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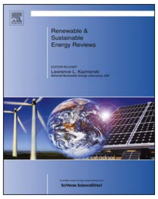

Plug-in electric vehicle batteries degradation modeling for smart grid studies: Review, assessment and conceptual framework

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ABSTRACT

The battery is a key component in Plug-in Electric Vehicles (PEVs) whose degradation should be considered in vehicle modeling and if the battery pack is to be used in a Vehicle to Grid (V2G) smart grid studies. Several researchers have proposed different methodologies for PEV batteries degradation modeling from various aspects. Most of the battery degradation literature consists of empirical-based studies with results extracted from experimental tests in laboratories. As such, the results have been presented in non-formulated forms and are of less effectiveness for smart grid researchers. Furthermore, the impact of battery degradation in V2G smart grid have not been examined in smart grid studies. This paper reviews and compares different battery technologies focusing on Lithium-ion batteries which dominant in today and future vehicle applications. After that the most prominent degradation models are assessed, the effects of degradation factors on battery performance are examined. The literature shows that the degradation causes can be categorized into two groups namely calendar ageing and cycling ageing. Generally, the calendar ageing is influenced by temperature, time, and state of charge, while the cycling ageing is influenced by cycle number, charge rate and depth of discharge. Finally, in this work a conceptual framework for battery degradation modeling is proposed that can be easily used in smart grid studies, without necessarily requiring a detailed understanding of fundamental electrochemical processes. The proposed framework considers not only the battery degradation modeling, but also that of other related components in a smart grid.

1. Introduction

Nowadays, the continuity of energy and water resources is one of the important concerns for governments. Several researches such as [1–3] have been carried out to address concerns regards to water resources. Similarly, various researchers have investigated the energy problems in the future societies. The transportation sector utilizes a significant amount of energy in worldwide. For example, the transportation sector consumes about 35% of annual energy in the United States, 97% of which is provided by petroleum [4]. Moreover, as shown in Fig. 1, the transportation sector energy demand has been increasing significantly since 1950. This fact is also supported by the National Household Travel Survey (NHTS) data in which the household vehicle number has increased in each subsequent until 2009 [5]. Additionally, petroleum use in vehicles significantly contributes to greenhouse gas emissions and reducing urban air quality [7,8]. Hence, the governments are trying to overcome these problems in societies.

Vehicles electrification through the development of Hybrid Electric Vehicles (HEVs) and Plug-in Electric Vehicles (PEVs) is the most practical option to address pollution concerns in transportation sector. More over the integration of the charging of these vehicles with ‘smart grid’ electrical distribution option offers even greater potential for emission mitigation. The charging of the vehicles from grid is often referred to as ‘grid to vehicle’ (G2V), however the use of the onboard vehicle battery pack for energy storage with the ‘smart grid’ also has potential for vehicle to grid (V2G). If the battery performance increases and the prices decrease, these options will be even more viable [9].

With the adoption of PEVs, especially in high market penetration scenarios, many of the aforementioned environmental concerns and emission will be shifted toward the electricity generation sectors. Moreover, the power systems, especially distribution networks, will be faced with significant stress. Many researchers have suggested several approaches based on using renewable energy for PEVs' charging and also coordinated charging strategies for reducing the PEVs impact on the power grid [10–12]. In addition, some researchers have also suggested Vehicle to grid (V2G) concept, in which PEVs support the grid through providing several services. These services include peak shaving, voltage and frequency regulation, renewable energy dispatch-

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Nomenclature

SOC_{dev}	Deviation of SOC in a given cycle
N	Cycle number
I	Current between anode and cathode
Q_{nom}	The nominal capacity of the battery
L	Life parameter
$Life(m)$	Change in life parameter over m-th time interval
K_{co}	Constant parameter in life parameter model
K_{cx}	Constant parameter in life parameter model
K_{soc}	Constant parameter in life parameter model
T_{fact}	Constant parameter in life parameter model
T	Reference battery temperature (K)
T_n	Battery absolute temperature (K)
$t_{shelflife}$	Constant parameter in life parameter model
SOC_{avg}	Average SOC over a cycle
(t_1, t_2)	Time interval
t_m	Time of the m-th cycle
M	Number of time intervals
C_{nor}	Normalized capacity of battery
R_{int}	Internal resistance of battery
α_{cap}	Ageing factor for capacity at calendar ageing tests
β_{cap}	Ageing factor for capacity at cycling ageing tests
α_{res}	Ageing factor for resistance at calendar ageing tests
β_{res}	Ageing factor for resistance at cycling ageing tests
t	Calendar aging time
Q	Charge throughput
$\alpha, \alpha_1, \alpha_2$	Aging parameters
β, β_1, β_2	Aging parameters
$V_{storage}$	Storage voltage
V_{avg}	Average cycling voltage
DOD	Depth of discharge
Q_{loss}	Percentage of capacity loss
A	Constant parameter in ageing model
B	Constant parameter in ageing model
C	Constant parameter in ageing model
$\mathfrak{R}$	Gas constant
n	Constant parameter in ageing model
C_{rate}	Absolute value of the current rate
SOC	State of charge
V_{simu}	Difference between cathode potential and abode potential
$V_{cathode}$	Cathode potential
V_{anode}	Anode potential
R_{avg}	Average Ohmic resistance of battery
x	stoichiometric coefficient
y	stoichiometric coefficient
$Q_{cathode}$	Capacity of cathode
Q_{anode}	Capacity of anode
x_0	Initial value of anode potential
y_0	Initial value of cathode potential
R_0	Initial value of Ohmic resistance of battery
K_{SEI}	Gain factor for proportional relationship description between ORI and LII
k_{LLI}	Decreasing rate of x due to LLI.
k_β	Reaction kinetics considering deviation
A_β	Frequency factor
c_β	Reactants concentration for reaction β
$E_{a,\beta}$	Activation energy
K_β	Reaction rate
i	Reaction order for the Arrhenius equation
j	Reaction order for the Arrhenius equation
β_{gen}	A general index
L_n	Length of cell (m)
j_n^{sei}	Local volumetric current density for side reaction (A/m^3)
A_n	Specific surface area of porous electrode
z_{sei}	Film thickness (m)
N_{sei}	Average molecular weight of the constituent compounds of the SEI layer
a_s	Specific surface area of negative electrode (m^{-1})
p_{sei}	Average density of the constituent compounds
F	Faraday's constant
C_{deg}	Battery degradation cost
$C_{battery}$	Battery cost
D_{total}	Battery total degradation
Q_0	Battery nominal capacity
Q_{useful}	Battery useful capacity
D_{cal}	Calendar degradation
D_{cycle}	Cycling degradation
η_1, η_2	Fitting parameters
ζ_1, ζ_2	Fitting parameters
$Q_{Loss,Rate}$	Battery degradation related to charging rate
Ψ	Pre-exponential factor
$\gamma_1, \gamma_2, \gamma_3$	Fitting parameters
$E(.)$	Expected value
X	The situation vector of the system
h	Function of equality constraints
g	Function of inequality constraints
SOC_t	SOC of PEV battery at time t
η	Overall efficiency of battery and converter
P_t^{ch}	Charge power of battery at time t
P_t^{disch}	Discharge power of battery at time t

ing, and reliability enhancement. [13–15]. In addition, the electric vehicles (EVs) can provide demand side management if they are utilized in a distributed manner and coordinated with other local loads [16]. However, the extra battery degradation created due to additional cycling operation is not considered or not properly investigated in the literature. As the batteries are one of the expensive and main components of the EVs, their degradation cost plays an important role in determining the financial feasibility of EVs smart charging/discharging. In other words, the PEV owners should be aware and satisfied with their vehicle battery's ageing guarantees to participate in the smart grid charging and energy storage strategies.

Currently in the design and sizing of onboard battery packs vehicle original equipment manufacturers (OEMs) will oversize the battery pack to account for some degradation to ensure that warranty obligations can be met. The United States Advanced Battery Consortium (USABC) defines onboard vehicle battery pack End-of-Life (EOL) via two metrics, specifically when: the battery has lost 20% of its power performance (power fade), or if the battery loses 20% of its rated capacity (capacity fade) [17,18]. As such, manufacturers typically assume that a battery will degrade 20% over the life cycle of the vehicle and design for such. This leads to oversized battery packs in an attempt to account for degradation as shown in Fig. 2. In other words, the battery is oversized to account for expected rates of degradation. Hence, a small degree of PEV battery degradation due to V2G participation may be acceptable to vehicle owners. Since the use, or cycling of onboard battery pack to support stationary energy storage applications will degrade the pack smart grid operators should consider PEV battery degradation in their scheduling and operational algorithms.

Battery degradation modeling requires chemistry knowledge and it may be confusing for smart grid researchers with an electrical engineering background to apply it in their scheduling. This concern is intensified when the other components and requirements of smart grid such as renewable energy resources, power market price, and