Estimation of cycling aging of lithium-ion batteries for photovoltaic applications

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Abstract. The installation of photovoltaic microgrids to meet energy needs has had a significant increase in recent years. Likewise, the use of lithium batteries to improve the performance of the microgrid is an issue that is being studied. In this sense, it is important to know the electrical response of the lithium battery under such environment and its degradation. In this sense, this paper presents a methodology developed for the mathematical modelling of the electrical behaviour of a lithium battery. This methodology has been developed from the integration of three mathematical models: dynamic model, thermal model and aging model. During its operation, the lithium battery will be subjected to constant charging and discharging processes (dynamic model), as well as to thermal stress, because of the combined effect of the current flow and the ambient temperature (thermal model), which will generate a lithium battery capacity loss (aging model). For the analysis, real data on photovoltaic production, residential consumption profile, ambient temperature and 48V 100Ah LFP battery datasheet have been used. The developed methodology allows estimating the aging of a lithium battery in real time.

1. Introduction
The charging and discharging processes which the battery is subjected during its operation generate a degradation that, if well estimated, can help to establish a series of strategies that allow defining an adequate charge/discharge working profile, as well as the moment in which the battery needs to be replaced, which generally occurs when the battery has lost about 20% of its nominal capacity.

The developed modelling will make it possible to estimate the useful life of the lithium battery and, if necessary, make some modifications in terms of its operation (establish power limits, temperature limits, etc.) to extend its useful life or to know when it should be replaced, according to its work profile. In this way, any operation stops of the microgrid due to damage or malfunction of the lithium batteries can be avoided.

2. Mathematical model
In this work, the electrical performance of a lithium battery integrated into a photovoltaic system is modeled, considering the power that it must deliver or receive (dynamic model), the ambient temperature variations and internal battery temperature (thermal model), as well as loss of capacity due to the combined effect of charging and discharging battery process along with ambient temperature variations (aging model).
2.1. Dynamic and thermal models
The present work models the electrical characteristic of a lithium battery using equation (1) for discharge curve and equation (2) for charge curve [1]. The dependence of the model parameters with respect to temperature and current have been established in [2].

\[
V = E_o(T) - i \cdot R(T) - k_{i,T} \cdot \frac{Q_{i,T}}{Q_{i,T} - it} \cdot (i^* + it) + A_{i,T} \cdot \exp(-B_{i,T} \cdot it) \tag{1}
\]

\[
V = E_o(T) - i \cdot R(T) - k_{i,T} \cdot \frac{Q_{i,T}}{it + 0.1Q_{i,T}} \cdot i^* - k_{i,T} \cdot \frac{Q_{i,T}}{Q_{i,T} - it} \cdot it + A_{i,T} \cdot \exp(-B_{i,T} \cdot it) \tag{2}
\]

Where, \(V\) is the battery voltage (V), \(E_o\) is the battery constant voltage (V), \(K\) is the polarization constant (V/Ah) or polarization resistance (Ω), \(Q\) is the battery capacity (Ah), \(it\) is the instantaneous battery charge (Ah), \(A\) is the exponential zone amplitude (V), \(B\) is the exponential zone time constant inverse (Ah\(^{-1}\)), \(R\) is the internal resistance (Ω), \(i^*\) is the filtered discharge current (A), \(i\) is the battery current (A) and \(T\) is the internal temperature of the battery (K).

2.1.1. Internal temperature
The internal temperature of the battery was modelled using equation (3) [1] and (4). It should be noted that to find the internal temperature of the battery for a given moment, an iterative process must be carried out.

\[
P_{loss,n} = (E_o(T) - V_n) \cdot i_n + \frac{\partial E_o}{\partial T} \cdot i_n \cdot T_n \quad T_o = T_a \tag{3}
\]

\[
T_{n+1} = T_n \cdot \exp \left( \frac{\Delta t}{t_c} + P_{loss,n} \cdot R_{th} + T_{a,n} \cdot \left( 1 - \exp \left( \frac{-\Delta t}{t_c} \right) \right) \right) \tag{4}
\]

Where, \(n\) refers to the \(n\)th sample, \(T\) is the internal temperature of the battery (K), \(T_a\) is the ambient temperature (K), \(\Delta t\) is the time interval between samples (s), \(R_{th}\) is the thermal resistance (°C·W\(^{-1}\)) and \(t_c\) is the thermal time constant (s). A value of \(t_c = 4,880\) s has been used as in [3].

2.2. Aging model
The aging of the battery was estimated using equation (5) [4] and (6). Equation 6 has been proposed to be able to calculate the battery aging in real time.

\[
Q_{loss,n} = 0.0032 \cdot \exp \left( -\frac{15162}{R_g \cdot T_n} - 1516 \cdot C_r,n \right) \cdot (Ah_n)^2 \quad Z = 0.824 \tag{5}
\]
\[
(Q_{\text{loss,Total}})^{1/z} = \sum_n (Q_{\text{loss,n}})^{1/z}
\]  \hspace{1cm} (6)

Where, \(Q_{\text{loss}}\) is the battery capacity lost (\%), \(Ah\) is the absolute value of the amount of ampere hours which passes through the battery, either for charging or discharging (\(Ah\)), \(R_g\) is the gas constant \(8.314 \ \text{J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}\), and \(C_r\) is the battery C-rate.

3. Parameter extraction

The extraction of the model parameters will be based on the discharge curves. The parameter \(E_o\) was estimated as in \[2\] and the parameters \(A\) and \(B\) are estimated as in \[5\]. The terms \(R_{T_{\text{ref}}}, \partial E/\partial T\) and \(\alpha\), that appear in \[2\] and which will also be used for this work, were estimated as in \[2\]. It has been assumed that \(K_{r_{\text{ref}}} = K_{T_{\text{ref}}}\) and \(Q_{r_{\text{ref}}} = Q_{T_{\text{ref}}}\), these terms also appear in \[2\] and are indicated in this work as \(K_r\) and \(Q_r\), respectively. Then, the parameters \(K_{(i,T)}\) and \(Q_{(i,T)}\) are estimated using equation (7) and (8).

\[
K_{(i,T)} = K_r \cdot \exp \left( \beta_i \cdot (i - i_r) + \beta_T \cdot \left( \frac{1}{T} - \frac{1}{T_r} \right) \right)
\]  \hspace{1cm} (7)

\[
Q_{(i,T)} = Q_r + \frac{\partial Q}{\partial t} \cdot (i - i_r) + \frac{\partial Q}{\partial T} \cdot (T - T_r)
\]  \hspace{1cm} (8)

Where \(\beta_i, \frac{\partial Q}{\partial t}\) and \(\frac{\partial Q}{\partial T}\) are estimated as in \[4\].

3.1. Estimation of \(\beta_T\) and \(K_r\)

For the estimation of these parameters, two discharge curves provided by the manufacturer \[6\] were used, one at \(25 \ ^\circ\text{C}\) and the other at \(10 \ ^\circ\text{C}\), because the ambient temperature range used for this work is between these values. For each of the previous curves, equations (9), (10), (11) and (12) were applied.

\[
a_1 = K_r \cdot \exp \left( \beta_T \left( \frac{1}{T_{\text{exp}}} - \frac{1}{T_r} \right) \right) \cdot \left( \frac{Q(T_a)}{Q(T_a) - Q_{\text{exp}}} \right)
\]  \hspace{1cm} (9)

\[
= \frac{(V_{\text{exp}} - V_{\text{full}}) - \left( \frac{\partial E}{\partial T} (T_{\text{exp}} - T_a) - i \left( R(T_{\text{exp}}) - R(T_a) \right) + A(i) \exp(-B(i) Q_{\text{exp}}) \right)}{(i + Q_{\text{exp}})}
\]

\[
a_2 = K_r \cdot \exp \left( \beta_T \left( \frac{1}{T_{\text{nom}}} - \frac{1}{T_r} \right) \right) \cdot \left( \frac{Q(T_a)}{Q(T_a) - Q_{\text{nom}}} \right)
\]  \hspace{1cm} (10)

\[
= \frac{(V_{\text{nom}} - V_{\text{full}}) - \left( \frac{\partial E}{\partial T} (T_{\text{nom}} - T_a) - i \left( R(T_{\text{nom}}) - R(T_a) \right) + A(i) \exp(-B(i) Q_{\text{nom}}) \right)}{(i + Q_{\text{nom}})}
\]

\[
a_3 = K_r \cdot \exp \left( \beta_T \left( \frac{1}{T_{\text{f}}} - \frac{1}{T_r} \right) \right) \cdot \left( \frac{Q(T_a)}{Q(T_a) - Q_f} \right)
\]  \hspace{1cm} (11)

\[
= \frac{(V_f - V_{\text{full}}) - \left( \frac{\partial E}{\partial T} (T_f - T_a) - i \left( R(T_f) - R(T_a) \right) + A(i) \exp(-B(i) Q_f) \right)}{(i + Q_f)}
\]
\[ \beta_T = \frac{\ln \left( \frac{a_1}{a_2} \cdot \left( \frac{Q_{(T_a)}}{Q_{(T_a)_{nom}}} - Q_{exp} \right) \right)}{\frac{1}{T_{exp}} - \frac{1}{T_{nom}}} = \frac{\ln \left( \frac{a_1}{a_3} \cdot \left( \frac{Q_{(T_a)}}{Q_{(T_a)_{nom}}} - Q_{exp} \right) \right)}{\frac{1}{T_{exp}} - \frac{1}{T_{f}}} \]  

Using a recursive method, \( \beta_T \) is calculated by varying the value of \( Q_{(T_a)} \), then the value of \( K_r \) can be found by any of equations (9), (10) or (11).

The process is repeated varying the value of \( R_{th} \) using a recursive method until \( K_r(25 \, ^\circ C) = K_r(10 \, ^\circ C) \). The value of \( \beta_T \) has been considered equal to the mean between \( \beta_T(25 \, ^\circ C) \) and \( \beta_T(10 \, ^\circ C) \). This is done because it has been observed that \( K_r \) has a greater influence on the shape of the discharge curve than \( \beta_T \).

3.2. Estimation of \( Q \) and \( K \) for constant ambient temperature

For the estimation of these parameters, two discharge curves provided by the manufacturer [6] were used, one at 0.2 C and the other at 0.5 C (the explanation of this choice is detailed in section 4) then equations (13), (14) and (15) were applied for each of these curves.

\[ b_2 = a_2 \cdot \left[ \exp \left( \beta_T \left( \frac{1}{T_{nom}} - \frac{1}{T_{f}} \right) \right) \right]^{-1} = K_{(i)} \cdot \left( \frac{Q_{(i)}}{Q_{(i)} - Q_{nom}} \right) \]  

\[ b_3 = a_3 \cdot \left[ \exp \left( \beta_T \left( \frac{1}{T_{f}} - \frac{1}{T_{r}} \right) \right) \right]^{-1} = K_{(i)} \cdot \left( \frac{Q_{(i)}}{Q_{(i)} - Q_{f}} \right) \]  

\[ Q_{(i)} = \left( Q_f - b_2 \cdot Q_{nom} \right) \cdot \left( 1 - \frac{b_2}{b_3} \right)^{-1} \]  

After \( Q_{(i)} \) is calculated, the value of \( K_{(i)} \) can be found by any of the equations (13) or (14).

4. Battery aging analysis

For battery aging analysis, a residential consumption profile of 20 dwelling, an ambient temperature profile and a photovoltaic production profile were used, all of them corresponding to a summer day, which are shown in figure 2.

Figure 2. Power and ambient temperature profiles. A negative power means that the battery is being charged.
The analysis begins with the extraction of parameters from the discharge curves given by the manufacturer and the result of these can be observed in table 1 and figure 3.

**Table 1. Estimated electrical and thermal parameters.**

| Parameter                  | Value     |
|----------------------------|-----------|
| $E_{oc}$ (V)               | 52.974    |
| $\frac{\partial E}{\partial T}$ (V/K) | 0.023     |
| $R_T$ (Ω)                  | 0.0199    |
| $\alpha$ (K)               | 4676      |
| $K_r$ (V/Ah) or (Ω)        | 0.0047    |
| $\beta_{ic}$ (A⁻¹)        | 0.0188    |
| $\beta_T$ (K)              | 2826.4    |
| $Q_r$ (Ah)                 | 101.39    |
| $\frac{\partial Q}{\partial i}$ (Ah/A) | 0.008   |
| $\frac{\partial Q}{\partial T}$ (Ah/K) | 0.1038   |
| $A_{ic}$ (V)               | 2.0168    |
| $\frac{\partial A}{\partial i}$ (V/A) | 0.0188   |
| $B_{ir}$ (Ah⁻¹)            | 4.8525    |
| $\frac{\partial B}{\partial i}$ (Ah⁻¹/A) | -0.0441  |
| $R_{th}$ (K/W)             | 0.0701    |
| $t_c$ (s)                  | 4880      |

**Figure 3.** Datasheet and simulated discharge curves.

Likewise, the electrical characteristics of a 48 V and 100 Ah lithium battery were used. According to the aforementioned profiles, the microgrid must deliver an amount of energy equal to 68,476 kWh.
with a peak power equal to 79,808 kW. Considering that the state of charge of the battery (SoC) has been limited between 30% and 80% (if the battery capacity is outside these limits, the microgrid stops, \( i = 0 \)), a battery bank composed of 29 units would be needed. However, the consumption and production of energy is not constant, therefore, shutdowns will be generated in the system due to the limits established by the SoC at times when there is a lot of energy consumption or too much photovoltaic production. In this sense, it has been proven that 75 is an adequate number of units for the battery bank to ensure continuous operation of the microgrid. A battery bank consisting of 29 or 75 units will make each battery work at a maximum C-rate between 0.6 C and 0.2 C. Figure 4 shows the result of the application of the developed methodology. The variation of the different electrical parameters of the battery can be observed according to the work regime. A continuous operation of the microgrid can also be observed when the battery bank consists of 75 units, which does not happen when 29 units are used.

![Figure 4. Electrical performance for each unit of a battery bank of 29 units (red line) and 75 units (blue line).](image)

5. **Discussions**
It is observed that a battery bank with a large number of units decreases the aging of each unit, but increases the cost of the system. On the other hand, a battery bank with a small number of units decreases the cost of the system, but increases the aging of each unit. Therefore, what is sought is that the replacement of the battery occurs at the appropriate time, depending on economic availability or at the time of general maintenance of the photovoltaic system. So, the number of units that make up the battery bank will depend on each particular case.

The present investigation can be completed with an experimental test. However, this experimental test can take months or years, before obtaining a measurable degradation, this is because large capacity lithium batteries are designed for long durability.

6. **Conclusions**
A methodology has been developed to analyse the electrical performance of a lithium battery and its degradation when it is operating within a photovoltaic microgrid. The developed methodology allows to analyse the degradation of the battery. Therefore, the proposed methodology helps to establish
corrective measures in the use of the battery to ensure the proper functioning and the extension of its useful life or if the battery must be replaced. It can also be observed that a higher work regime produces shutdowns in the system \((i = 0)\), as well as greater heating and greater battery degradation. The developed methodology also serves to estimate the optimal number of units that should make up the battery bank, since this does not depend only on the energy required, but also on the consumption profile.

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References
[1] Mathworks Generic battery model https://www.mathworks.com/help/physmod/sps/powersys/ref/battery.html
[2] V Nakama et al 2021 J. Phys.: Conf. Ser. 1841 012008
[3] Njouya S, Lupien-Bedard A, Dessaint L, Fortin-Blanchette H and Al-Haddad K 2017 A generic electrothermal Li-ion battery model for rapid evaluation of cell temperature temporal evolution IEEE Transactions on industrial electronics vol. 64 N°2
[4] Song Z, Li J, Han X, Xu L, Lu L, Ouyang M and Hofmann H 2014 Multi-objective optimization of a semi-active battery/supercapacitor energy storage system for electric vehicles Applied Energy 135 212-224
[5] Tremblay O, Dessaint L and Dekkiche A 2007 A generic battery model for the dynamic simulation of hybrid electric vehicles IEEE Vehicle Power and Propulsion Conference 284-289
[6] RELION RB48V100 Lithium Iron Fosfate battery https://ceb8596f236225acd007-8e95328c173a04ed694af83ee4e24c15.ssl.cf5.rackcdn.com/docs/product/Relion-DataSheet_RB48V100_Jan2021.pdf