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Design and development of a three-phase off-board electric vehicle charger prototype for power grid voltage regulation

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ABSTRACT

This paper discussed the design and development of a 2 kVA three-phase off-board electric vehicle charger prototype with a practical voltage control, where the procedures of the experimental construction were comprehensively presented. For the experimental setup, the effectiveness of the interface circuits and auxiliary power supply units were individually validated. Moreover, the electric vehicle charger utilized a Digital Signal Processor to employ the control strategies of vehicle charging and power grid voltage regulation. The proposed control can simultaneously charge the battery of electric vehicle, maintain a constant DC-link voltage and also provide the appropriate reactive power compensation to regulate the grid voltage to the desired level. While complying with the power quality standards, the experimental results had validated the practicality of the integrated electric vehicle charger and the control performance. The charger prototype had effectively regulated the grid voltage to the pre-charge voltage of 0.96 per unit while maintaining the DC-link voltage at 150 V during various charging currents of up to 5 A.

1. Introduction

The conventional Electric Vehicle (EV) charger is typically used for unidirectional charging purposes. Nevertheless, additional features can be accomplished by the existing charger's converter with the implementation of a proper control strategy. Therefore, this research is motivated to design the comprehensive procedures for the development of an EV charger prototype with a smart control, which can support the power grid during charging of EV.

There are two main contributions in this paper. The first contribution is to present the development of a 2 kVA three-phase off-board EV charger prototype, which includes the power circuit, measurement units, sensor interface, Digital Signal Processor, gate driver interface and auxiliary power supply units. The procedures of the entire prototype construction and also the individual experiments will be comprehensively demonstrated. Another contribution of this paper is to present the EV charging and power grid voltage control (P–V control) for the EV charger prototype. The proposed control can automatically determine the appropriate amount of reactive power required to regulate the grid voltage of the EV interconnection point to the desired level while charging the EV. The practicality of the constructed charger prototype with the P–V control will be validated experimentally.

The rest of the paper will be organized into several sections. Section 2 presents the literature survey. Section 3 shows the concept and design of the P–V control. The general structure of the experimental setup is discussed in Section 4. The description and design of the power circuit, measurement units, interface circuits, processor and auxiliary power supply units will be comprehensively demonstrated here. Section 5 presents the experimental validation of the EV charger prototype with the P–V control, while Section 6 concludes the paper.

2. Literature survey

The conventional internal combustion engine vehicles employ the fossil fuel combustion process to drive the vehicles. Nonetheless, unwanted by-products along with the combustion process are the emissions of air pollutants [1]. The transportation sector has been the main source of greenhouse gas emissions [2]. Literature had reported that road transport was the largest contributor to the

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Nomenclature

α	Phase-shift angle
δ_D	Delay angle
δ_E	Voltage angle of E_p
δ_V	Voltage angle of V_p
θ	Phase-locked loop angle
θ_f	Angle of the modulating signal
$C_{A,n}$	Capacitors in auxiliary power supply units, where $n = 1, 2, 3, \ldots$
C_{buck}	Capacitor in the DC/DC converter
$C_{G,n}$	Capacitors in the gate driver circuit, where $n = 1, 2, 3, \ldots$
$C_{S,n}$	Capacitors in the sensor interface circuit, where $n = 1, 2, 3, \ldots$
D	Duty ratio of the buck converter
E_{abc}	Front-end three-phase voltages of the EV charger
E_p	Phase voltage (root mean square) at AC side of the AC/DC converter
f_C	Cutoff frequency
f_S	Signal frequency
FSF	Frequency scaling factor
I_{abc}	Three-phase currents
I_{batt}	Battery current
$I_{battref}$	Reference of battery current
$I_{DC\text{ - }link}$	DC-link current
K	Gain factor
L_{buck}	Inductor in the DC/DC converter
M_{abc}	Modulating signals for the AC/DC converter's control
M_{dc}	Modulating signal for the DC/DC converter's control
M_{tri}	Carrier waveform
mag	Magnitude of the modulating signal
mag_{dc}	Output signal of the DC/DC converter's controller
P_{batt}	Charging power of the EV battery
P_s	Active power flow between the power grid and EV charger
Q	Quality factor
Q_s	Reactive power flow between the power grid and EV charger
$R_{A,n}$	Resistors in auxiliary power supply units, where $n = 1, 2, 3, \ldots$
$R_{G,n}$	Resistors in the gate driver circuit, where $n = 1, 2, 3, \ldots$
$R_{S,n}$	Resistors in the sensor interface circuit, where $n = 1, 2, 3, \ldots$
R_{switch}	Resistor of the battery switch
S_1	First contactor of the battery switch
S_2	Second contactor of the battery switch
t	Real time
V_{abc}	Three-phase voltages of the power grid
V_{batt}	Battery voltage
V_d	Direct voltage
$V_{DC\text{ - }link}$	DC-link voltage
$V_{DC\text{ - }linkref}$	Reference of the DC-link voltage
V_{dref}	Reference of the direct voltage
$V_{g,in}$	Input signal of the gate driver interface
$V_{g,out}$	Output signal of the gate driver interface
V_p	Power grid phase voltage (root mean square)
V_q	Quadrature voltage
$V_{S,in}$	Input signal of the sensor interface
$V_{S,out}$	Intermediate output signal of the sensor interface
V_{S,out_f}	Output signal of the sensor interface
X	Filter reactance

transport emissions in Europe, which took up to 72% of the total transport emissions [3]. Furthermore, the fossil fuel reserve depletion poses challenges to the current transportation sector [4]. The anxiety over the depletion of fossil fuel resources in the near future has thrust the necessity for alternative options in the transportation sector [5]. In order to cater for both problems, the electrification of road transport is a promising effort to alleviate tailpipe emissions by diversifying the energy sources for the vehicle propulsion, which are shifted from the fossil fuels to electrical batteries [6]. Recently, the tremendous growth of EV stocks have taken up significant vehicle shares across the world [7]. According to the Global EV Outlook 2016, the global EV stocks had reached approximately 1.26 million units with 80% of the EVs were located in the United States, China, Japan, the Netherlands and Norway [8].

EV batteries require regular recharging operations, which can be accomplished by regenerative braking and external charging [9]. The former recharging process occurs in all the EV types, especially the hybrid EVs [10]. The vehicle momentum is converted into electrical energy and stored in the EV battery during the deceleration process [11]. However, this energy recovery mechanism is not sufficient to recharge an EV with a large battery pack. This problem is solved by the latter recharging approach. The external charging approach is applicable to most of the recent EVs, where these EVs can be plugged-in to the power grid through the charger units to receive the batteries charging. Several EV charging standards were established by the Society of Automotive Engineers (SAE), International Electromechanical Commission (IEC) and CHAdeMO [12]. These standards governed the charger requirements, interconnection methods and safe charging rates [13]. For instance, the IEC 61851-1 had established four charging modes depending on the quantity of power received by the EV, the type and level of voltage, the communication mode between the charging station and the EV, as well as the location of the protections [14].

Extensive attentions have been placed on two major aspects of the EV charger, which are the development of converter topologies and the design of control strategies [15]. Various converter topologies of EV charger have been summarized in Ref. [16]. The most common charger configuration consists of a front-end AC/DC converter and a back-end DC/DC converter [17]. On the other hand, the design of control strategies is essential to manage the converters switching of the EV chargers to achieve specific functions. A typically employed control strategy for an EV charger is the decoupled active and reactive power control [18]. The implementation of the active power control is solely to control the charging rate for the EV charging operation while the reactive power control can be utilized to improve the overall power factor, provide the reactive power support to the power utility and reduce the power grid losses [19].

Several papers had validated their proposed charger configurations and control strategies by conducting tests using experimental prototypes. Utilizing a 12.5 kVA three-phase off-board EV charging station, the authors in Ref. [20] had successfully verified the proposed active and reactive power control which can provide reactive power support to the power utility during the EV charging operation. A similar charger control was proposed in Ref. [21], but validated using a 1.44 kVA single-phase on-board experimental charger. Meanwhile, a reduced-capacity smart EV charger prototype with a minimized DC capacitance was constructed in Ref. [22] to control the power factor of the power grid side. The optimized EV