Energy Storage: Batteries

Part II: Equivalent Circuits and Connection to Main Grid

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Equivalent Circuit models for Batteries

- Batteries are often modeled as equivalent circuit diagrams based on the Thevenin's theorem;
- Those models are available under three different forms, namely:
  - The internal resistance model (IR);
  - The one time constant model (OTC), and
  - The two time constants model (TTC).

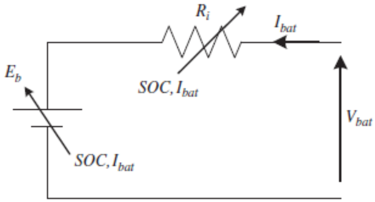
The Internal Resistance Model

- The model consists of a voltage source, E_b, and an internal resistor, R_i, where

$$E_b = f(SoC) \qquad R_i = f(I_{bat}, SoC, T)$$

- E_b is the open circ. voltage, due to energy stored in the batt;
- R_i represents the losses, and is invers. proport'l to the SoC (when batt is descharging, R_i is increasing);
- Circuit equation:

$$V_{bat}(t) = E_b(t) + I_{bat}(t)\ R_i$$



Example: losses and low charging rates

A 100 Ah, 12 V batt with a voltage of 12.5 V (at its current SoC) is charged at C/5 rate, during which time the applied voltage is 13.2 V. Using the IR model:

a) Estimate R_i;

b) What fraction of the input power is lost in R_i?

c) If charging is done at C/20 rate, what fraction of the input power would be lost due to R_i?

Solution (1/2)

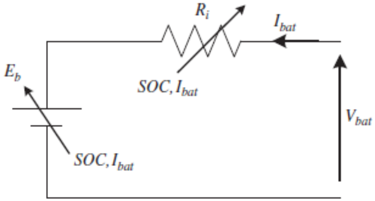
a) Estimation of R_i:

At C/5:

$$I_{bat} = \frac{100\ Ah}{5\ h} = 20\ A$$

$$R_i = \frac{V_{bat} - E_b}{I_{bat}} = \frac{13.2 - 12.5}{20}$$

$$R_i = 0.035\ \Omega$$



b) Fraction of the input power lost in R_i :

$$\frac{\text{Loss in } R_i}{\text{Input Power}} = \frac{I_{bat}^2 R_i}{V_{bat} I_{bat}} = \frac{(20)^2 \times 0.035}{13.2 \times 20} = 0.053 = 5.3\%$$

Solution (2/2)

c) Fraction of the input power lost in R_i at C/20:

At C/20:

$$I_{bat} = \frac{100\ Ah}{20\ h} = 5\ A$$

The input power to drive 5 A through $R_i = 0.035\ \Omega$ is:

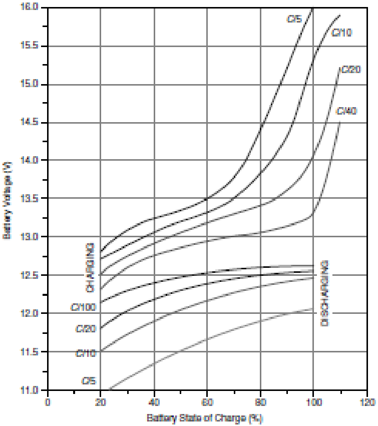
$$V_{bat} = E_b + I_{bat}\ R_i = 12.5 + 5 \times 0.035 = 12.68\ V$$

So at the $(C/20) = 5\ A$ rate, the loss are now only

$$\frac{\text{Loss in } R_i}{\text{Input Power}} = \frac{I_{bat}^2 R_i}{V_{bat} I_{bat}} = \frac{(5)^2 \times 0.035}{12.68 \times 5} = 0.014 = 1.4\%$$

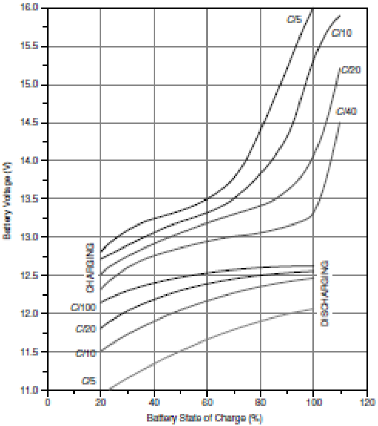
Limitations of the IR Model and Real Battery Curves

- The IR model is useful, but complicated by the fact that both E_b and R_i depend on the SoC, temp, and batt history;
- The figure show realistic values of E_b for different charging/discharging rates as a function of SoC;
- Curves are for 12 V lead-acid batteries.



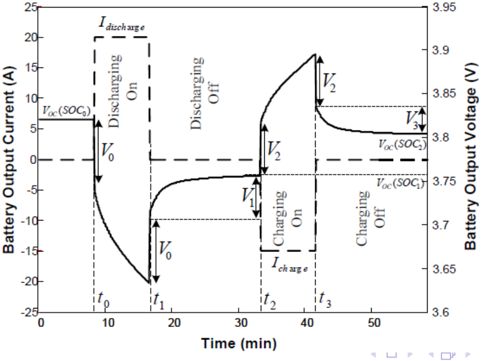
Lead-Acid batteries: practical aspects

- Charging: sudden rise of cell voltage around 14 V level $\Rightarrow$ poor charging efficiency + gassing;
- Water removed from batt has to be replaced or plates will be damaged;
- VRLA batts reduce gas emission by over 95%;
- Charge controllers slow charging rates and minimize losses+gassing.



The One Time Constant Model (1/2)

- The *IR* model does not represent the transient behavior of batteries, and in particular of Li-ion cells;
- Li-ion cell curves for batt *V* and *I* during charging/discharging cycles (notice they are typical of *RC* circuits):



The One Time Constant Model (2/2)

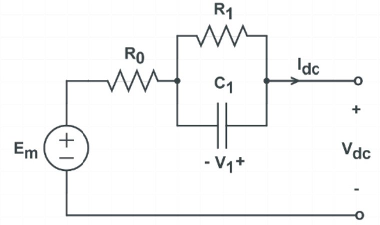
- The OTC model adds a parallel RC network in series with the internal resistance:
  - R_0 : internal resistance;
  - R_1, C_1 : parameters of RC network.
  - E_m : open circuit voltage

- Mathematical model:

.

$$\dot{V}_1 = -\frac{1}{R_1 C_1} V_1 + \frac{1}{C_1} I_{dc}$$

$$V_{dc} = E_m - V_1 + R_0 \; I_{dc}$$



The Two Time Constants Model (1/2)

- The TTC model is aimed at improving the dynamic behavior and flexibility of the OTC model;
- An extra RC network is added in series with the OTC circuit;

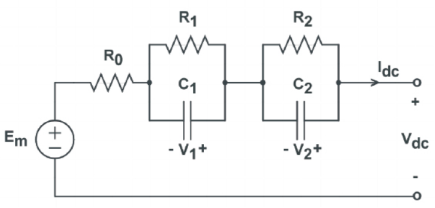
- Mathematical model:

$$\dot{V}_1 = -\frac{1}{R_1 C_1} V_1 + \frac{1}{C_1} I_{dc}$$

.

$$\dot{V}_2 = -\frac{2}{R_2 C_2} V_2 + \frac{1}{C_2} I_{dc}$$

$$V_{dc} = E_m - V_1 - V_2 + R_0 \, I_{dc}$$



Final Remarks on Battery Equivalent Circuits

- The parameters of the two improved models (OTC and TTC) are estimated through laboratory experiments and the use of a nonlinear least squares algorithm (nonlinear data fitting);

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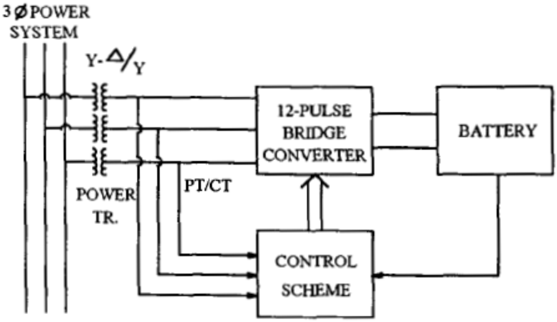
- It is generally considered that the OTC model approximately describes the dynamic characteristics of a battery, but the TTC model is more accurate for Li-ion batteries and should be preferred;
- Those models can be used to develop enhanced methods for SOC estimation.

Connection of Battery Storage Energy Systems to the Grid

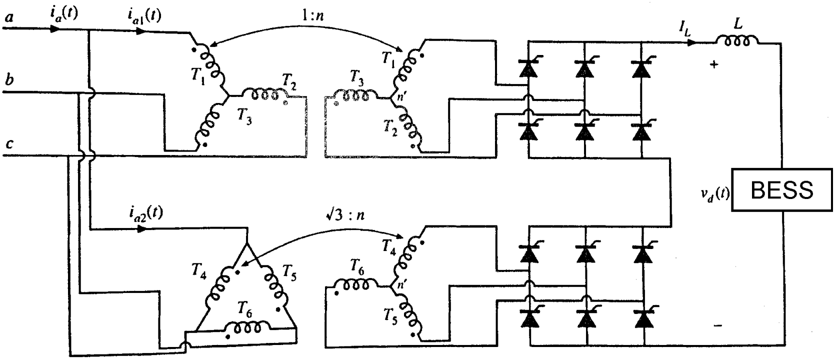
- There are different means to connect a BESS to an AC grid;
- A possible arrangement for such connection is based on a 12-pulse converter equipped with a controler:



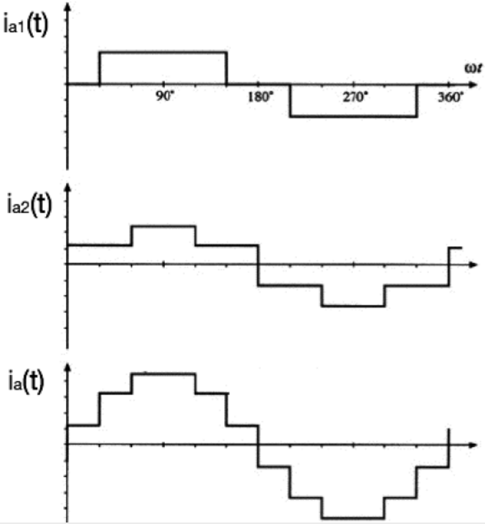
The 12-pulse converter: topology (1/2)

- It is formed by associating two 6-pulse converter bridges in parallel, each of them connected to the grid by a distinct transformer;
- In order to reduce the input harmonics of the 3-phase rectifiers, phase-shifting transformer circuits are used:
  - One of the 6-pulse rectifier bridge is connected through a Y-Y transformer;
  - The other 6-pulse rectifier bridge is connected through a Y-Δ transformer.
- Since $\Delta - Y$ transformers cause a 30^o phase shift between primary and secondary line-to-line voltages, this scheme eliminates low-order harmonics, such as the fifth and seventh.

The 12-pulse converter: topology (2/2)



The 12-pulse converter: current waveforms



Rectifier Control Strategies

- There are two possible control strategies for the 12-pulse converter:
  - P-Q modulation: allows the (joint) control of active and reactive power;
  - P modulation: reactive power supplied by the BESS is set to zero, and only active power is controlled.
- For frequency control, which requires only incremental active power variations, the P-modulation scheme is employed.