



# A Review of Three Phase AC-DC Power Factor Correction Converters for Electric Vehicle Fast Charging

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## Abstract

Electric vehicle charging station for fast DC charging performs AC-DC conversion at off-board. In recent years, three-phase AC-DC power factor correction (PFC) converters are dealt with fast charger. These converters are developed using unidirectional and bidirectional power flow structure. In this study, three-phase AC-DC PFC converter topologies, providing bidirectional power flow, are evaluated in terms of performance. The aim is to present the latest technology of bidirectional multilevel AC-DC PFC converters for EV fast charging. This paper provides a comprehensive and practical review for researchers interested in fast charging infrastructure for electric vehicles.

**Keywords:** Improved power quality, AC-DC converters, Power factor correction, Three-phase AC-DC converters, Fast charging infrastructure.

## Elektrikli Araçların Hızlı Şarjı için Üç Fazlı AA-DA Güç Faktörü Düzeltme Dönüştürücülerinin İncelenmesi

### Öz

Hızlı DA şarj için elektrikli araç şarj istasyonu, araç dışında AA-DA dönüşümü gerçekleştirir. Son yıllarda, üç fazlı AA-DA güç faktörü düzelten (GFD) dönüştürücüler hızlı şarj cihazı ile birlikte ele alınmaktadır. Bu dönüştürücüler, tek yönlü ve çift yönlü güç akışı yapısı kullanılarak geliştirilmiştir. Bu çalışmada, çift yönlü güç akışı sağlayan üç fazlı AA-DA GFD dönüştürücü topolojileri performans açısından değerlendirilmiştir. Amaç, elektrikli araç hızlı şarjı için en yeni üç fazlı çift yönlü çok seviyeli AA-DA GFD dönüştürücü teknolojisini sunmaktır. Bu makale, elektrikli araçlar için hızlı şarj altyapısıyla ilgilenen araştırmacılar için kapsamlı ve pratik bir inceleme sunmaktadır.

**Anahtar Kelimeler:** İyileştirilmiş güç kalitesi, AA-DA dönüştürücüler, Güç faktörü düzeltme, Üç fazlı AA-DA dönüştürücüler, Hızlı şarj altyapısı.

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# 1. Introduction

Researches based on the use of clean and efficient fuels in the automotive sector continue. Therefore, the interest in electric vehicles is increasing. However, electric vehicle (EV) users are concerned about the charging times of the vehicles and the range they can travel. This situation leads researchers to improve the charging infrastructure in fast charging stations.

Electrical energy is not in a form that can be directly applied to the EV battery. EV chargers transmit energy as the form of high voltage AC or DC current. AC chargers provide AC power form to the EV, then AC power form is converted to DC using on-board charging unit. On-board chargers are slow because they operate at lower currents (Metwly et al., 2020; Sam et al., 2021; Yuan et al., 2021). DC (off-board) chargers transform AC current externally and provide high power directly to the EV battery (Chlebis et al., 2014; Monteiro et al., 2020). Therefore, it is quite fast. Fast DC charging stations established for commercial purposes provide desired high energy with three-phase power supply (Monteiro et al., 2018; Yildirim et al., 2020). Figure 1 shows general fast charging infrastructure for EV.

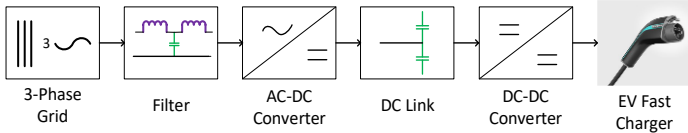


Figure 1. General fast charging infrastructure for EV

The fast charging infrastructure has a power system flow and power electronics converters affect the occurred harmonics and reactive power in this system. AC-DC converters are used with passive, active and hybrid filters due to power quality problems as in (Balasubramanian et al., 2016; Justus Rabi et al., 2015; Kushwaha et al., 2020a; Sah et al., 2021). However, filters are quite costly, bulky and have losses. These reduce the AC-DC converters performance (Singh et al., 2011). The converters selected for EV charging are important in terms of power quality, THD, reduced-rippled DC output and control approaches (Praneeth et al., 2018).

AC-DC converters supplied from three-phase AC mains are developed by using diodes, thyristors and controlled switches to provide controlled-uncontrolled and unidirectional bi-directional DC power in high power applications. Power quality problems and fluctuating DC output at the load end occur in the converter due to the injected current harmonics. Therefore, designers take into account standards guidelines. When we look at the literature, we can see that three-phase bidirectional multilevel AC-DC PFC converters are used for fast charging because of their efficiency as in (Khaligh et al., 2012; Nayak, 2019; Sandoval et al., 2015; Sharma et al., 2020; Singh et al., 2004; Tan et al., 2016; Verma et al., 2019; Yilmaz et al., 2013; Zhang et al., 2012). Therefore, this paper provides information about these converters topologies in detail.

Three-phase AC-DC converters are widely employed in adjustable-speeds drive (ASDs), uninterruptible power supplies (UPSs), high voltage DC transmission (HVDC), renewable energy systems, battery management systems and EV fast charging, etc. (Akter et al., 2015; Alves et al., 2018; Chen et al., 2016; Garg et al., 2015; J. H. Lee et al., 2011; J. Y. Lee et al., 2020; Soeiro et al., 2012; Wang et al., 2019). In the literature, this converters are classified as switch mode rectifiers (SMRs), power

factor correction converters (PFCs), pulse width modulation (PWM) rectifiers (Bhat et al., 2008). These topologies are presented in detail in Figure 2.

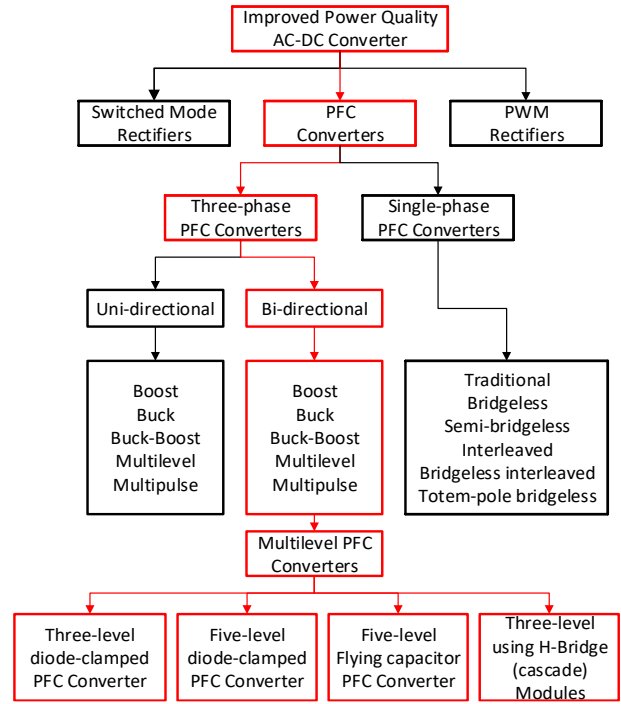


Figure 2. Classification of AC-DC converters with improved power quality

Today developed AC-DC converters with improved power quality are controlled by switching elements such as MOSFETs, IGBTs, GTOs, etc. (Elrajoubi et al., 2019). On-board and off-board charging topologies are included in the AC-DC PFC section as in (K. T. Chau, 2016; Kushwaha et al., 2020b). Firstly, single-phase and three-phase AC-DC PFC topologies for EVs charging were examined. Since the research is for high power applications, three-phase topologies are discussed.

In this study, the aim is to compare three-phase bi-directional PFC converters used in EV fast charging station. Then, multilevel PFC converter topologies ones were evaluated. With detailed information, researchers can obtain information fast about EV off-board charging.

## 2. Evaluation of Three-Phase Bidirectional PFC Converters

Three-phase unidirectional AC-DC PFCs are supported by choppers, SEPIC, Cuk, Zeta, full-bridge-half-bridge, fly-back or multi-level converters following a three-phase full diode bridge to provide high power factor.

Three-phase bidirectional AC-DC PFCs consist of basic converters such as voltage source inverter topology or current source inverter topology (Bhat et al., 2008). Three-phase unidirectional AC-DC PFCs show a distortion greater than 5% in terms of phase current harmonic as in (Channegowda et al., 2015). This is not suitable for the standards given in IEEE 1030-1987. Three-phase bidirectional buck, boost, buck-boost, multi-pulse and multilevel converter topologies give similar results. However, they are developed in terms of performance. For this reason, they are used for different target (Liu et al., 2020). Table 1 shows the required element number for multilevel PFC converters.

Table 1. Comparison of power components required per-phase between multilevel PFC converters

Table Head	Multilevel PFC Converters			
	3-Level Diode-clamped	5-Level Diode-clamped	5-Level Flying-capacitor	3-Level H-bridge cascaded
Main power switches copy	4	8	8	4
Clamping diodes	2	12	0	0
DC-Bus capacitors	2	4	4	1
Balancing capacitors	0	0	6	0

Table 2. Comparative features of three-phase AC-DC PFC converters (Monteiro et al., 2018)(Bhat et al., 2008; “IEEE 597-1983 - IEEE Standard Practices and Requirements for General Purpose Thyristor DC Drives,” n.d.)

Three-phase AC-DC PFC Converters	Number of Switches	Switch Stresses	Conducted EMI	Power levels	Efficiency	Performance	Cost
Boost Converter	Large in two-stage conversion, small in single-stage conversion	less with soft-switching techniques	Can be lesser with soft-switching techniques	Low with DCM but can be high with CCM	good, with sensor less topologies and applications with reduced magnetic size can be further improved	Better	Low for high power application and single stage conversion
Buck Converter	Large in two-stage conversion, small in single-stage conversion	Low, can be lesser with soft-switching techniques	Low	Usually low, if the converter is based GTO, then high	Good, can be further improved with Soft switching and transformer isolation"	Better, It also has short-circuit protection, good open-loop control	Low for in low-power application
Buck-Boost Converter	Less	Low, can be lesser with soft-switching techniques	Low	Medium	Fairly good	good with DCM	Low
Multilevel Converter	Large	Least	Less with low dv/dt and can be lesser with soft switching techniques	High	Very high	Excellent	High due to large number of switches

When we look at Table 2, we can see that three-phase bi-directional multilevel PFC topologies show the best PFC effect and reduce the voltage stress on the circuit elements, have lower THD and have good performance. Three-phase bi-directional multilevel PFC topologies provide high power quality, reduce THD and EMI, and have higher regulated DC output voltage (Habib et al., 2018; Turksoy et al., 2018). Using three-phase multi-level bidirectional converters is more appropriate for level 3 fast DC charger. These PFC converters are more efficient for grid input and safer compared to other topologies.

### 3. Three-Phase Bidirectional Multilevel PFC Converters for Fast Charging

High efficiency and low THD is important for high power and bi-directional power flow applications.

Three-phase bi-directional multilevel AC-DC PFC converters evaluated for fast charging are following. IGBT and MOSFET are ideal switch for low and medium power applications, but GTO is used for high power applications [42]. These converters are more successful than the applications with transformers according to (Yilmaz et al., 2013) and (Yaramasu et al., 2021).

Figure 3 shows three-level diode-clamped bi-directional PFC converter topology. Bidirectional boost converter and bidirectional neutral point clamped (NPC) topologies are compared in (Monteiro et al., 2018). NPC topology has the smallest ripple at the main current and shows smaller fluctuation in DC output. (Yilmaz et al., 2013) refers that this converter shows lower switching stress for level 3 fast charger applications.

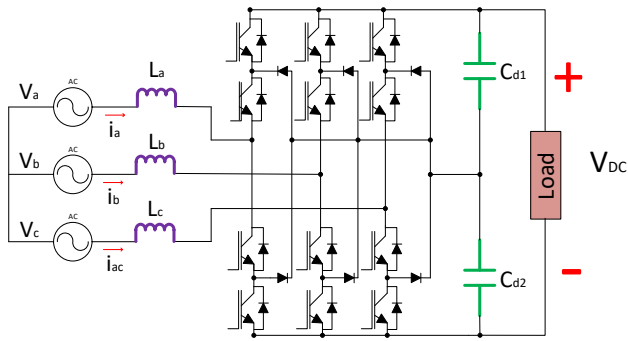


Figure 3. Three-level diode clamped bidirectional PFC converter

Figure 4 shows five-level flying capacitor bidirectional PFC converter topology. (Kamaga et al., 2011) specifies that harmonics decrease if the number of converters levels increase, however, it will not be practical because of the large number of capacitors. The performances of five-level flying capacitor and five-level diode clamped topologies are compared in (He et al., 2016). Diode-clamped topology is preferable in terms of cost and performance.

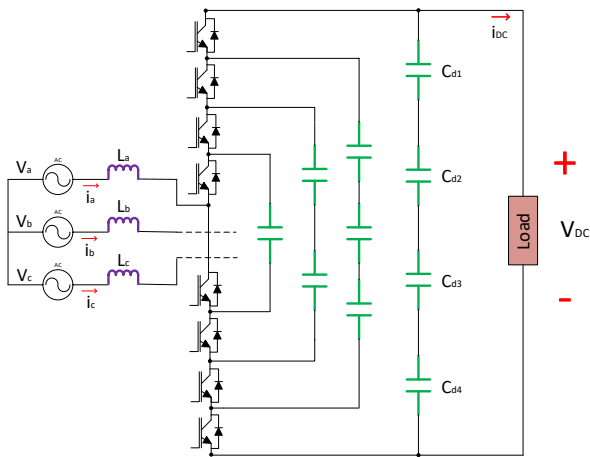


Figure 4. Five level flying capacitor bidirectional PFC converter

Figure 5 shows five-level diode-clamped bidirectional PFC converter topology. As the number of converter levels increase, the phase-to-phase THD decreases in diode-clamped converters. However, since the component number increase, the cost of the system increases (Prajapati et al., 2014).

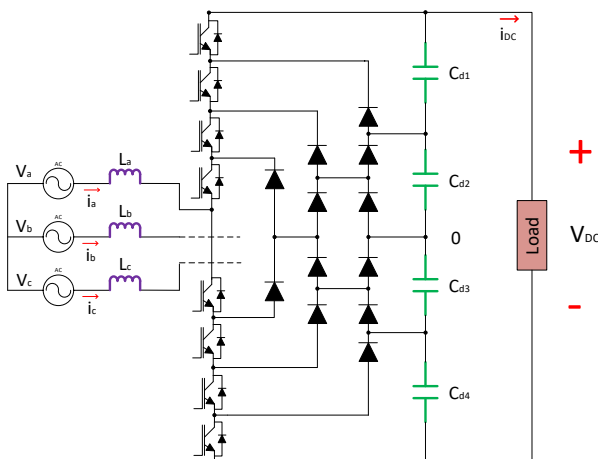


Figure 5. Five-level diode-clamped bidirectional PFC converter

The cascade H-bridge converter provides multilevel voltage with the separate power supplies that operates each H-bridge converter, shown in Figure 6. Five-level diode-clamped and five-level flying capacitors multilevel converters are compared with cascade module converter. Among the three topologies, the cascade module gives the minimum harmonics in the output voltage (Prayag et al., 2017). However, the need for many DC choppers is not practical in application (Shaikh et al., 2021).

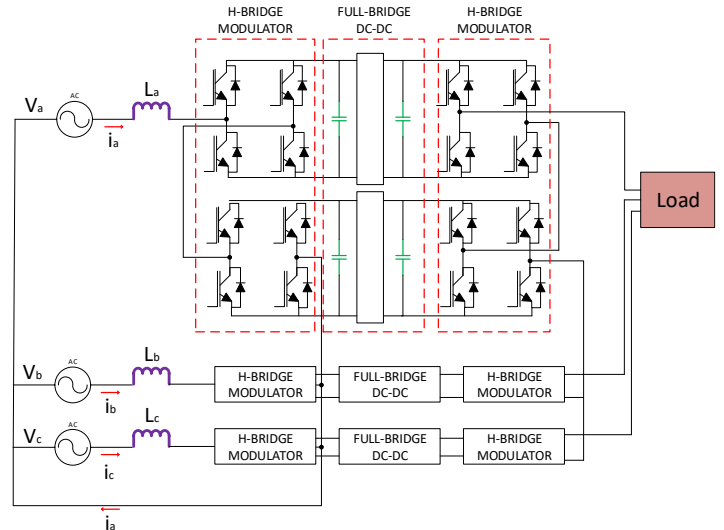


Figure 6. Three-level converter using PFC cascade modules

Capacitor charge and discharge can be balanced when using a multilevel bidirectional converter for reactive power compensation without voltage imbalance problem (Singh et al., 2004). Diode-clamped multilevel converters control is easier in terms of reactive power flow. However, they require more clamping diodes. The disadvantage of multilevel converters with flying capacitors is that many capacitors are required because of the number of levels; this makes the system less reliable and more bulky. The biggest disadvantage of cascade multilevel converters is that they need separate DC sources. Therefore, it limits the user in terms of application (Bhat et al., 2008; Cui et al., 2018).

### 4. Control Strategies

Control strategies are developed to improve EV charging system performance and system quality (Saleeb et al., 2019). The described topologies emphasize the balance of the neutral point potential. There are many control techniques in the literature for their control. The conversion part and the soft switching part are controlled in AC-DC PFC converters.

Control strategy is very important for high PF. All modulation techniques such as SPWM, SVPWM developed for inverters can also be used in these rectifiers. Controlling the DC link voltage of bidirectional AC-DC PFC converters require a feedback control loop. The DC output voltage is the system output. It is used as feedback in various control techniques such as PI controller, PID controller and sliding mode control.

While the converters are controlled, the error signal is found by comparing the DC output voltage in the rectifier with a reference voltage. This error is used to generate a sample sinusoidal waveform with the same frequency as the grid. This sample waveform is used to create the PWM to control the switches in rectifier. Switching signals are controlled as a voltage



source current controlled or a voltage controlled PWM rectifier. While current controller is used for input current, the voltage controller is used for magnitude and phase of the voltage (Sayed et al., 2016).

There are many control techniques for controlling multilevel converters (Yacoubi et al., 2005). Space vector pulse width modulation (SVPWM) techniques in particular perform well for control of these converters. Therefore, SVPWM control techniques are developed (Menon et al., 2021; Sreedhar et al., 2021; Vivek et al., 2021). General control block diagram for AC-DC PFC converters is shown in Figure 7.

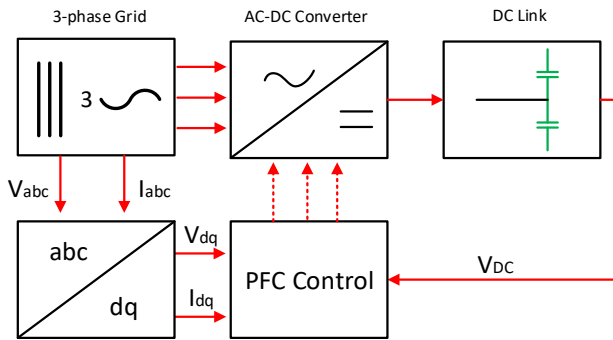


Figure 7. General control block diagram for AC-DC PFC converters

$dq$  transform is applied to the sensed voltage and current signals to simplify the control analysis in three-phase converters. The converted voltage or current is used in closed loop controllers to derive reference voltage or current signals.

## 5. Selection Criteria of Three-Phase AC-DC PFC Converters for EV Fast Charging

Three-phase bidirectional multilevel AC-DC PFC converters are preferred for new technology high voltage and high power applications. The following factors are considered in the selection of these converters, which are also considered for fast charging (Kavianipour et al., 2021).

- input power quality (THD and PF),
- The fluctuation of the DC voltage output,
- Unidirectional and bidirectional power flow,
- DC power requirement at the output
- Cost, size and weight;
- Efficiency;
- Noise level (EMI, RFI, etc.),
- Reliability;
- Environment (ambient temperature, pollution, humidity)

In summary, we can say that DC output regulation, high input power factor and low THD are important for EV chargers.

## 6. Conclusion and Future Development

In this paper, detailed information is given about the three-phase bidirectional multilevel AC-DC PFC topologies for EV fast charging. The mentioned PFCs are used in high power applications. Today, the aim is to reduce switching losses at high

switching frequency in these topologies, to reduce the size of the elements, and to reduce the use of bulky filters. Therefore, control algorithms and soft switching techniques are developed. Multilevel converters are popular as they offer less stress and low THD in devices. In addition, solid state device technology developed for switching elements has made these converters attractive. New developments in control algorithms will provide support for three-phase PFC converters in the near future. This paper can be a good reference for selection of the right topology for EV charging infrastructure.

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