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A Fuzzy Logic-Based Controlling Battery Charger with Bidirectional Capability for Electric Vehicles

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***Abstract* - The environmental effects of petroleum transport networks and the fear of peak oil have combined with technological developments and renewed enthusiasm for renewable energy to cause an increase in the popularity of electric vehicles. Furthermore, because of the growing number of electric cars, which may double as mobile storage units, grid-to-vehicle (G2V), vehicle-to-grid (V2G), and vehicle-to-vehicle (V2V) have received a lot of attention. The ability to discharge power from a battery boosts its versatility in terms of supplying energy back to the grid, and it also helps to power stand-alone loads like emergency rescue equipment or outdoor lights. The electrical vehicle (EV) charger must thus include simultaneous operation, a high density of power, and good efficiency. High efficiency and bidirectionality are hallmarks of dual active bridge (DAB) converters. This paper describes the workings of a DAB converter and its closed-loop regulation using one of the phase shifts regulating methods, as well as its power and flow properties. To accomplish bidirectional operation for charging the battery in Fuzzy based on assessment of state of charge (SOC), a closed loop control method is designed.**

Keywords: grid to vehicle, vehicle to grid, fuzzy control, SOC.

I. INTRODUCTION

The first demonstration electric vehicles (EVs) were made in the early 1800s; later on, they were used as commercial EVs by the end of the 19th century. However, EVs did not achieve massive success as compared to internal combustion (IC) engine vehicles because of their low ranges. For the last 20 years, there has been a drastic increase in the production and research of electric vehicles. Due to involvement in renewable energy to get different power generation sources like solar energy, wind energy, and tidal energy to fulfill the power demands, the carbon footprint varies depending on the fuel and technology used for electric generation. So in the last few decades, we have moved to electric vehicles in place of internal combustion engines. The electricity can be stored in the battery, flywheel, or super capacitors. Apart from various advantages, there are a few challenges faced by the electric vehicle industry. The battery is the main component of the electric vehicle to store energy, so it takes time to charge. The charge time of the new batteries has been reduced by a few hours, but it takes much longer as compared with a fuel tank. Another problem is that the battery is more expensive. Batteries in cars have a limited range and are also costly as compared to internal combustion engines of the same size and quality. Presently, we are concerned about the environment, particularly pollution and exhaust emissions that can be reduced by the use of renewable energy like batteries and fuel cells in favor of electric vehicles.

To begin with, there are growing concerns about the environment, both in terms of global carbon dioxide emissions and local emissions of poisonous chemicals that are unpleasant to breathe. Battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV), and hybrid electric vehicles (HEV) are the three categories of electric cars now on the market where solely electricity from batteries is used to power the vehicle. These cars are emission-free. An AC adapter or DC rapid charger is used to charge its battery from a source of power from the outside. Hybrid electric cars use a combination of gasoline and electricity for propulsion. The power comes from the car's braking system. The energy created when the brakes are applied causes an electrical current to flow. Regenerative braking refers to this transformation. Battery-powered and gas-powered PHEVs are described by the acronym EV. The battery may be charged through an outlet. Battery cell life depends on different factors, like

- The rate of charging and discharging. Higher C rates adversely impact battery life. Higher the charging rate lower will be the life of battery.
- Temperature dependence of life: a higher temperature (40 °C or more) implies a smaller number of life cycles. Lower temperatures are equally problematic.
- State of charge (SOC): The SOC of a battery is a measure of the percentage of the battery charged.
- Depth of Discharge (DOD): It means the percentage of battery used. The life cycle decreases with increasing DOD. So, among the available battery types, lithium-ion (Li-ion) batteries are the most promising for electric vehicle storage applications because of their high energy density, high specific energy and power, and low weight. Charging a battery means restoring battery energy that is exhausted because of its usage. A battery charger is a device that uses an electric current to force energy into a rechargeable battery. The EV chargers are mainly classified into three types: Level 1 chargers, Level 2 chargers, and Level 3 chargers [1].

TABLE I. SAE CHARGING LEVELS

Charging level	Charger location	Number of phases	Power level
Level 1 120V (AC)	On-board	Single-phase	1.4-1.9kW
Level 2 240V (AC)	On-board	Single-phase or three-phase	4-20kW
Level 3 200-600V (AC or DC)	Off-board	Three-phase	20-100kW

Each phase of the selected bidirectional charger is described below.

According to the "vehicle to grid" or "grid collaboration" theory, an EV is linked to the electrical grid in such a way that electrical energy may flow between and within the battery depending on grid power requirements. Vehicle-to-grid technology (V2G) is attractive due to the increasing number of EVs, which can serve as moving storage units that can feed battery energy back to the grid or stand-alone loads such as urgent rescue or outdoor lighting. An average personal vehicle uses only 10–20% of the day, which means we only use some part of the stored energy so that energy can be used for household appliances, and also during peak hours we can use that power back to the grid so that there will be power stability between source and load. Grid integration benefits utilities in a variety of ways. The benefits of receiving a flow of electricity in both directions from an electric vehicle are listed below Peak load distribution.

Peak load distribution and load balancing stability of the power system decreased peak-hour losses. With decreased peak-hour generating capacity, there are a few obstacles to overcome when integrating electric vehicles into the grid. The EV batteries' shorter life span. Bidirectional charging stations aren't provided. It is becoming more and more common to use the charger to draw electricity from an electric vehicle's battery to support independent loads or connect to the grid. As a result, for an electric vehicle's portable charger, bidirectional operation, high power density, and high efficiency are critical.

A. Literature Review

Keun et al. explained the DC-DC converter circuit, full-bridge converters, phase shift full-bridge converters, and dual active bridge converters used. Each topology's design process is described in [2]. In [3], the power flow from grid to vehicle and vehicle to grid is compared using a single-phase shift. A charger is designed by using a controller. A simple interconnection between the charger and energy management system limits power. [4] gives insight into the modes of operation of DAB, various parameter calculations, and the power flow analysis of isolated DAB. The basic differences between the different phase shifting techniques used for the control of DAB are also presented. Bidirectional DC-DC DAB modeling and average dynamic evaluation are described in [5].

The control design and typical models of the construction block component are explored in depth in [6], which specifies the arrangement and control techniques for a building unit module that are appropriate for use in a completely modular DC-DC electric power conversion design. The contributions of the paper are given as follows:

- The primary objective is to design a charger for electric vehicles with bidirectional power transfer capability.
- The current THD (total harmonic distortion) for V2G mode is 7.19 as compared to [7].
- Reduce the voltage THD for V2G mode to 2.09 as compared to [7].

II. Structure of the Bidirectional Charger

As can be seen in Fig. 1. A bidirectional charger may be installed either on or off the vehicle. Either the charger goes inside the vehicle or stays at a dedicated charging station, depending on how much juice is needed to fully charge the battery. Table I displays the different US charging rates as specified by the SAE standard. The charger in this paper is made up of a three-phase bidirectional AC/DC adapter and a discrete bidirectional DC/DC adapter. Consequently, Fig. 2's adapter may be used with either level 2 or level 3 charging. As an alternative to mounting it outside the automobile at a dedicated charging station, it may be installed inside the car for low-power charging.

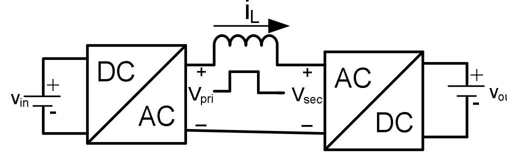

Fig. 1. Charger architecture in electric vehicle powertrains

A. LCL filter

To ensure low THD at the grid side, the LCL filter shown in Fig. 2 is employed to decrease the grid current ripple. Fig. 2 [8] depicts the grid-side filter's three-phase circuit. The values of the filter's elements $((L_{f,}C_{f,}L_c))$ must be determined while preserving system stability. Because of this, the transfer function of the filter is established:

$$\frac{i(s)}{v_S(s)} = \frac{1}{L_C s}\left(\frac{L_f L_c C_f s^2 + L_c}{L_f L_c C_f s^2 + (L_f + L_c)}\right) \quad (1)$$

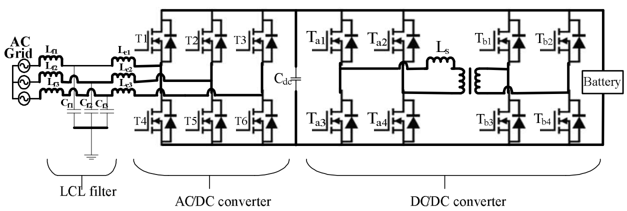

Fig. 2. The layout of the bidirectional charger

B. AC/DC converter

This application uses a three-phase VSI (Voltage Source Inverter) as the AC/DC converter. By altering the kind of switches used, this bidirectional converter, which allows electricity to flow both from and to the car battery, may be made to accommodate a variety of charging power levels [9]. For a standard EV, the DC connection at the AC/DC converter's output is regulated at 700V.

C. DC/DC converter

A DAB (Dual Active Bridge) converter from DC to DC is used for pairing the BESS (battery energy storage system) to the device. The isolation provided by the transformer between the BESS and the grid, which is significant for several reasons, including safety, is one of this structure's key characteristics [10]. As a bidirectional DC-DC converter, the DAB can guarantee appropriate V2G and G2V operation of the car. Additionally, as one of the key goals in building this charger was to guarantee adequate power quality across the three operating modes, this arrangement is essential in this kind of application. The DAB now has a significant advantage over competing devices in that it can operate at a variety of BESS voltages [11]. In reality, a traditional DC/DC converter (like a Buck/Boost converter) has a lower duty cycle as the voltage difference between the output and input gap grows. This is because bigger filters are needed, which lowers the power quality of both voltage currents. (phase shift modulation) among both signals of the two bridges that's able to regulate the output voltage is used to set up the DAB control. This crucial characteristic enables the bidirectional adapter to be utilized in PHEV purposes as well as EV applications, where the actual battery voltage of the hybrid vehicle is greater compared to that of the former and the voltage provided by the grid is lower.

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III. Converter Topology and Operation

The dual active bridge converter (DAB) is a two-way dc-dc converter that is isolated by a high-frequency transformer, an energy transfer inductor, and a dc-link capacitor. It consists of two symmetrical H-bridges that the DAB can control and keep apart. The reason why it was selected for the bi-directional charger design.

The circuit of a dual-active bridge converter is shown in Fig.2, having two identical H-bridges with their AC terminals connected to the primary and secondary windings of a high-frequency transformer. The switches Ta1-Tb4 are controllable semiconductor switches, and Ls is the leakage inductance of the high frequency. The switching action of MOSFETs can be used to generate a high-frequency wave. The electricity will flow from the leading bridge to the trailing bridge because the high-frequency waves are phase-shifted to each other. If we vary the angle, we can send current in either direction. If the angle is positive, we get positive power flow from source to load. The amount of power flow can be changed by adjusting the phase shift between the two bridge waveforms, and the power flow can be easily reversed by reversing the phase shift between the two bridges. At the same time, the switches in both the main and secondary bridges function at a duty cycle of 50%. Each bridge has a diagonal switch that, when turned off and on concurrently, produces a square wave. The switching process may be broken down into four distinct phases according to the inductor current waveform and the phase difference between the main and secondary voltage waveforms of the transformer.

Fig. 3 gives the waveforms of voltage across the primary secondary of the transformer, leakage inductor voltage, and its current. In this, the secondary voltage lags the primary voltage by dTs/2. t1=dTs/2, t2 = Ts/2, and Tx is the time at which the inductor current equals zero. Interval I: (t0 ≤ t ≤ t1), Interval II: (t1 ≤ t2), Interval III: (t2 ≤t< t3), and Interval IV: (t3≤t≤ t4)

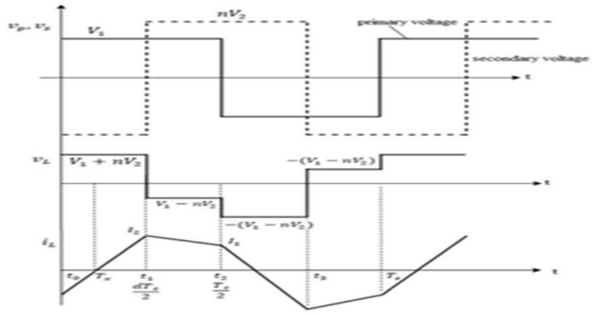


Fig. 3. Single-phase-shifted waveforms from a dual-active-bridge converter

A. Dual active bridge controller

The amount of power for every action is controlled by the DAB controller, which depends on two fuzzy variables. The DC bus and voltage of the batteries are stabilized through power-level regulation before the amount of power available to measure the battery voltage is used to set a cap on the voltage controller's current output. Therefore, this A controller is utilized for tuning the regulation of inductor current by limiting the reference current based on the available power. We employ one more fuzzy regulator for voltage-specified current to regulate the power and the voltage of the battery controller for V2G

B. Controller for V2G

In the basic operation of dc-dc conversion for V2G, we compare battery bus voltage and reference voltage, then we get an error that is directly fed to the controller, which improves how much power we can provide by comparing it with the energy boxes. Firstly, we identified the maximum and minimum values so that how much power is improved. Here we are comparing the reference of the voltage bus, which is given to the summing block bus voltage, and the reference value, which means that it is coming from a vehicle, so both can be compared with the summing point. So errors are fed to the voltage of the fuzzy controller, i.e., error, battery voltage, and bus voltage. The maximum value of the energy box is directly fed to Imax. So all four are compared with the voltage of the fuzzy controller to find out the bus voltage error. The charger's control system during G2V operations is shown in Fig. 5. Using Park and Clark conversions, grid-like currents are determined and converted to i_{sd} and i_{sq}. A PLL (phase-locked loop) technique can be utilized to determine the phases used during the park conversion [12]. In order to achieve a unity power factor, reference signal values used in PWM are obtained by regulating the electrical currents i_{sd}, and i_{sq} while making sure that the standard of the d-axis electric charge corresponds to zero [13]. The phase shift between the AC-to-DC converter side and the BESS end converter is used to control the DAB. While ensuring that the maximum voltages are greater than the BESS voltages and the battery current is greater than the battery cut-off current, the battery charging process starts in CC mode. Once the BESS voltage reaches its maximum value, the charging switches from the CC method to the CV mode, and the battery current starts to decline until the battery has been completely charged.

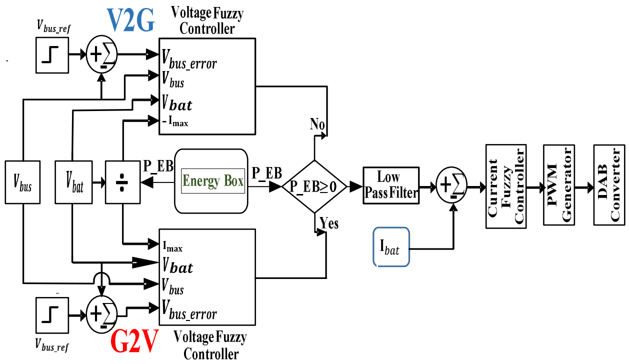


Fig. 4. Shows the controller for the DC/DC converter in the V2G and G2VFig. modes of operation.

C. Controller for G2V

In the controller for G2V in the grid to the vehicle, we are selecting the battery voltage as a reference, and the actual value is given to the summing block to find out the battery error voltage. So in both cases, we are controlling the voltage, but the operating reference is different for V2G and G2V. Both conditions are compared with the energy box if P_EB ≥ 0

If the condition is satisfied, the switch is connected to the yes condition, and vice versa, the battery current is compared with the PI current controller. Then that value is passed through the filter.

D. Active filter operation

When the automobile is linked to the grid but there is no power transfer between the BESS and the electrical grid, the bidirectional charger's effective filter operation, or rather, the AC/DC portion of the charger, occurs. If the BESS has been completely charged or if it is not required to pump electricity into the grid, this may occur. Fig. 5 displays the overall layout along with the controls of the AC-DC converter. A diode bridge rectifier supplying an RL load is used to show the home loads. The instantaneously reactive power theory is the foundation for the control strategy used for the AC-DC converter [14].

The grid voltages ($v_{s,abc}$) and the load currents ($i_{L,abc}$) are transformed using Clarke's transformation $v_{s,\alpha}$, $v_{s,\beta}$, $i_{L,\alpha}, i_{L,\beta}$. These four signals are used to calculate the instantaneous active power p_L and reactive power q_L, using equations (2) and (3):

$$p_L = v_{s,\alpha} i_{L,\alpha} + v_{s,\beta} i_{L,\beta} \quad (2)$$

$$q_L = v_{s,\alpha} i_{L,\beta} - v_{s,\beta} i_{L,\alpha} \quad (3)$$

The determination of a reference active and reactive power (p_{ref} and q_{ref}) involves the utilization of the voltage across the DC link and the magnitude of the grid voltages. Subsequently, equation (4) is employed to derive the reference currents, , $i_{\alpha,ref}$ and $i_{\beta,ref}$ which are then utilized for generating the pulse width modulation (PWM) signals of the six switches that are needed, $T_{1,\ldots,}T_6$

$$\begin{bmatrix} i_{\alpha,ref} \\ i_{\beta,ref} \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p_{ref} \\ q_{ref} \end{bmatrix} \quad (4)$$

Note that the DAB switches remain open during the active filter operation since the DC/DC converter and the battery are not used.

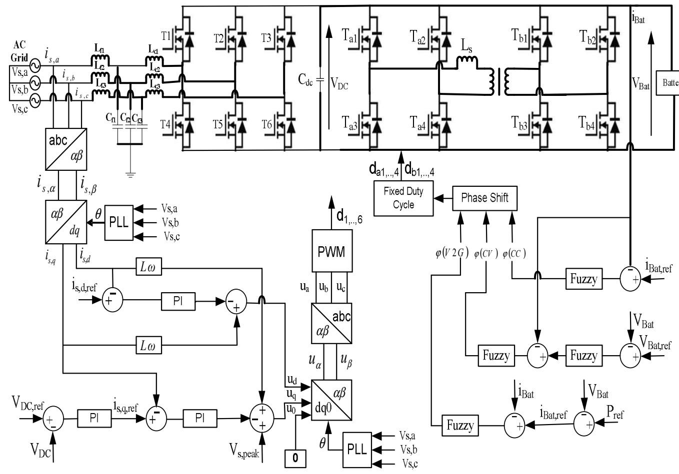


Fig. 5. Bidirectional charger control circuit for V2G and G2V operation.

IV. FUZZY LOGIC CONTROLLER

Fuzzy logic uses "degree of truth" rather than "true" or "false" in its computational logic. Instead of just 0 and 1, it has a range of values between those two extremes. Fuzzy logic takes in information, organizes it into a set of approximate facts, and then, when certain thresholds are exceeded, produces a new set of outcomes. The use of fuzzy logic has several benefits over other types of controllers due to its simplicity, cheap cost, and ability to be designed without the need for a mathematical model. There are several commercial and domestic uses for fuzzy logic. There are four main parts to a fuzzified, inferential, rule-based, and defuzzified fuzzy logic control system. DC voltage error (e) and change in error (ce) are inputs to the fuzzy logic controller that translate the input signal into fuzzy values. with the aid of belonging to a linguistic category.

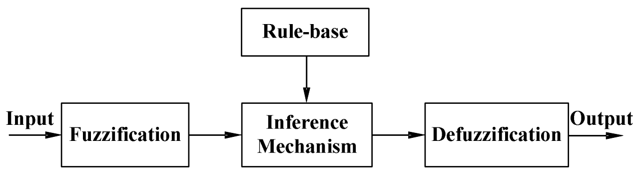


Fig. 6. Fuzzy logic controller block diagram

In knowledge base data for linguistic description, fuzzy information applies a set of control rules to convert the input signal into fuzzified output.

A. Rules of Fuzzy Controller

The rules are based on common knowledge about systems and what should be done if system output decreases or increases, depending on the condition that the duty cycle will decrease when the output voltage is higher than the reference voltage and increase if the output voltage is lower than the reference voltage.

TABLE II. RULES OF THE FUZZY CONTROLLER

ΔE/E	N	Z	P
N	**PB**	**PS**	**ZE**
Z	**PS**	**ZE**	**NS**
P	**ZE**	**NS**	**NB**

AND operator is used for rule bases in logical operators. Six linguistic variables are used for error and change in error. NB: Negative Big; NM: Negative Medium; NS: Negative Small; Z: Zero; PB: Positive Big; PM: Positive Medium; PS: Positive Small.

V. RESULTS AND DISCUSSION

A. System Specifications

The system parameters that are considered for the analysis of the dual active bridge converter shown in Figure 2 are tabulated in Table 3.

TABLE III. SYSTEM PARAMETERS FOR ANALYSIS

S. No	Parameter	Value
1	Input Dc Voltage ($V1$)	325 V
2	Load Power	2300W
3	Load Voltage ($V2$)	108V
4	Transformer turns ratio (*n:1*)	2:1
5	Switching frequency(F_S)	20kHz
6	Energy transfer inductance (L)	$7.6\mu H$
7	Capacitor (C)	10mF
8	Maximum Power	460W

The control strategy described in Section 3.1 is implemented on an isolated dual-active bridge converter using MATLAB. Simulink and various waveforms are presented. Figs. 7 and 8 depict the simulation outcomes for voltage, current, and power at the battery packs and DC bus, along with the state-of-charge (SoC) of the batteries. The verification of dynamic current modifications is demonstrated in Figs. 7 and 8 for each power reference. The voltage levels remain stable and align with the expected values, particularly for the DC bus.

The utilization of two parallel Li-ion battery packs, each with a nominal voltage of 36 V, does not result in notable fluctuations in the battery voltage. The battery pack exhibits a commendable capacity and is capable of sustaining its power output without experiencing any peak power for a duration exceeding one minute. The proposed approach is applicable to other battery chemicals as well.

The Pref levels were intended to test the charger's changing behavior with a range of power levels while staying within the limits of the smaller system. Figs. 9 and 10 show the transient behavior from 0 to 460W in 0.5 seconds. The setup can go from 0 to PMax in 0.5 s, even if the control and acquire methods are only implemented in the actual time processor, which has a slower reaction time. For both G2V (modulated rectifier) and V2G (inverter) modes of operation, the corresponding AC and DCBUS voltages as well as current curves are shown in Figs. 11 and 12, respectively. Each of the modes may be tested at two different arbitrary levels of power to ensure they are working properly. The acquired power levels show that the parameters for G2V and V2G operations have been correctly established. Due to the tiny time slot of the applied power pattern and the aforementioned qualities of the Li-ion simultaneous battery pack, the SoC also displays a narrow development in both states. For a 460W power level, the scenario when the batteries' SoC approaches 100% is shown in Fig. 9's current with Fig. 10's power and the SoC, demonstrating the right power reference and the accompanying lower filling current value based on SoC development. To avoid damaging the battery, a specific battery regulator will make adjustments to the charge rate when the SoC fast hits 100%. Figs. 9 and 10 show how the battery's power consumption decreases as a function of the system on a chip (SoC).

Fig. 12 enables us to verify that for each case previously presented in Fig. 11, the power factor achieved is practically one and the THD results are low. Thus, this charger presents a low PQ impact on the interconnection point, which lies within the international standards (voltage THD < 5% and current THD < 8%) [15].

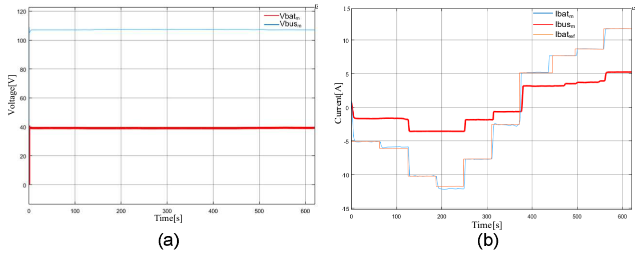


Fig. 7. (a)Voltage and (b)current values obtained in the DAB for the full profile.

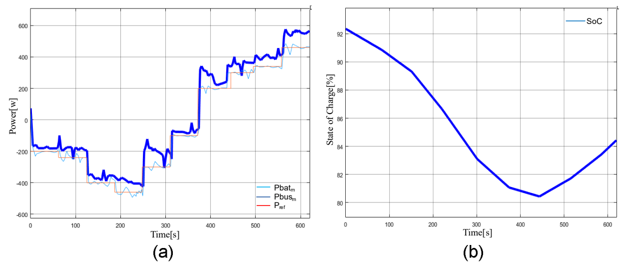


Fig. 8. (a)Full charger power profile and (b) corresponding battery SoC evolution.

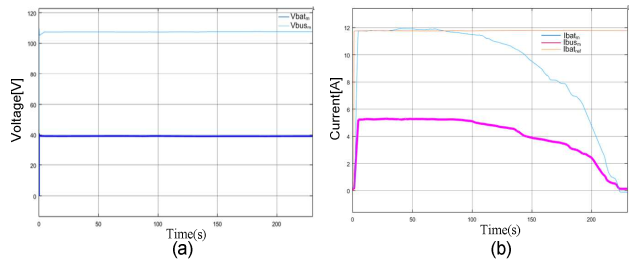


Fig. 9. Absorbed battery (a) voltage and (b). current evolution 100% soc.

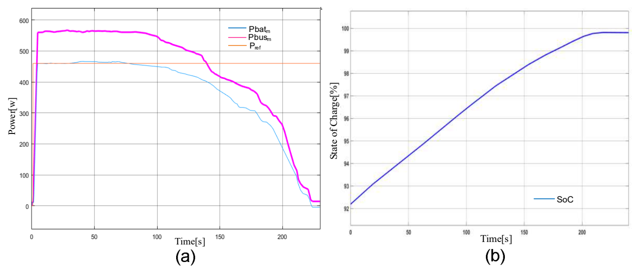
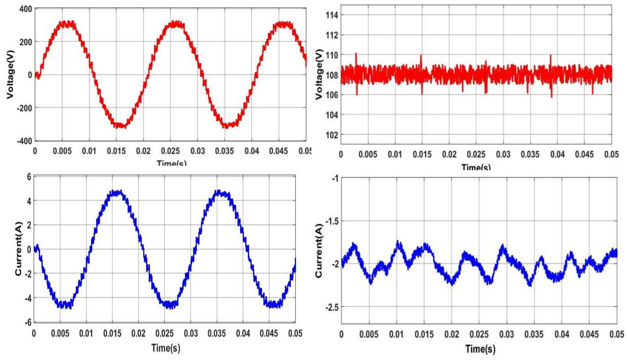
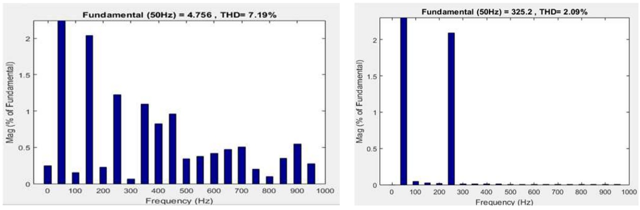


Fig. 10. Charging (a) power profile and (b) corresponding battery SoC evolution for 460 W.



(a) (b)

Fig. 11. Inverter voltage and current curves for (V2G mode). (a) AC side and (b) *DC bus* side.



(a) (b)

Fig. 12. AC/DC converter THD analysis for inverter (V2G mode). (a) Current THD and (b) Voltage THD.

VI. Conclusions

The research discussed here offers a simple and practical bidirectional plug-in electric vehicle (or stationary battery) charger architecture that may improve the possibilities of combined storage and automated EMS operation in a home environment, to the advantage of both end-users and utilities and system operators. There is also an emphasis on the PEV's function as a load or power source. This charger may be set to charge or discharge at any power level supplied by the EMS, rather than only the greatest amount of power level to maximize efficiency. It is advantageous to incorporate power allocation and setting up for all home loads due to the charging device's power flexibility and bidirectionality, as its power electronics architecture permits conducting charge and discharge actions at various power levels. Users need to just specify when they must have the vehicle, and the EMS will charge it (or even sell excess energy back to the grid) in the most efficient way feasible, taking into account all other load demands and grid indications of prices. A DSP-based, scaled-down experimental setup has been used to validate the suggested charger. The offered examples predict a satisfactory relationship between the charger and an independent EMS, with the required power limitations met and the PQ effect on the coupling point falling within the bounds of international guidelines across both G2V and V2G modes of operation. This approach is flexible enough to be used at greater power levels (single phase), and it works with any kind of battery chemistry regardless of the voltage, current, or depth of discharge constraints it may have.

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