Component-based Modelling of EV Battery Chargers

Citation for published version:
https://doi.org/10.1109/PTC.2015.7232690

Digital Object Identifier (DOI):
10.1109/PTC.2015.7232690

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
IEEE PowerTech

Publisher Rights Statement:
(c) 2015 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other users, including reprinting/ republishing this material for advertising or promotional purposes, creating new collective works for resale or redistribution to servers or lists, or reuse of any copyrighted components of this work in other works.

General rights
Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.
Component-Based Modelling of EV Battery Chargers

Xu Xiao, He Molin, Paraskevi Kourtza,
Adam Collin, Gareth Harrison and Sasa Djokic
The University of Edinburgh
Edinburgh, Scotland, UK

Abstract—This paper reviews typical circuit topologies and control algorithms for on-board unidirectional single-phase electric vehicle battery chargers (EVBCs) and provides simple yet reasonably accurate component-based models for their representation for power system analysis. The accuracy of the developed models is validated against measurements of actual EVBCs, for both ideal voltage supply conditions and typically distorted voltage supply waveforms. The paper also provides exponential and polynomial EVBC model interpretations, as well as some discussion of the further use of the presented models for the analysis of existing networks and future smart grids with high penetration levels of EVBCs.

Index Terms—Active power factor control, electric vehicle battery chargers, load modelling, power system analysis.

I. INTRODUCTION

Electric vehicles (EVs) are recognised as one of the most promising technologies to help reduce the fossil fuel dependency in the road transportation sector. However, the connection of a large number of EV battery chargers (EVBCs) will present a major challenge for the operation of existing distribution networks, as these loads might cause significant changes in power flows, with an inherent impact on voltage profiles, harmonic emissions and overall system performance. Currently, these changes are not fully understood. For example, a study in [1] suggested that uncontrolled charging of EVs with a relatively low (10%) penetration might increase peak demands by up to 18%. On the other hand, study in [2] suggested that connection of a number of different types of EVBCs could result in significant harmonic cancelation, which is beneficial to the distribution network operation.

To study the extent and range of these changes, in terms of impact on power flows and power quality, correct models of EVBCs are required. Depending on the type of charger and purpose of modelling, a variety of component-based EVBC models have been described in existing literature (with a broad summary in [3]). However, simplified models suitable for a large area network studies are still not widely available, as most of existing literature (e.g. [4], [5]) focuses on the design of EVBCs, presenting models which generally could not represent the electrical characteristics of existing commercial EVBCs. This paper addresses the above issues and presents component-based models of single-phase unidirectional on-board EVBCs, which are representative of those available on the EU domestic market and are capable of reproducing relevant electrical characteristics with a reasonable accuracy.

The research presented in this paper continues the EVBC modelling work presented in [6], aimed at producing simple yet accurate models for analysing the effects of increased penetration of EVs on low voltage (LV) and medium voltage (MV) networks. The capability of the presented models to correctly represent both steady-state and harmonic power flow characteristics of the modelled EVBCs is validated against available measurements.

II. TYPICAL EVBC CIRCUITS AND CONTROLS

The battery charger is an important component of the EV, as it has direct impact on battery life and required charging times, modes and conditions. There are several possible variants of EVBCs, with classification based on: charging voltage and current (single-phase, three-phase, or dc), charger location (on-board, or off-board) and power flow direction (unidirectional, or bidirectional).

The requirements for EVBC performance vary depending on EV application and have significant impact on EVBC’s input characteristics, with [7] and [8] specifying limits for the single-phase unidirectional on-board chargers considered in this paper. As EVBCs are a relatively new type of load, there is still no specification of dedicated harmonic limits in [7], which instead recommends the requirements for Class A equipment from [8]. Accordingly, EVBCs will typically have an active power factor control (a-PFC) circuit, to limit their harmonic emissions and reactive power demands. However, if the input ac supply voltage waveform is distorted, as is typically true in LV residential networks, the control of the a-PFC circuit will not be able to produce the desired ideally sinusoidal input ac current [9]. This clearly indicates that the correct modelling of EVBCs should include a-PFC circuit.

A. Full Circuit EVBC Model

The EVBC is a complex power electronic circuit, with main components illustrated in Fig. 1. The key functional blocks are described in the subsequent text, with the full circuit model presented overleaf in Fig. 2.

![Figure 1. Main components of a single-phase unidirectional EVBC.](image-url)
Before the boost converter, typical EVBC circuits have standard diode bridge rectifier (DBR) and input filter, as shown on the left-hand side of Fig. 2. Their main functions are: to rectify input ac voltage to dc, and to filter the high-frequency harmonics of input current. The EVBC front-end circuit could use a number of converter topologies, e.g. boost, buck, buck-boost, cuk, flyback or forward. However, the most widely used a-PFC topology is a boost converter with inductor current kept in a continuous conduction mode [3, 10], which is implemented in the EVBC models presented in this paper.

1) **Front-end DC-DC Boost Converter and a-PFC Control:** There are a variety of a-PFC control techniques, including average or peak current control and fixed-band or sinusoidal hysteresis current control. They typically consist of an outer voltage loop and an inner current loop control, where the value for the reference inductor current in the inner current loop is given by the amplified dc voltage error in the outer voltage loop, with the aim to maintain dc-side voltage at a desired value. The current control keeps inductor current (and hence input ac current) within the defined upper and lower boundary, while the control of the switching of the front-end converter is reconstructing the sinusoidal waveform, with either fixed or variable switching rate of inductor’s current.

The a-PFC circuit from the developed full circuit EVBC model is shown in Fig. 3. Unlike traditional current control circuit, in which reference input current is obtained from the amplified dc-link voltage error, the applied modified peak current control neglects the voltage loop and sets the reference magnitude of input current directly in the current control loop, in order to better fit the measured data. The used control circuit is based on a conventional peak current control, with an added lower boundary for inductor current. The inductor current is first compared with its lower boundary, and boost converter is switched on if current is lower than its boundary value, resulting in an increase of the inductor current. When inductor current is above its lower boundary, the difference between the inductor current and its upper boundary is compared with a ramp signal to generate pulse width modulation (PWM) control for the boost converter switch. The frequency of the ramp signal is set at 35.8 kHz, which is also the switching frequency of the boost converter in the front-end circuit of a measured EV charger.

Fig. 4 illustrates the results for the applied modified peak current control circuit, showing that it can better model the input ac current waveform characteristics, i.e. its total harmonic distortion (THD) and harmonic magnitudes/phase angles, than the other three considered a-PFC control circuits.

2) **High-frequency transformer:** In the EVBC circuit, a high-frequency transformer is typically (but not always) used for galvanic isolation, safety and better control of the voltages supplied to the battery by the back-end converter circuit.

3) **Back-end DC-DC Full-bridge Converter with Battery Charging Control:** The back-end dc-dc full-bridge converter is operated as a part of a battery management unit, to regulate battery charging in two general modes: constant current (CC) and constant voltage (CV). Initially, the battery current is
kept constant at the reference value (CC mode). When battery voltage reaches its reference value, it is kept constant (CV mode). From testing of EVs, it is found that the CC charging mode is active up to around 80%-90% of battery’s full state of charge and that its duration is much longer than the CV mode, which typically lasts only a few to several tens of minutes (and sometimes even less than that).

The control circuit of the full-bridge converter in the developed EVBC model is shown in Fig. 5. The reference values for battery current and voltage are set at 6.5A and 360V respectively, which is derived from the actual measurement data, as shown in Fig. 6. The PWM signal for controlling the switching of the transistors is generated by comparing the amplified voltage or current error with a ramp signal, with the same switching frequency as the front-end boost converter.

Figure 5. The control circuit of the dc-dc full-bridge converter.

The relationship for \( R_{\text{eq}} \) under 0.8pu - 1.2pu sinusoidal input ac voltage is written as (2), which is obtained after a detailed analysis and fitting of model parameters to the values measured in tests with actual EVBCs.

\[
R_{\text{eq}} = (0.0135\text{SoC} + 0.117)v_b + 0.216\text{SoC}^2 + 0.0845\text{SoC} + 0.268
\]

To validate the developed EVBC models, a commercially available single-phase on-board EVBC was connected to a controllable power source and subjected to a number of tests.
The main criteria for the validation was ability of the EVBC models to reproduce the measured input ac current waveforms for a range of input ac supply voltage conditions and source impedances. The three characteristic supply voltage waveforms applied in the tests are shown in Fig. 9, while only results for zero source impedance are given in this paper.

Comparisons of simulation and measurement results for 1pu ideally sinusoidal, ‘pointed-top’ and ‘flat-top’ input ac voltage waveforms are shown in Fig. 10, 11 and 12, respectively. Fig. 13 provides further validation of the developed EVBC models, with respect to their capability to reproduce voltage-dependent electrical characteristics. While measurement data were available for 0.8pu-1.1pu range of input ac voltages, simulation data are obtained for the range of 0.8pu-1.2pu, in order to better quantify the EVBC behaviour.

A. Ideally Sinusoidal Input AC Supply Voltage Waveform

Figure 10. Comparison of measured and simulated input ac currents for 1 pu ideally sinusoidal input ac supply voltage.

B. Distorted Input AC Supply Voltage Waveform

Figure 11. Comparison of measured and simulated input ac currents for 1 pu “pointed-top” input ac supply voltage.

Figure 12. Comparison of measured and simulated input ac currents for 1pu “flat-top” distorted input ac supply voltage.
C. Comparison of Electrical Load Characteristics

Figure 13 compares electrical characteristics derived from measurement and simulation data for the considered range of input ac voltages (0.8pu-1.2pu). The electrical characteristics are represented by plotting dependencies of active power, $P$, fundamental reactive power, $Q_f$, and total current harmonic distortion, $THD_i$, as well as true, displacement and distortion power factors ($PF$, $PF_d$, and $PF_{th}$, respectively) on ac supply voltage magnitude (for ideally sinusoidal waveforms). All calculations are performed in accordance to definitions in [11].

It can be seen from Fig. 13 that the EVBC models can reproduce the relevant electrical characteristics of the tested EVBC with a reasonable accuracy. A somewhat higher error between the measured and simulated $THD_i$ values is due to the corresponding differences in the calculated values of the 5th and 7th input ac current harmonic magnitude. Due to the low $THD_i$ values, however, the absolute error is small.

The $P$-$V$ and $Q_f$-$V$ characteristics in Figs. 13a and 13b are of particular interest for modelling EVBCs in network studies. Fig. 13a shows that the modelled EVBC will change its active power demand characteristics from (an approximately) constant current load type to (an approximately) constant power load type for $V_i > 0.95pu$. The $Q_f$-$V$ characteristic in Fig. 13b (normalized using $Q_i$ at nominal voltage) are similar, with a change from an approximately constant impedance load type to an approximately constant current type for $V_i > 0.95pu$. This is discussed further in the next section.

![Figure 13](image_url)

<table>
<thead>
<tr>
<th>Parameter Values of the EVBC Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1$ (mH)</td>
</tr>
<tr>
<td>1.01 E-03</td>
</tr>
</tbody>
</table>

IV. DISCUSSION OF NETWORK MODEL APPLICATIONS

The presented equivalent circuit EVBC model (Table I) can be applied directly in network studies, or as a part of an iterative time and/or frequency domain modelling approach. Standard steady state load model forms, i.e. exponential or ZIP models (Table II), can be extracted from the presented EVBC models due to their ability to reproduce voltage-dependent power demand characteristics. This allows the presented models to be used in most, if not all commercial power flow software packages to analyse LV/MV networks. For example, voltage dependency of active and reactive power demands is particularly important for assessing the EVBC potential for conservation voltage reduction in future networks with large penetration levels of EVs, as well as for the general assessment of network voltage profiles and power flows.
and simulations confirm that the presented EVBC models are capable of correctly representing EVBCs in power system studies, including analysis of their harmonic emissions for power quality assessment.

The paper also discussed the use of the developed EVBC models for assessing the impact of increasing EVBC penetration levels on power flows and performance of LV and MV networks. For that purpose, exponential and polynomial/ZIP model interpretations are formulated, in order to specify and implement appropriate EVBC steady state load models for a large area network studies.

The dependency of EVBC characteristics on supply voltage distortions clearly indicates that the correct modelling of EVBCs should include a-PFC circuit and raises important questions about the suitability of compliance verification tests in [8], which require sinusoidal voltages for testing loads with a-PFC circuit. This is one of the possible directions for future work, together with the further development and specification of simple and accurate aggregate models of a large number of EVBCs, aimed at the analysis of existing LV and MV networks and future “smart grids”.

REFERENCES