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On-Board Electric Vehicle Battery Charger with Enhanced V2H Operation Mode

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***Abstract*—This paper proposes an on-board Electric Vehicle (EV) battery charger with enhanced Vehicle-to-Home (V2H) operation mode. For such purpose was adapted an on-board bidirectional battery charger prototype to allow the Grid-to-Vehicle (G2V), Vehicle-to-Grid (V2G) and V2H operation modes. Along the paper are presented the hardware topology and the control algorithms of this battery charger. The idea underlying to this paper is the operation of the on-board bidirectional battery charger as an energy backup system when occurs a power outages. For detecting the power outage were compared two strategies, one based on the half-cycle rms calculation of the power grid voltage, and another in the determination of the rms value based in a Kalman filter. The experimental results were obtained considering the on-board EV battery charger under the G2V, V2G, and V2H operation modes. The results show that the power outage detection is faster using a Kalman filter, up to 90% than the other strategy. This also enables a faster transition between operation modes when a power outage occurs.**

Keywords*—Backup Power Supply, Bidirectional Battery Charger, Electric Vehicles, Kalman Filter, Enhanced Vehicle-to-Home (V2H)

I. Introduction

Electric Vehicles (EVs) are being introduced as a new promising transport in different countries around the world [1–3]. As example, for the US it is foreseeable that EVs will represent 64% of the light vehicles sales in 2030 [4]. As consequence of this new paradigm, new challenges and opportunities will arise. The main challenge is related with the regulation of the battery charging process from the power grid [1], [5]. This represents a challenge because will be required a significant amount of energy during the charging process and power quality problems cannot be neglected in such scenario [6–8]. On the other hand, the main opportunity that must be addressed is related with the capacity of these vehicles to store a significant amount of energy. Thereby, besides the battery charging process, identified as Grid-to-Vehicle (G2V) [9], the EVs can also be used to produce reactive power [10] and to deliver part of energy stored in the batteries back to the power grid. This process is identified as Vehicle-to-Grid (V2G) [11–14]. These challenges and opportunities are more relevant considering the advances in smart grids and micro-grids [15], where these vehicles will be a key technology [16], [17]. In this scenario, also mobile information systems for EVs will be an important field to the electric mobility development [18].

This paper proposes an opportunity to the EVs operation that is associated with the Vehicle-to-Home (V2H) paradigm [19]. This opportunity consists in use the EVs as a home backup power supply. Therefore, is proposed an enhanced V2H operation mode. The operation of the EVs as voltage source was already proposed by NISSAN through the "LEAF-to-Home" system. This system uses a dedicated "EV Power Station" to supply home loads [20]. This type of opportunity for smart homes will be a key technology for the expansion of electric mobility sector in smart grids [21], [22]. According to NISSAN, this initiative is a contribution to a zero-emissions society. The main drawback of the "LEAF-to-Home" is that it can only be used in the place where the equipment is installed. In order to avoid this drawback, in [23] is presented an on-board bidirectional battery charger capable to operate as G2V, V2G and V2H in the place where the EV is parked. As presented, through the operation as V2H, the EV can provide energy to any load connected to the EV in island mode. However, it has not the capability to operate as backup power supply. This paper joins the main benefits of aforementioned systems, i.e., the EV can be used as backup power supply at home and supply loads in isolated mode. This opportunity is more relevant taking into account that private vehicles are parked at home between 9 p.m. and 6 a.m. [24].

The most common backup power supply is the Uninterruptible Power Supply (UPS), which can be on-line or off-line [25]. Despite the benefits of the on-line UPS in protect the loads continuously, in most of the situations, the off-line UPS is suitable to protect the loads during power outages. Therefore, this paper proposes the use of an on-board EV battery charger as backup power supply operating like an

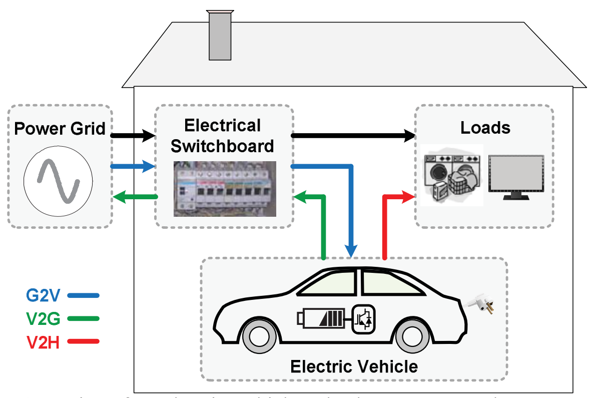

Fig. 1. Operation of an Electric Vehicle as backup power supply.

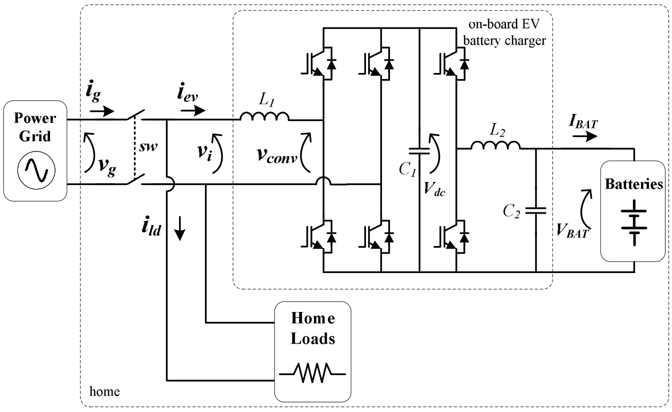

Fig. 2. Topology of the battery charger and the setup that was used to obtain the experimental results presented in the paper.

off-line UPS. The EV on-board battery charger are capable to perform a smooth transition between operation modes when a voltage sag or a power outage is detected. Fig. 1 shows the use of EVs as backup power supply.

II. On-board EV Battery Charger Prototype

Aiming to assess the operation of EVs as backup power supply it was adapted a bidirectional EV battery charger prototype to operate in accordance with the proposed enhanced V2H operation mode. The topology of this battery charger and the setup that was used to obtain the experimental results is presented in Fig. 2.

The battery charger that was used is divided in two power stages: one ac-dc front-end power converter; and one dc-dc non-isolated power converter. During the operation as G2V the ac-dc converter operates as active rectifier with sinusoidal current and unitary power factor, and the dc-dc adjusts the current and voltage to charge the batteries. In the V2G the ac-dc converter operates as inverter with sinusoidal current, and the dc-dc converter discharge the batteries with constant current. During the V2H mode, the ac-dc converter operates as controlled voltage source and the dc-dc converter is used to maintain the dc-link regulated. In order to synchronize the ac-dc converter with the power grid fundamental voltage was used a single-phase Phase-Locked Loop (PLL) [26]. From this algorithm is obtained a sine-wave signal *pll* that corresponds to the fundamental component of the power grid voltage. This signal is used to obtain the current reference for the G2V and V2G operation modes. It can also be used to obtain the voltage reference in the V2H operation mode. Therefore, PLL is the first algorithm implement in the control.

A. Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G)

The control of the ac-dc and dc-dc converters is similar during the G2V and V2G operation modes. In both of the modes, the dc-link is regulated by the ac-dc converter through a Proportional Integral (PI) controller. Also in both operation modes the current reference to the ac-dc converter is function of the power to charge (G2V) or discharge (V2G) the batteries. The digital current reference in discrete time, at each instant *k*, is expressed as:

$$i_{ev}^*[\mathrm{k}] = \frac{P_{DC}^*[k] + I_{BAT}[k]\, V_{BAT}[k]}{V_g[k]^2}\, pll[k]\,, \quad (1)$$

where, P_{DC}^* is the reference obtained from the PI to regulate the dc-link, V_g is the rms value of the power grid voltage, pll is the output of the PLL, and I_{BAT} and V_{BAT} are the current and voltage in the batteries, respectively. During the G2V operation mode the current I_{BAT} and the voltage V_{BAT} are positive, which results in a positive current reference. On the other side, during the V2G operation mode the current I_{BAT} is negative and the voltage V_{BAT} remains positive, which results in a current reference in phase opposition with the power grid voltage.

In order to the ac-dc converter produce a voltage that results in the desired current (i_{ev}^*) was used a predictive current control. Taking into account that the ac-dc converter has a full-bridge structure, the reference that is compared with the 20 kHz triangular carrier is expressed as:

$$\begin{aligned} v_{conv}[k] = v_g[k] - \frac{L_1}{T}\,(2i_{ev}^*[k] - i_{ev}^*[k-1] \\ - i_{ev}[k] - i_{ev\_error}[k-1])\,, \end{aligned} \quad (2)$$

where, *k* denotes the actual sampling and *k-1* the previous sampling. In this current control was used a unipolar PWM strategy. To mitigate the dead-time effects in the produced voltage was used a strategy that consists in add a constant value to the voltage reference ($v_{conv}[k]$) during the positive semi-cycle, and subtract the same value during the negative semi-cycle. This value is calculated in function of the carrier amplitude and the delay introduced by the dead-time. To charge the batteries (G2V operation mode) in accordance with the batteries manufacture recommendations, the dc-dc converter requires two control strategies. The first consist in charge the batteries with constant current according to (3). The second consist in charge the batteries with constant voltage according to (4).

$$\delta_{buck}^*[k] = V_{BAT}[k] - \frac{L_2}{T}\,(I_{BAT}^*[k] - I_{BAT}[k])\,. \quad (3)$$

$$\delta_{buck}^*[k] = \frac{V_{BAT}^*[k]}{V_{dc}[k]}\,. \quad (4)$$

In order to discharge the batteries (V2G operation mode) with constant current is required a single control strategy. In this case the dc-link voltage is regulated by the ac-dc converter and is injected a current with variable amplitude (that is function of the batteries discharging current) in the power grid. In order to maintain the battery discharging current constant, the duty-cycle for the dc-dc converter is expressed by:

$$\delta_{boost}^*[k] = 1 - \frac{V_{BAT}[k]}{V_{dc}[k] \;+\; \frac{L_2}{T}\,(I_{BAT}^*[k] - I_{BAT}[k])}\,. \quad (5)$$

B. Vehicle-to-Home (V2H)

In the V2H operation mode the ac-dc converter is used to produce a voltage. The duty-cycle (δ_{ac-dc}) at each instant k is expressed as:

$$\delta_{ac-dc}{}^{*}[k] = \frac{v_i{}^{*}[k]}{V_{dc}[k]}. \quad (6)$$

Also in this operation mode was used the aforementioned strategy to mitigate the effect of the dead-time in the produced voltage. In this mode the dc-dc converter is used to regulate the dc-link voltage, where the duty-cycle for the dc-dc converter is expressed by:

$$\delta_{boost}{}^{*}[k] = 1 - \frac{v_{BAT}[k]}{V_{dc}{}^{*}[k]}. \quad (7)$$

III. Algorithms to Detect Power Outages

In order to detect power outages, several algorithms can be implemented. Nevertheless, in the scope of this paper were analyzed and obtained experimental results with two algorithms. The first is based on the traditional calculation of the rms value and the second is based on the determination of the rms value using a Kalman filter. For both modes it was defined that occurs a voltage sag when the rms value is below 85% of its nominal value (standard EN 50160). These two control algorithms are described in detail. In the scope of this paper was assumed that when is detected a power outage the switch *SW*, represented in Fig. 2, is open and the home is disconnected from the power grid. When the voltage is restored the switch *SW* is closed, however, only after a delay necessary to the complete synchronization of the PLL with the power grid voltage. Both situations are illustrated in Fig. 3.

A. Traditional RMS Value Calculation

A simple algorithm to detect voltage sags is based in the traditional calculation of the rms value. This method consists in calculate the rms value during one cycle of the power grid voltage and detect when it falls beyond a predefined threshold. The rms value is calculated according to:

$$V_{G(RMS)}(t) = \sqrt{\frac{1}{T}\int_0^T v_g{}^2(t)\,dt}\,, \quad (8)$$

and the digital implementation is:

$$V_{G(RMS)}[k] = \sqrt{\frac{1}{N}\sum_{k=1}^{k=N} v_g{}^2[k]}\,, \quad (9)$$

where, N is the number of samples used in each cycle of the power grid voltage. Aiming to speed up the detection of changes in the rms value, it can be calculated using only half-cycle of the power grid voltage and using a sliding average across the square values of the power grid instantaneous values. The sliding sum used in the sliding average is calculated using:

$$sum[k] = sum[k-1] - v_g{}^2[k-N] + v_g{}^2[k]\,, \quad (10)$$

and the rms value of the power grid voltage (half-cycle) is calculated using:

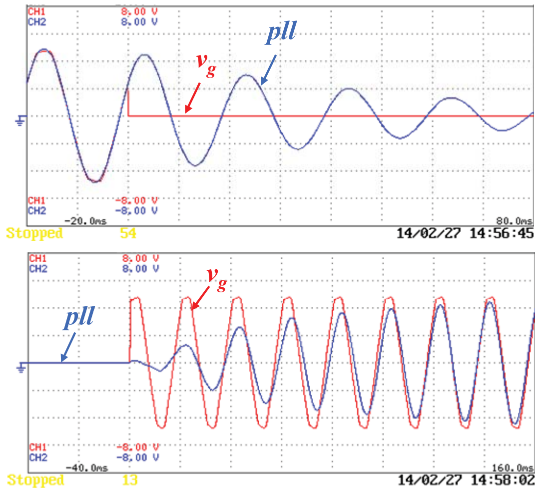

Fig. 3. Experimental results: Synchronization of the PLL with the power grid voltage before and after a power outage.

$$V_{G(RMS)}[k] = \sqrt{2\,\frac{sum[k]}{N}}. \quad (11)$$

Fig. 4 shows the power grid voltage (v_g), the output voltage of the ac-dc converter (v_i), and the rms value ($V_{G\,(RMS)}$), using this method and the limit of 85% of the rms nominal value (230 V). As shown, the power outage occurs a little after the beginning of the negative semi-cycle, and were required 3.3 ms to detect the power outage.

B. RMS Value Estimation Based on Kalman Filter

The algorithm for estimating the rms values using the Kalman filter is more complex than the traditional method presented before, however in most of the situations is faster to detect variations in the rms value. The Kalman filter used in this paper is based in the estimation of the instantaneous amplitude of the fundamental component of the power grid voltage and its quadrature signal, denoted as $s[k]$ and $q[k]$, respectively. The Kalman filter is based in two distinct set of equations: Prediction and Correction [27]. Assuming that there are only Additive White Gaussian Noise (AWGN) in the measured signal, it is possible establish the following estimation state model:

$$\hat{x}[k] = A\,\hat{x}[k-1]\,, \quad (12)$$

where, $\hat{x}[k]$ is the estimation state model that comprises the in-phase and quadrature signals, where $x[k]$ is defined as:

$$x[k] = \begin{bmatrix} s[k] \\ q[k] \end{bmatrix} = \begin{bmatrix} V_g \sin(\omega kT) \\ V_g \cos(\omega kT) \end{bmatrix}, \quad (13)$$

and A is the state transition matrix defined by:

$$A = \begin{pmatrix} \cos(\omega T) & \sin(\omega T) \\ -\sin(\omega T) & \cos(\omega T) \end{pmatrix}, \quad (14)$$

where, ω is the angular frequency of the power grid voltage and T is the sampling period. The estimation of the process covariance is defined as:

$$\hat{P}[k] = A\,P[k-1]\,A^T + Q\,, \quad (15)$$

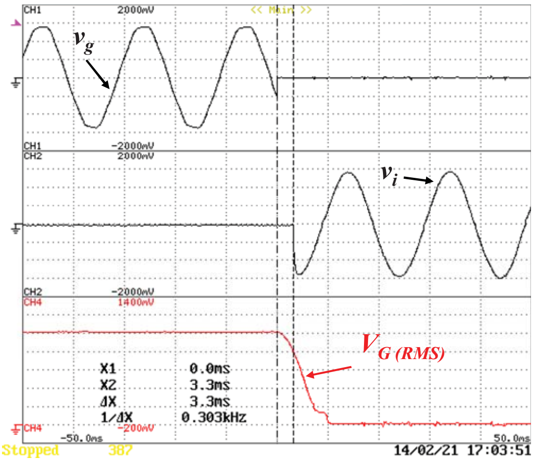

Fig. 4. Experimental results: Power grid voltage rms value estimation using a traditional method.

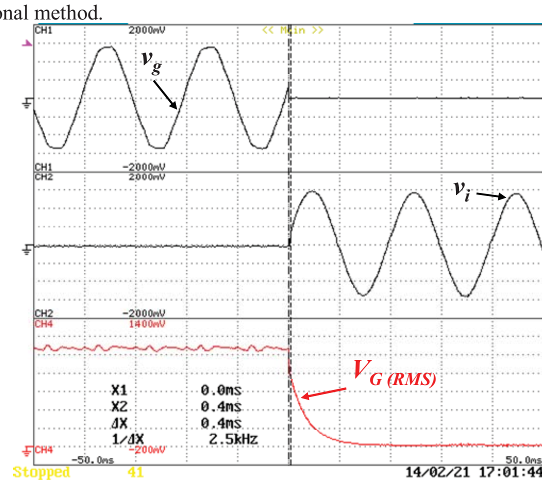

Fig. 5. Experimental results: Power grid voltage rms value calculation using a Kalman filter.

where, Q is the covariance matrix. Equations 10 and 13 are related with the set of Prediction equations. In the set of Correction equations the first step is determine the optimal Kalman gains, which improves the estimation at each sampling frequency. The optimal Kalman gain matrix is described by:

$$k[k] \;=\; \hat{P}[k]\, H^T\, (H\, \hat{P}[k]\, H^T \;+\; R)^{-1}\,, \tag{16}$$

where, $\hat{P}[k]$ is the estimation of the process covariance, R is represented by a scalar, and H is defined as:

$$H = [1 \quad 0]\,. \tag{17}$$

With the information obtained from the equation above the state estimation can be updated by:

$$\hat{x}[k] = \hat{x}[k-1] \;+\; K\,(v_i - H\,\hat{x}[k-1])\,, \tag{18}$$

and the covariance can be updated by:

$$P[k] \;=\; (I - KH)\,\hat{P}[k]\,. \tag{19}$$

The estimation of the rms value of the power grid voltage is given by:

$$\widehat{v_g}_{RMS}[k] = \sqrt{\frac{\hat{s}[k]^2 + \hat{q}[k]^2}{2}}\,. \tag{20}$$

In this method, after estimate the rms value of the power grid voltage, when is identified that this value is below 85% of its nominal value, it is assumed a power outage and the EV must operate in V2H. Fig. 5 shows the power grid voltage (v_g), the output voltage of the ac-dc converter (v_i), and the rms value ($V_{G\,(RMS)}$). In this situation, the power outage occurs a little after the beginning of the positive semi cycle, and was required 0.4 ms to detect the power outage. It must be referred that, although the detection moments are different, the Kalman filter method is faster than the traditional method.

IV. Battery Charger Operation Modes

The battery charger prototype was submitted to a set of operation tests, mainly focusing the V2H operation mode as a backup power supply. These tests were performed with the battery charger connected to the power grid at 115 V. The dc-link voltage was regulated to 200 V, and was used a set of 12 sealed 12 V 33 Ah Absorbed Glass Mat (AGM) batteries connected in series in order to perform 144 V. To simulate the home loads were used resistances with the total value of 52 Ω. The aforementioned digital control algorithms were implemented in a DSP TMS320F28335 using a sampling frequency of 40 kHz. Fig. 6 shows the laboratory workbench used to validate the proposed V2H operation mode and to obtain the experimental results, which were registered with a *Yokogawa DL708E* digital oscilloscope.

A. Grid-to-Vehicle and Vehicle-to-Grid

As aforementioned, during the G2V operation mode the energy flows from the power grid to the batteries and in the V2G in the opposite way. In both operation modes, in the ac side, the current is sinusoidal. Fig. 7 shows the power grid voltage and the EV battery charger current for the G2V (Fig. 7 (a)) and V2G (Fig. 7 (b)) operation modes.

B. Vehicle-to-Home

During the V2H operation mode the power flows from the batteries to the home loads. Besides the V2H operation mode, in which the EV battery charger is used as backup power supply, it can also be used to provide energy to any load connected to the EV in an island mode in the place where the EV is parked.

C. Enhanced Vehicle-to-Home

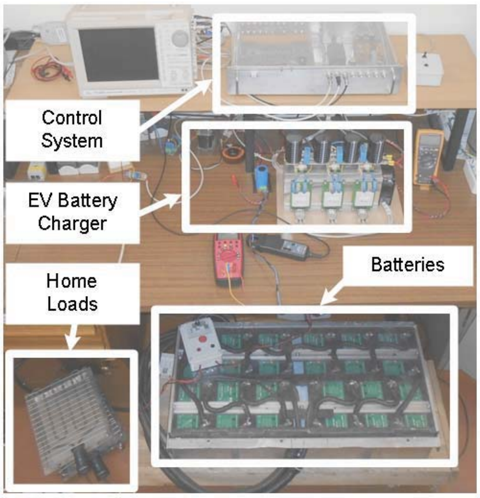

Fig. 6. Laboratory setup used to obtain the experimental results.

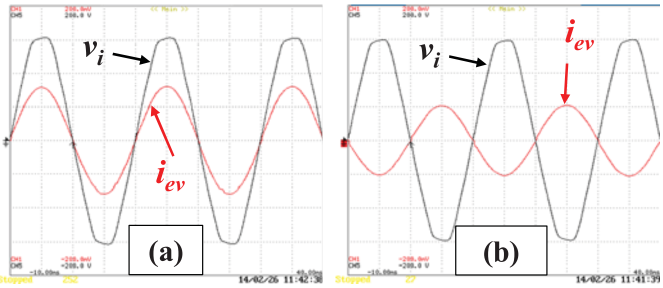

Fig. 7. Power grid voltage (50 V / div) and current (5 A / div) in the battery charger: (a) During G2V operation mode; (b) During V2G operation mode.

During the enhanced V2H operation mode as backup power supply, the power flows from the batteries to the home loads. In this operation mode the ac-dc converter produces a sine-wave voltage and the current waveform is determined by the loads, and the dc-link voltage is regulated by the dc-dc converter. Considering that this operation mode can be triggered when the EV is only plugged in the home, or when it is plugged and in charge, this item is separated in these two distinct cases.

1) Electric Vehicle Plugged but not in Charge

In the enhanced V2H operation mode were obtained experimental results with the traditional rms voltage calculation and using a Kalman filter. Fig. 8 (a) shows the voltage in the loads and the current in the battery charger using the traditional rms voltage calculation. As shown, to detect when the rms value decreases above 85% of its nominal value were required 3.8 ms. On the other hand, Fig. 8 (b) shows the voltage in the loads and the current in the battery charger when is used the Kalman filter to detect the power outage. In this case, to detect when the rms values decreases above 85% of its nominal value were required only 0.3 ms.

2) Electric Vehicle Plugged and in Charge

Also in the enhanced V2H operation mode were obtained experimental results, when the EV is charging, with the traditional RMS voltage calculation and using a Kalman filter to estimate the rms value. Fig. 9 shows the voltage in the loads and the current in the battery charger using the traditional rms

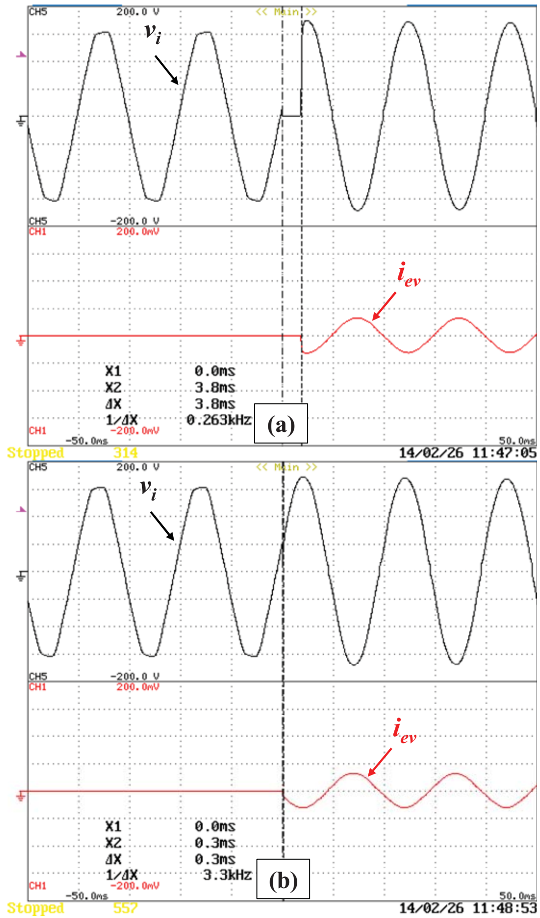

Fig. 8. Voltage (50 V / div) in the load and current (5 A / divV) in the battery charger when the EV is plugged in but not in charge, when a power outage occurs: (a) Using a traditional RMS value calculation; (b) Using a Kalman filter do estimate the rms value.

voltage calculation and a Kalman filter, respectively. As shown, to detect when the rms values decreases above 85% of its nominal value were required 5.4 ms and 0.3 ms, respectively. As shown during the battery charging process the current is in phase with the voltage, and after the power outage detection is in phase opposition.

V. Conclusions

This paper presents a study conducted in order to assess the utilization of an on-board Electric Vehicle (EV) battery charger operating as a backup power supply. The hardware topology and the control algorithms of the developed bidirectional battery charger prototype are described along the paper. In the scope of this paper it was defined that a power outage occurs when the rms value of the power grid voltage is 85% of its nominal value. To determine the rms value were compared two strategies: one based on the traditional rms calculation of half-cycle of the power grid voltage, and another based on a Kalman filter. The experimental results obtained show that using a Kalman filter the rms value detection is faster (typically 90%) than with the traditional method. The operation of the battery charger was demonstrated through experimental results in Grid-to-Vehicle (G2V), Vehicle-to-Grid (V2G), and enhanced Vehicle-to-Home (V2H) operation modes. For the transition to the V2H operation mode two distinct cases were

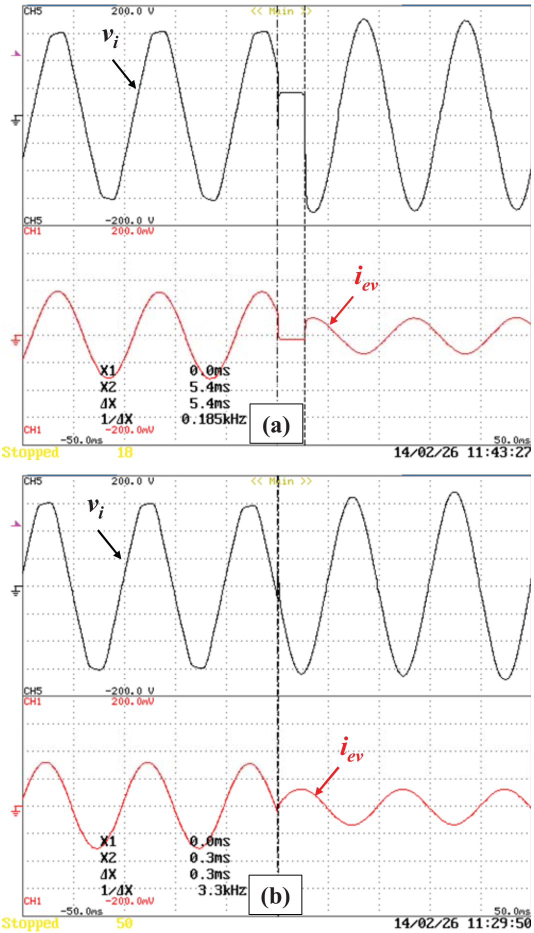

Fig. 9. Voltage (50 V / div) in the load and current (5 A / div) in the battery charger when the EV is plugged in and in charge, when a power outage occurs: (a) Using a traditional RMS value calculation; (b) Using a Kalman filter to estimate the rms value.

considered: when the EV was only plugged in to the home, and when the EV was plugged in and in charge (operating in G2V mode).

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