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A unified multi-functional on-board EV charger for power-quality control in household networks

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HIGHLIGHTS

- Designing a feasible unified control system for a multifunctional on-board EV charger.
- The EV charger can operate in V2G/G2V mode as its main function.
- The EV charger can simultaneously perform three ancillary functions of a STATCOM and an APF.
- Stress on the EV battery is reduced using a two-leg buck-boost DC/DC converter.
- Simulation and experimental results verify the efficacy of the proposed system.

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ABSTRACT

This paper presents a feasible and reliable unified control system for a single-phase 4.5 kVA on-board multi-functional electric-vehicle (EV) charger that is connected to a low-voltage household network. Based on the proposed control system, the EV charger can operate as both a single-phase four-quadrant static synchronous compensator (STATCOM) and an active power filter (APF). The proposed EV charger can simultaneously perform four functions: charging/discharging the electric-vehicle's (EV's) battery; reactive power compensation; voltage regulation; and, harmonic reduction, which are important concerns of the existing power grid. Accordingly, it can enhance the building s voltage profile, power quality, and reliability, which makes the proposed method a complete solution for low-voltage household networks. The stress on the EV battery is also reduced, which can enhance its lifetime. A stability analysis of the proposed unified control system is provided in this paper. The simulation results, with two loads, static and dynamic, confirm the efficacy and reliability of the proposed system. The performance of the designed unified control system is also validated by experimental results.

1. Introduction

In recent years the demand for EVs has been growing significantly in developed countries, including Australia [1]. It is predicted that the number of EVs will grow to be 64% of the vehicles on the road in the United States (U.S.) by 2030, and 45% in Australia by 2030 [2,3]. Due to the increased penetration of EV chargers in household charging stations, some critical concerns have appeared for power systems, such as harmonics and voltage fluctuations [4–7]. Modern power electronic devices, for example personal computers, laptops and smart TV power supplies, have also adversely impacted power quality, not only in a house network but also in power systems. Moreover, the growing numbers of inductive and non-linear loads, like washing machines, refrigerators, etc. in a house demand the delivery of more reactive power from the grid than ever before. Therefore, a unified advanced control system is required which can provide an effective solution to improve the power quality and provide the required reactive power for each individual house. Many utilities over the last decade have tried to utilize EV charging stations as an effective solution to operate as both chargers and harmonic eliminators, voltage regulators or reactive power compensators (capacitor bank) [8–10]. Such ancillary functions are provided by integrating a control algorithm with the power circuits of the EV charger. According to recent literature, single-phase EV chargers are designed to provide reactive power while also charging or discharging the EV battery [11–16]. The authors in [17–21] address the harmonic problem caused by non-linear loads in a house, or by the

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Nomenclature

EV	electric vehicle
STATCOM	static synchronous compensator
APF	active power filter
OSG	orthogonal signal generation
V2G	vehicle to grid
PCC	point of common coupling
PWM	pulse width modulation
THD	total harmonic distortion
PF	power factor
v_s	source voltage
v_{PCC}	PCC voltage
v_c	converter output voltage
v_{ca}	grid-side capacitor voltage
v_{PWM}	PWM voltage
V_B	battery voltage
V_D	DC-link voltage
V_{sd}	D-axis of the source voltage
V_{sq}	Q-axis of the source voltage
V_{PCCd}	peak value of the PCC voltage
V^*_{PCCd}	reference value of V_{PCCd}
V_{Cd}	D-axis voltage control signal
V_{Cq}	Q-axis voltage control signal
i_s	source current
i_L	load current
I_B	battery current
$I_{Bripple,rms}$	RMS value of the battery ripple current
I_{Bmean}	mean value of the battery current
i_c	converter output current
i_{ca}	filter capacitor current
i_α	α-axis of the grid-side current
i_β	β-axis of the grid-side current
i_{href}	reference harmonic generated by harmonic controller
I_d	D-axis of the grid-side current
I_q	Q-axis of the grid-side current
I_{dref}	total reference value of I_d
I_{dref1}	reference value of I_d generated by active controller
I_{dhref}	reference value of I_d generated by harmonic controller
I_{dref}	total reference value of I_q
I_{qref1}	reference value of I_q generated by reactive controller
I_{qref2}	reference value of I_q generated by voltage controller
I_{qhref}	reference value of I_q generated by harmonic controller
θ	angle
P	active power demand
P_{ref}	total reference active power
P_c	converter output active power
S_{ref}	reference apparent power
Q	reactive power demand
Q_{ref}	total reference reactive power
Q_{ref1}	reference reactive power generated by reactive controller
Q_{ref2}	reference reactive power generated by voltage controller
Q_c	converter output reactive power
PF_c	converter-side power factor
PF_L	load-side power factor
PF_s	source-side power factor
f	line frequency
f_{sw}	switching frequency
C_D	DC-link capacitor
C_f	filter capacitor
C_B	battery-side capacitor
$C_{snubber}$	snubber capacitor
L_f	filter inductor
L_{sys}	total series inductance
L_1	DC-side inductor 1
L_2	DC-side inductor 2
L_D	total DC-side inductance
R_s	feeder resistance
X_s	feeder reactance
$u(t)$	input signal of harmonic control algorithm
$y(t)$	fundamental component of $u(t)$
$K_1(t)$	estimated amplitude of the sine term of $u(t)$
$K_2(t)$	estimated amplitude of the cosine term of $u(t)$
$x(t)$	difference between $u(t)$ and $y(t)$
D	duty cycle
ω	angular frequency
P_a	DQ transformation matrix
T_s	time delay
CF	crest factor

operation of the EV charger itself. As a result, an EV charger can operate as an APF to reduce or filter out the harmonics of the network. In [22] a single-phase EV charger is utilized to tackle the voltage disturbances caused by motor startup or inductive loads by operating as a STATCOM. In [23,24], while a single-phase EV charger works in the V2G or G2V mode, it is designed to support reactive power and/or harmonic reduction. As presented in the above literature, the majority of the designed EV chargers are single-functional and only a few of them are double-functional and, thus, are unable to remove all the three mentioned ancillary functions at the same time. Moreover, a single-phase EV charger which is able to improve the voltage profile of a household network is less focused in the literature.

The effect of plug-in electric vehicles (PEVs) on the voltage profile of one phase in a low-voltage residential feeder is investigated in [25,26]. It is concluded that the EVs' operation can adversely affect the voltage profile of the residential feeder, particularly where the EVs are plugged in close to the end of the feeder. Similarly, a rooftop photovoltaic (PV) installation can also cause an unbalance voltage in a household network to more than the standard limit [27]. As a solution, the authors in [28,29] propose a transformerless hybrid series active filter for residential buildings in order to combat the voltage disturbances caused by charging/discharging the PEVs. This system is a separate unit and is independently connected to a household network. Although it tackles the mentioned voltage disturbances, it would not be economical to be installed as a separate unit beside an EV charger in household networks. Moreover, this system works as a dynamic voltage restorer (DVR) to eliminate the voltage fluctuation (such as sag or swell), thus it needs a battery energy storage that also increases the cost. Accordingly, it would be a desired solution to equip the single-phase EV chargers to tackle the voltage fluctuations caused by their own operation and occasionally the installed rooftop PV's operation. As a result, no extra unit such as the one presented in [28,29] is required to be purchased and installed in houses.

However, it must be noted that, depending upon the feeder parameters such as the R/X ratio of residential feeders, active control and/or reactive control is required to maintain the voltage profile in an acceptable region. In [30,31] the impact of the R/X ratio in improving the voltage profile of a residential feeder using PV inverters and droop-based battery storages is studied in detail. This study concludes that the reactive power capability of PV inverters is sufficient to improve the voltage profile of urban areas where the R/X ratio is less than a critical ratio (identified as 4.5–5), whereas in rural areas where the critical R/X ratio is greater than that critical ratio (more resistive feeder), both reactive and active compensations are required. Such an investigation is followed in this paper to design an EV charger which can improve the voltage profile of a residential network for urban areas.