and hybrid electric vehicles. EV battery chargers have been categorized as off-board and on-board. Besides, the battery chargers can be realized in two types as single stage and two stage. In this paper, two stage battery charger has given in specifically. All the topologies in the literature on AC/DC power factor correction and DC/DC converter, which are two main parts of battery chargers, are given in detail. As AC/DC PFC circuit, conventional boost PFC circuit works at small power but it is insufficient for big power. For large powers, bridgeless interleaved PFC circuitry is available, which solves the heat problem of the switches and greatly reduces the EMI problem. The topology suitable for small powers in DC / DC converter circuit topologies is the non-isolated sepic converter. The optimal topology for large powers is the full bridge phase shift cycle, which is fewer elements and more efficient than other circuits. The optimal topology for large powers is the full bridge phase shift topology, which is fewer elements and more efficient than other circuits.

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Nomenclature

EMI	Electromagnetic Interference
PFC	Power Factor Correction
EV	Electric Vehicle
PEV	Plug-in Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle

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