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Definitions and reference values for battery systems in electrical power grids

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ABSTRACT

Since more and more large battery based energy storage systems get integrated in electrical power grids, it is necessary to harmonize the wording of the battery world and of the power system world, in order to reach a common understanding. In this regard this article presents different battery content values and their relation to each other. Battery operations typically lead to a change of battery's electric charge or energy content. Based on a simplified battery model the basic values necessary to describe battery operations are clarified. Then the reference values and some acceptance criteria for batteries and secondary cells are defined. Also values describing limited usable energy content caused by operational restrictions are provided. In order to be as close as possible to existing definitions and practical applications, care is taken to be conform to current standards wherever possible in this article. The given set of consistent battery definitions can be used for an agreed design of battery storage systems and provides options for battery performance criteria.

1. Introduction

Although batteries are a quite old and principally well known technology there is still not always a common understanding about characteristic and reference values of primary and secondary cells, batteries and battery systems. Especially since huge battery systems get more and more interesting as stationary storage solutions for electrical power systems besides well known values like capacity in ampere-hours and C-rate also typical electrical values like energy and power shall be provided by the system integrator. Therefore this article gives an overview about some characteristic and reference values of battery systems, primary and secondary cells.

Battery model

For all definitions in this document the simplified battery model with the circuit diagram in Fig. 1 is used ([1,2]). The battery open-circuit voltage $v_{Bat,OCV}$ (t) describes the source voltage of the battery ($v_{Bat,OCV}$ $(t) > 0$).

The equivalent, internal impedance $Z_{eq,i}$ is typically specified by manufacturer and summarizes all internal impedances of the battery. Besides ohmic parts also the diffusion resistance and the charge-transfer resistance have an influence on the internal resistance of a battery. The internal impedances also depends on battery's temperature and state of charge. If for simplification a constant resistance with only ohmic influences is taken into account, the internal impedance $Z_{eq,i}$ is equal to internal ohmic battery resistance $Z_{eq,i} = R_i$. The battery current $i_{Bat}(t)$ flows through the internal battery impedance. In this article the index '*Bat*' signalizes that the dedicated value is present at the battery terminals.

In no-load operation ($i_{Bat}(t) = 0$) it follows $v_{Bat}(t) = v_{Bat,OCV}(t)$. As reference system of the battery current i_{Bat} (t) the consumer reference system (Fig. 2, left side) is used in this article. Therefore i_{Bat} $(t) > 0$ signalizes battery charging and i_{Bat} $(t) < 0$ battery discharging. The battery voltage $v_{Bat}(t)$ at the battery terminals can be calculated by

$$v_{Bat}(t) = v_{Bat,\,OCV}(t) + Z_{eq,\,i} \cdot i_{Bat}(t). \tag{1}$$

With battery current and battery voltage (v_{Bat} $(t) \geq 0$) the battery power p_{Bat} (t) at the battery terminals can be derived

$$p_{Bat}(t) = v_{Bat}(t) \cdot i_{Bat}(t). \tag{2}$$

In consumer reference system the sign of the battery power also specifies, if the battery is charged ($p_{Bat}(t) > 0$) or discharged (p_{Bat} $(t) < 0$). Optionally the generator reference system may be used (Fig. 2, right side), in which the opposite signs of battery current and battery power specify, if the battery is charged (i_{Bat} $(t) < 0$, p_{Bat} $(t) < 0$) or discharged (i_{Bat} $(t) > 0$, p_{Bat} $(t) > 0$).

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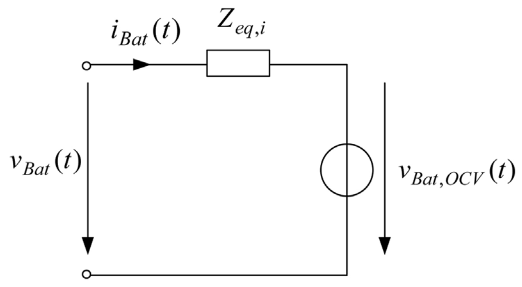

Fig. 1. Simplified battery model with open circuit voltage.

After explanation of different energy content values of batteries in the following the basic values which are important, to describe the battery operation are presented. Then battery reference values and possible acceptance criteria are provided. Finally values for constricted battery operating ranges are characterized.

2. Energy content values of batteries

2.1. Electric charge

One main characteristic of a battery is the ability to store electric charge. Therefore '*stored electric charge*' *q(t)*, which is usable for applications, is an important value.

2.1.1. Stored electric charge q(t)

The electric charge which a battery can deliver under specified discharge conditions between its present electric charge content and its empty state is called '*stored electric charge'*. For stored electric charge which is expressed in ampere hours (Ah) the sign *q(t)* is used.

'*Full state*' of a battery is the state of charge wherein the battery has been completely charged in accordance with the manufacturer's recommended charging conditions (see also *SOC* value below). Accordingly '*empty state*' of a battery is usually defined by the battery supplier.

With q_{Start} and q_{End} as stored electric charge at the beginning and at the end of a charging or discharging process the change of stored electric charge ΔQ can be calculated by:

$$\Delta Q = \int_{q_{Start}}^{q_{End}} dq \tag{3}$$

In consumer reference system a negative sign of ΔQ signalizes that at the end of the time period the battery contains less electric charge than at the beginning ('*discharged*'); a positive sign of ΔQ signalizes that at the end of the time period the battery has got more electric charge than at the beginning ('*charged*').

Furthermore battery current $i_{Bat}(t)$ (charge or discharge), the start time t_{Start} and the end time t_{End} of the current flow can be used to derive the change of stored electric charge ΔQ ('*Coulomb Counting*'):

$$\Delta Q = \int_{t_{Start}}^{t_{End}} i_{Bat}(t) \cdot dt \tag{4}$$

In regard to '*Coulomb Counting*' also time values can be used to describe battery's electric charge content. See also '*constant current discharge time*' and '*constant current charge time*' below.

2.1.2. Capacity C

The (actual) capacity *C* of a battery is the electric charge which a fully charged cell or battery can deliver under specified discharge conditions, between its full state and its empty state. During lifetime of a battery the capacity decreases in comparison to the capacity at '*beginning of life*' (BOL). Therefore an index can be added to the capacity *C* which specifies the battery aging. For example C_{EOL} expresses that the given capacity is valid at the '*end of life*' (EOL). As for electric charge the SI unit for capacity *C* is coulomb (1C = 1As) but in practice, capacity is usually expressed in ampere hours (Ah).

2.1.3. State of charge SOC

State of charge *SOC* of a battery is the amount of stored electric charge *q(t)* related to the actual capacity *C*:

$$SOC = SOC(t) = \frac{\text{stored electric charge}}{(\text{actual})\ \text{capacity}} = \frac{q(t)}{C} \quad (0\% \leq SOC \leq 100\%) \tag{5}$$

'*Full state*' (*SOC* = 100%) is the reference value for stored electric charge *q(t)* and means *q(t)* = *C*. '*Empty state*' (*SOC* = 0%) means *q(t)* = 0Ah. The other way round stored electric charge of a battery can be expressed by using the *SOC* value:

$$q(SOC) = SOC \cdot C \tag{6}$$

Since the value of capacity changes during lifetime due to battery aging, an index of *SOC* can specify the capacity *C*, which is the reference for *SOC* value. For example SOC_{BOL} means that the capacity *C* at beginning of life (BOL) is used as *SOC* reference value

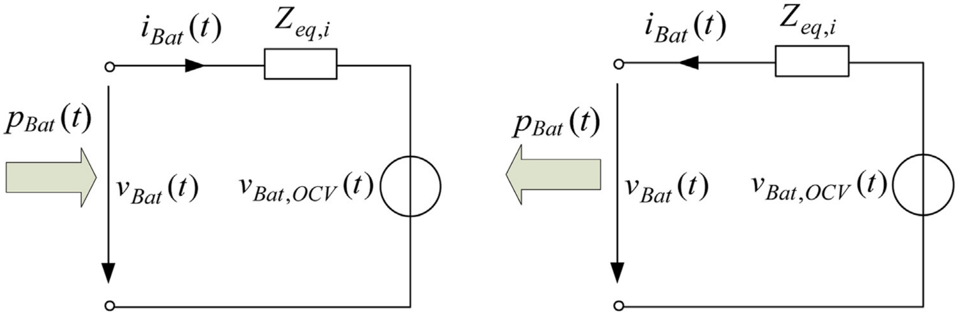

Fig. 2. Consumer and generator reference system.