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Research Article

Noninvasive Vehicle-to-Load Energy Management Strategy to Prevent Li-Ion Batteries Premature Degradation

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Today, electric vehicles available in the market aspire to offer different connections to the end user, for instance, Vehicle to Grid (V2G), Vehicle to Building (V2B), Vehicle to Home (V2H), Vehicle to Vehicle (V2V), and Vehicle to Load (V2L), among others. Notwithstanding these versatility options toward the development of a sustainable society, the additional degradation of the energy storage systems once those operate in extra discharge modes is inevitable. Therefore, in this paper, an energy management strategy (EMS) which operates autonomously and noninvasively as an additional layer to the battery management system (BMS) is proposed. The EMS limits the current flow avoiding high and low temperatures, low state of charge (SoC), high deep of discharge (DoD), noncentered DoD around an optimal SoC point, and high charge and discharge rates. The proposed EMS is evaluated by long-term simulations with a Li-Ion battery degradation model and realistic weather conditions, during standard driving cycles including the V2L operation. The effectiveness and simplicity of tuning of the proposed EMS allow estimating and increasing the life expectancy of the Li-Ion battery bank, by limiting the energy used for V2L operation.

1. Introduction

Nowadays, the electric vehicle (EV) is a forced reality more than a futurist conception mostly, due to the high pollution levels and the increasing fossil fuel prices [1–3]. Beyond the difficulties in the generation of green energy that must satisfy an exponentially growing demand [4–8], a future is forecasted in which a vehicle can bring electric power to places or situations wherever it is not available by the usual means. Currently, recognized researchers direct their efforts to the study of technologies and strategies to achieve the smart interaction of an EV with a grid (Vehicle to Grid, V2G, [9]), a building (Vehicle to Building, V2B, [10]), a home (Vehicle to Home, V2H, [11]), another EV (Vehicle to Vehicle, V2V, [12]), and to a lesser extent a load (Vehicle to Load, V2L, [13]) and even improve the power quality ([14–16]). Additionally, some authors consider that V2L is the first approximation to real Vehicle to Everything (V2X) applications, if they act like an independent cluster of generations [17, 18]. V2L capability will enable the EV to replace the usual electric generator to power an isolated load [17] and there is no coordination with the grid system operator, but there is basic local communication from EVs to the loads [18]; also, several EVs governed by a local coordinator could support a mobile hospital in a Vehicle to Premise (V2P) configuration.

Currently, the science of Li-Ion batteries allows the use of the power bank of the VE to feed point loads (V2L) in addition to extended VE's autonomy. However, it has also been reported that there may be premature degradation ([19–25]) that depends predominantly, to the authors' knowledge, on the temperature, state of charge (SoC), charge and discharge current rate (C-rate), and depth of discharge (DoD) during its usage and in some cases also during its storage. That is, although the State of Health of a battery (SoH) will inevitably decrease due (a) to the number of cycles during its usage (cycling aging) and (b) to its inherent expiration date (calendar aging), the SoH decay rate can be modeled as function of factors such as temperature, SoC, the DoD, and

the C-rate during its regular use as well as the temperature and SoC during storage [18–28].

In other words, preventing model-based battery degradation is not a trivial task, and it usually involves a mechanical/chemical redesign and/or an invasive battery management system (BMS) specific to the device's chemistry and equalization. However, such systems are black-box focused in the charging behavior and very likely not designed to avoid long-term degradation of the battery in a V2L scenario, where extra discharge cycles are introduced. For instance, in [29], a system to collect data from charging sessions has been presented, to correlate with the corresponding EV and some relevant information and evidence of the battery degradation.

An alternative to overcome this difficulty is using an additional layer when the EV operates in V2L. For instance, the authors in [30] introduced a just-in-time strategy from a smart grid perspective (overall cycling) to extend the Li-Ion battery life, benefiting from the storage with low SoC property and a prediction of the EV usage. In such work, the EV energy provided and required in a V2G scenario flows only when possible to avoid premature degradation and such scenario does not include the V2L operation. In other words, unfortunately, this strategy involves a smart grid recharge becoming cluster-dependent, hardly restricts (shutdown) the provided energy, and can leave the vehicle without enough recharging for unusual utilization.

It should be noted at this point that there is very little research into the development of closed-loop control systems to prevent long-term battery degradation in V2L scenarios. For instance, authors in [31] developed a semiempirical Li-Ion battery capacity degradation model and a Battery Energy Storage System to avoid the degradation from the recharge side; in other words, the recharging behavior is optimized to avoid the premature degradation but a V2L discharge scenario is not the aim of such investigation. Additionally, in [32–35] the authors presented devices that can be used in a V2L operation; however, none of them demonstrates the aim to avoid long- term Li-Ion battery degradation.

As can be seen from the previous state of the art review, only some authors have aimed to diminish the degradation of the batteries in V2G scenarios but, for V2L, there is still a lack of energy management systems that allow estimating a priori and regulate the premature degradation of the batteries since the EV acts as a grid-independent generation device. In this paper, a current limiter, energy management strategy (EMS) for a V2L operation layer whose dynamic criteria are based on generic Li-Ion battery degradation mechanisms, is presented. This EMS represents an improvement over V2L and even V2X systems, since it allows establishing a priori the level of additional degradation of the energy storage system based on Li-Ion batteries. This limiter can be easily implemented and tuned for online and on-board operation allowing an independent cluster generation and it is easily tunable. Long-term simulations with accepted degradation models are presented to show the benefit of the proposed controller.

The remainder of this paper is structured as follows. In Section 2 the battery degradation model is presented. In Section 3 the EMS is developed and in Section 4 representative simulations and results are shown, to conclude in Section 5.

2. Degradation Model

Many battery degradation models are encountered in literature depending on the chemistry and modeled variables. Most of these models are semiempirical since actual battery life can be extended to tens of years. Three primary semiempirical models are known as the NREL Model [36], the Wang Model [37], and the MOBICUS Model [38]. These models exhibit the nonlinear electromechanical behavior of degradation in form of calendar and cycling aging whose drivers are Temperature, SoC, C-rate, DoD, and the total extracted energy (Ah throughput) with varying sensitivities to the capacity and power fade.

These models almost coincide to avoid both high and low temperatures, high charge and discharge rates, high DoD, DoD noncentered around an optimal SoC point (50%), and low SoC operation (some authors did not mention all these factors but coincide with the rest).

In particular, the NREL is the most complete battery degradation model found, since it describes that the calendar aging cannot be separated from cycling aging effects, allows for reduced calculation time, and is particularly interesting as it demonstrates an understanding for and incorporates nearly all degradation drivers for cost estimation [27].

In this paper, the model presented in [39] is adopted since it includes the characteristics of the NREL model being the most complete for Li-Ion chemistry and the validation includes realistic load profiles in EV. The discharge voltage is

$$v_d = E_0(T) - K(T)\frac{Q(T_a)}{Q(T_a) - i_t}(i + i_t) + Ae^{-Bi_t} - Ci_t \tag{1}$$

$$V_{batt}(T) = v_d - R(T) * i \tag{2}$$

The charge voltage is

$$v_c = E_0(T) - K(T)\frac{Q(T_a)}{i_t + 0.1Q(T_a)}i - K(T)\frac{Q(T_a)}{Q(T_a) - i_t}i_t + Ae^{-Bi_t} - Ci_t \tag{3}$$

$$V_{batt}(T) = v_c - R(T) * i \tag{4}$$

In Table 1 the nomenclature is presented while

$$E_0(T) = E_{0,ref} + \frac{\partial E}{\partial T}\left(T - T_{ref}\right) \tag{5}$$

$$K(T) = K_{T_{ref}} e^{\alpha(1/T - 1/T_{ref})} \tag{6}$$

$$Q(T_a) = Q\left(T_{a,ref}\right) + \frac{\partial Q}{\partial T}\left(T_a - T_{ref}\right) \tag{7}$$

Table 1: Nomenclature and nominal values (if applicable).

Parameter/variable	Description	Nominal (LiFeMgPO4)	Units
E_0	Constant voltage	12.6	V
E	Exponential zone dynamics	13.1	V
S	Battery mode (0 for discharge, 1 for charge)	-	1
K	Polarization constant	0.5	V/Ah
i	Low frequency current dynamics	-	A
i_t	Extracted capacity	-	Ah
Q	Maximum battery capacity	40	Ah
T_{ref}	Nominal battery temperature	20	C
T	Cell/internal temperature	-	C
T_a	Ambient temperature	-	K
$\frac{\partial E}{\partial T}$	Reversible voltage temperature coefficient	-	V/K
α	Arrhenius rate constant for the polarization resistance	0.5	1
β	Arrhenius rate constant for the internal resistance	0.5	1
$\frac{\partial Q}{\partial T}$	Maximum capacity temperature coefficient	-	Ah/K
C	Nominal discharge curve slope	0.016	V/Ah
R_{th}	Thermal resistance, cell to ambient	0.6411	C/W
t_c	Thermal time constant, cell to ambient	4880	s
DoD	Depth-of-Discharge of battery	-	1
DoD_{ref}	Maximum DoD recommended for SoC centering	50	1
SoC	State-of-Charge of battery	-	1
SoC_{ref}	Minimum SoC for V2L operation	50	1
H	number of cycles	-	1
ψ	Exponent factor for the DoD	0.5	1
Ψ	Arrhenius rate constant for the cycle number	0.5	1
I_d	Average discharge current during a half cycle duration	20	A
I_c	Average charge current during a half cycle duration	20	A
γ_1	Exponent factor for the discharge current	0.12	1
γ_2	Exponent factor for the charge current	0.14	1
w_1	Weight for allowed temperature	10	1
w_2	Weight for allowed SoC	1	1
w_3	Weight for allowed DoD	1	1
C-rate	Charge and discharge current	-	Ah

$$R(T) = R_{T_{ref}} e^{\beta(1/T - 1/T_{ref})} \tag{8}$$

$$T(t) = \mathscr{L}^{-1}\left(\frac{\left(\left(E_0(T) - V_b(T)\right) i + (\partial E/\partial T)\, iT\right) R_{TH} + T_a}{1 + t_c s}\right) \tag{9}$$

The aging effect due to cycling on the battery capacity is

$$Q(n) = Q_{BoL} - \epsilon(n)\left(Q_{BoL} - Q_{EoL}\right) \tag{10}$$

where

$$n = kT_h \tag{11}$$

for k cycles,

$$\epsilon(n) = \epsilon(n-1) + \frac{0.5}{N(n-1)\left(2 - \left(DoD(n-2) + DoD(n)\right)/DoD(n-1)\right)}, \tag{12}$$

and

$$N(n) = H\left(\frac{DoD(n)}{100}\right)^{-\psi} e^{-\Psi(1/T_{ref} - 1/T_a(n))} I_d^{-\gamma_1}(n)\, I_c^{-\gamma_2}(n). \tag{13}$$

3. Energy Management Strategy

The EMS of this paper is intended to limit the current flow during V2L operation based on avoiding

(1) High and low temperatures

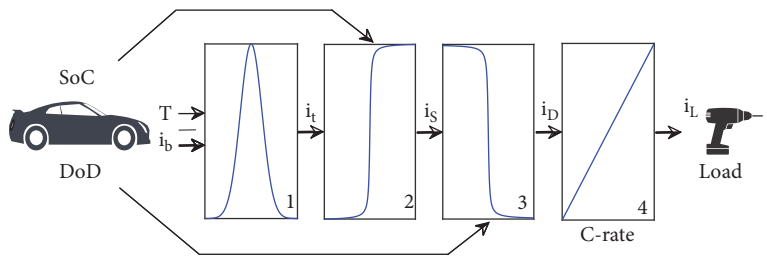

Figure 1: EMS block diagram.

(2) Low SoC

(3) High DoD

(4) DoD noncentered around an optimal SoC point

(5) High charge and discharge rates

These previous generic rules are inferred from previous works and they are semiempirical. In this work continuous semiempirical strategies are designed to comply with the rules as described separately in the following subsections. A continuous behavior is adopted in order to be implemented in either an analog or a digital platform. In Figure 1 a block diagram of the overall EMS of this paper is shown. The sequence of the first three rules of this cascade controller/limiter can be interchanged since they only have a multiplicative (reduction) effect and the last rule must be at the end to smooth high current demand rates that can degrade the battery. However, it is recommended to implement all of the rules in a real application since a single degradation mechanism is enough to deteriorate the battery prematurely.

3.1. High and Low Temperature. A Fuzzy-like membership function is proposed to limit the current throughput depending on the temperature; this means it is undesirable to operate in V2L when the temperature is either too low or too high ([22, 27, 28, 36–38]). A Gaussian function is selected to continuously limit the battery current i_b in function of the battery's temperature:

$$i_t = i_b e^{-(T-T_{ref})^2/w_1^2} \tag{14}$$

In Figure 1 this rule is depicted in block 1; the output current i_t, fed by the EV's battery (i_b), is limited by the temperature T.

Function (14) can be easily tuned by selecting a weight w_1 which is the width of the Gaussian function and T_{ref} is the nominal operation temperature. The weight $w_1 = 10$ means approximately a 60% reduction for $T_{ref} \pm w_1$ with $T_{ref} = 30$. In Figure 2 the temperature membership function with the mentioned values is depicted.

3.2. Low SoC. A Fuzzy-like membership function is proposed to limit the current throughput depending on the SoC. While the optimal SoC point is suggested to be 50%, it is recommended to avoid a low SoC operation ([22, 27, 28, 36–38]) and preferably maintain a high SoC level for further usage. A sigmoid function is selected to continuously limit the current from the temperature limiter (14), as depicted in block 2 of Figure 1:

$$i_S = i_t \left(0.5 + 0.35 atan\left(\frac{SoC - SoC_{ref}}{w_2}\right)\right) \tag{15}$$

where $SoC_{ref} = 50\%$ is the inflection point (obtained from the manufacturer) and $w_2 = 1$ is the slope of decay to get approximately 0% with $SoC = 45$. This logic/function is illustrated in Figure 2 with the SoC membership function for the mentioned values. The sigmoid percentage, to a lesser extent, overcomes the [0 − 100] % but the energy demand is inherently limited in a real application; if necessary, the constants (0.5, 0.35) with w_2 can be adjusted to avoid such kind of overcoming.

3.3. High DoD. A Fuzzy-like membership function is proposed to limit the current throughput depending on the DoD while the centering is obtained by the low SoC rule; it is recommended to avoid a high DoD operation ([22, 27, 28, 36–38]). A reverse sigmoid function is selected to continuously limit the current from the SoC limiter (15), as depicted in block 3 of Figure 1:

$$i_D = i_S \left(0.45 - 0.35 atan\left(\frac{DoD - DoD_{ref}}{w_3}\right)\right) \tag{16}$$

where DoD_{ref} (inflection point) is the maximum recommended DoD for SoC centering that maximizes the number of operation cycles; this data can be obtained from the manufacturer. $w_2 = 1$ is the slope of decay to get approximately 0% with $DoD = 55$. This logic/function is illustrated in Figure 2 with the DoD membership function for the mentioned values. The sigmoid percentage, to a lesser extent, overcomes the [0 − 100] % but the energy demand is inherently limited in a real application; if necessary, the constants (0.45, 0.35) with w_3 can be adjusted to avoid such kind of overcoming.

3.4. High Discharge Rate. A Fuzzy-like membership function is proposed to limit the current rate while on V2L operation. The above is to avoid abrupt changes in the current that degrade the battery ([22, 27, 28, 36–38]). This rule limits the rising first derivative of the current:

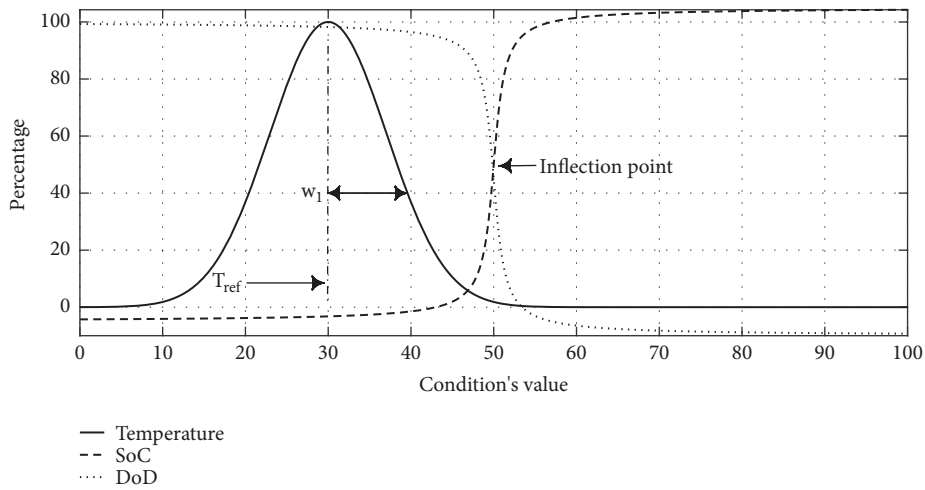

Figure 2: Membership functions for the current limiter.

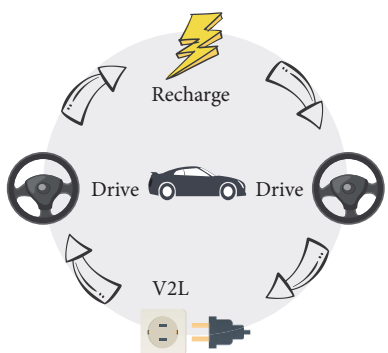

Figure 3: Testing routine for V2L battery degradation.

$$i_L(t) = \begin{cases} R[t-\tau] + i_L(t-\tau) & \text{if C-rate} < \text{discharge rate} < 0 \\ i_L(t-\tau), & \text{elsewise} \end{cases} \quad (17)$$

where the C-rate can be obtained from the manufacturer or tuned to a lesser value and τ is the sample rate. This rule is depicted in Figure 2 as block 4.

4. Simulations and Results

4.1. Setup. In order to show the benefit of the proposed controller, numerical results obtained in Matlab are presented. For the simulations, the workday routine for V2L operation illustrated in Figure 3 is used; such routine consists of driving to a workplace/facility, using V2L, and driving to home using 2 hours for each stage, recharging overnight (slow charge to 1Q), and repeating for 500 days. Standard drive cycle and vehicle are used, namely, the WLTC drive cycle for a Class-3 vehicle ([40]), since they include low, medium, high, and extrahigh speed. The power demand is scaled proportionally to a single cell with the parameters described in Table 1 and it is proposed that the demanded current for the load be 1/2Q on average with peaks of 70% of the maximum driving cycle peak current. In Figure 4 the current demand for a single day without the recharge period is shown. The environment temperature is emulated from statistical data obtained from a local Davis VANTAGE PRO2 weather station (years 2014-2016 in Celaya, Guanajuato, México) and shown in Figure 5; this dataset is available in a link at the end of this paper.

4.2. Numerical Results. In Figure 6 a comparison of the battery capacity in Ah for diverse scenarios is shown. The compared scenarios are V2L without limiter control, V2L with limiter control, and no V2L operation up to 500 workdays. Although the temperature has a direct effect on capacity (oscillatory behavior), an early degradation (the End of Life is premature) can be clearly observed when V2L is used; but also, the behavior with the proposed limiter almost equals the behavior without the use of V2L. In Figure 7 the smoothed version of Figure 6 is shown, in which a premature degradation is clearly observed in approximately 25 workdays in the case of V2L without current limiter with respect to the 290 workdays of life of the proposal in this paper. In Figure 8 is shown the original power profile (assumed) against the limited with the proposal of this paper. Clearly, avoiding premature degradation of the battery has a cost that depends on the amount of energy used in V2L operation and is a highly nonlinear function. In this sense, one can design the current limiting control system to obtain a degradation that is not so premature but allows a V2L operation adequate up to a certain load; such tuning can be obtained by modifying the weights $w_1 - w_3$ and the inflection points by simulations.

4.3. About Implementation. The implementation of the current limiter presented in this paper does not require expensive components. A DSP can be enough to perform the rules and communicate with electronic devices (integrated circuits) designed to estimate the SoC (Texas Instruments, Linear Technologies, and Maxim among other suppliers provide such devices). The current throughput can be regulated by a DC-DC current converter that can later provide AC levels if

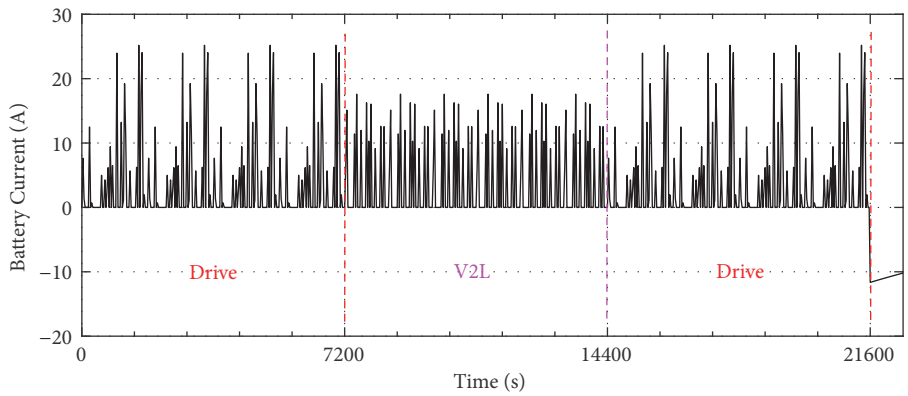

Figure 4: Current demand for single testing routine.

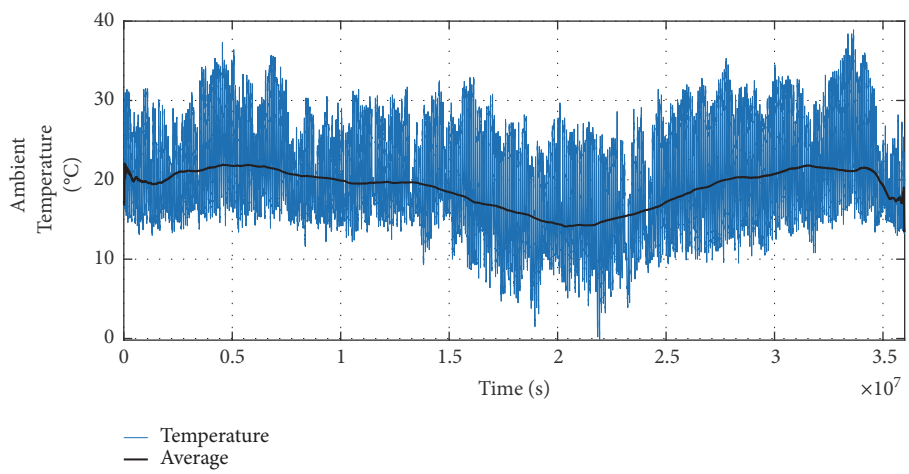

Figure 5: 2014-2016 ambient temperature and its average for Guanajuato, México.

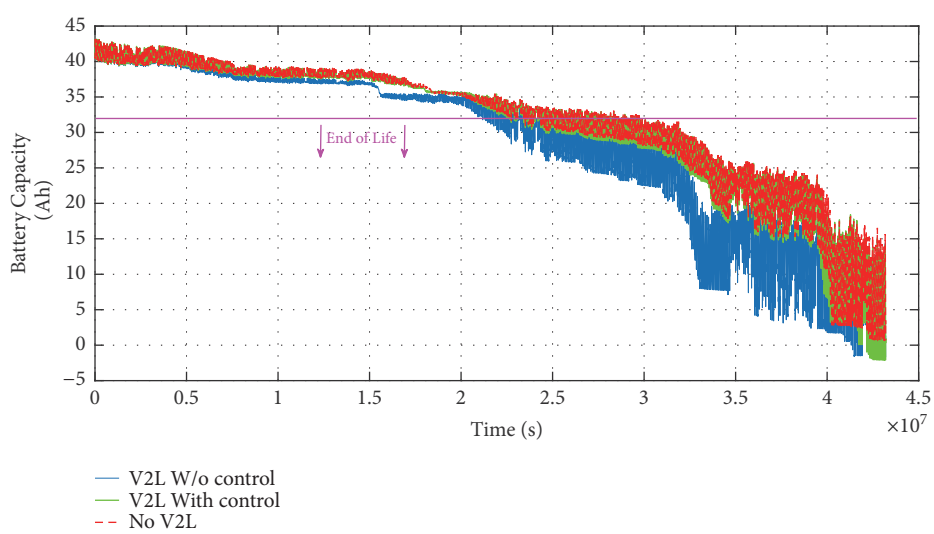

Figure 6: Battery capacity comparison for V2L, V2L with limiter, and no V2L.

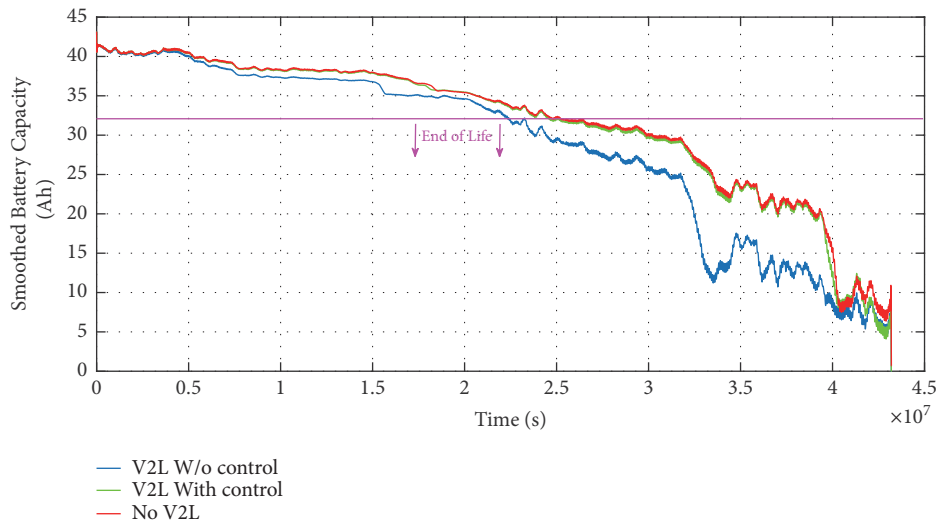

Figure 7: Filtered battery capacity comparison for V2L, V2L with limiter, and no V2L.

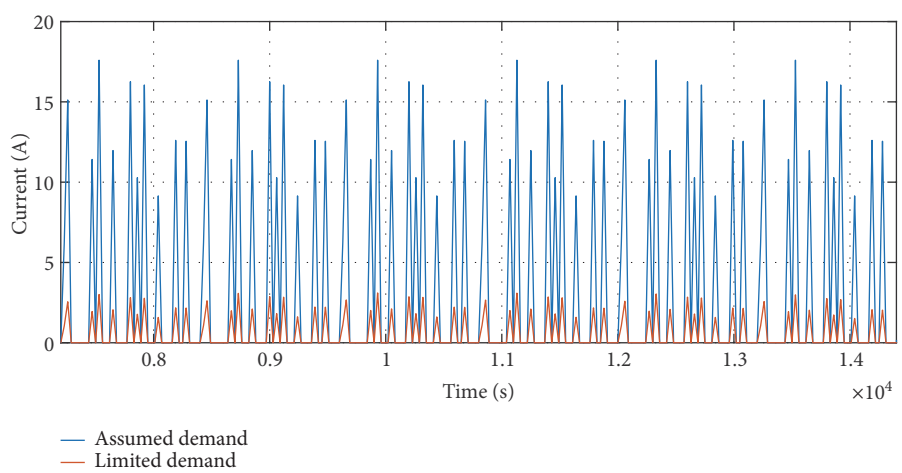

Figure 8: Load current profile, assumed vs limited.

necessary, such that the presented scheme does not invade the battery.

5. Conclusions

In this paper a new current limiter control for V2L applications is proposed. This limiter control is based on rules extracted from the main degradation mechanisms for Li-Ion batteries. Avoiding premature degradation of the battery in V2L operation depends on the amount of energy used and on the degradation variables as highly nonlinear functions. The main advantage of this controller is that it can be tuned to obtain a degradation that is not so premature but allows a V2L operation.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request. A dataset of weather is available at https://www.dropbox.com/s/csegzrrthwsnhva/GtoTempLog14-16.rar?dl=0.

Additional Points

Featured Application. The proposed energy management strategy can be used in Vehicle-to-Load or similar applications with Li-Ion batteries when avoiding battery degradation is imperative.

Disclosure

Martín-Antonio Rodríguez-Licea, Francisco-J. Perez-Pinal, Allan-Giovanni Soriano-Sánchez, and José-Antonio Vázquez-López current address is Antonio García Cubas, no. 600, Colonia Fovissste, Celaya, Guanajuato, 38010.

Conflicts of Interest

The authors declare no conflicts of interest for this paper.

Authors' Contributions

Conceptualization, methodology, software, validation, and formal analysis were performed by Martín-Antonio Rodríguez-Licea. Resources, writing, review, and editing were made by Martín-Antonio Rodríguez-Licea, Allan-Giovanni Soriano-Sánchez, Francisco-J. Perez-Pinal, and José-Antonio Vázquez-López.

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