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# The role of battery models in investment appraisal: the case of Primary Control Reserve

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Nowadays, the utilization of Lithium-ion Battery Energy Storage Systems (BESSs) for grid-tied application is a promising application to guarantee the security and reliability of the electric power system with the increasing share of renewable sources. This work evaluates the utilization of a BESS for Primary Control Reserve (PCR) provision by developing an approach to properly simulate BESS dynamic response. The core part of the approach is the different battery models which can be used to evaluate the techno-economic results. The methodology ends with economic analyses to assess the profitability on a defined period and to enable decision-makers to evaluate their investment.

## Battery models

- *Empirical*: based on coulomb counting with a **constant efficiency** set to 95%. Lifetime is modelled through a constant **maximum number of cycles** set to 5000.
- *Analytical*: based on **efficiency curve** (derived from efficiency tests). The value of efficiency varies as function of the actual C-rate of the battery. Lifetime is modelled through a maximum number of cycles which depends on a **capacity decay factor** derived from cycling test.
- *Electrical*: based on a passive **electrical impedance-based model** developed in CSEM and Politecnico di Milano and derived from EIS and OCV measurements. By using combinations of resistances and capacitances it identifies the different physical phenomena which are labelled in the EIS of Figure 1. The SoC estimation is based on the simulated OCV.

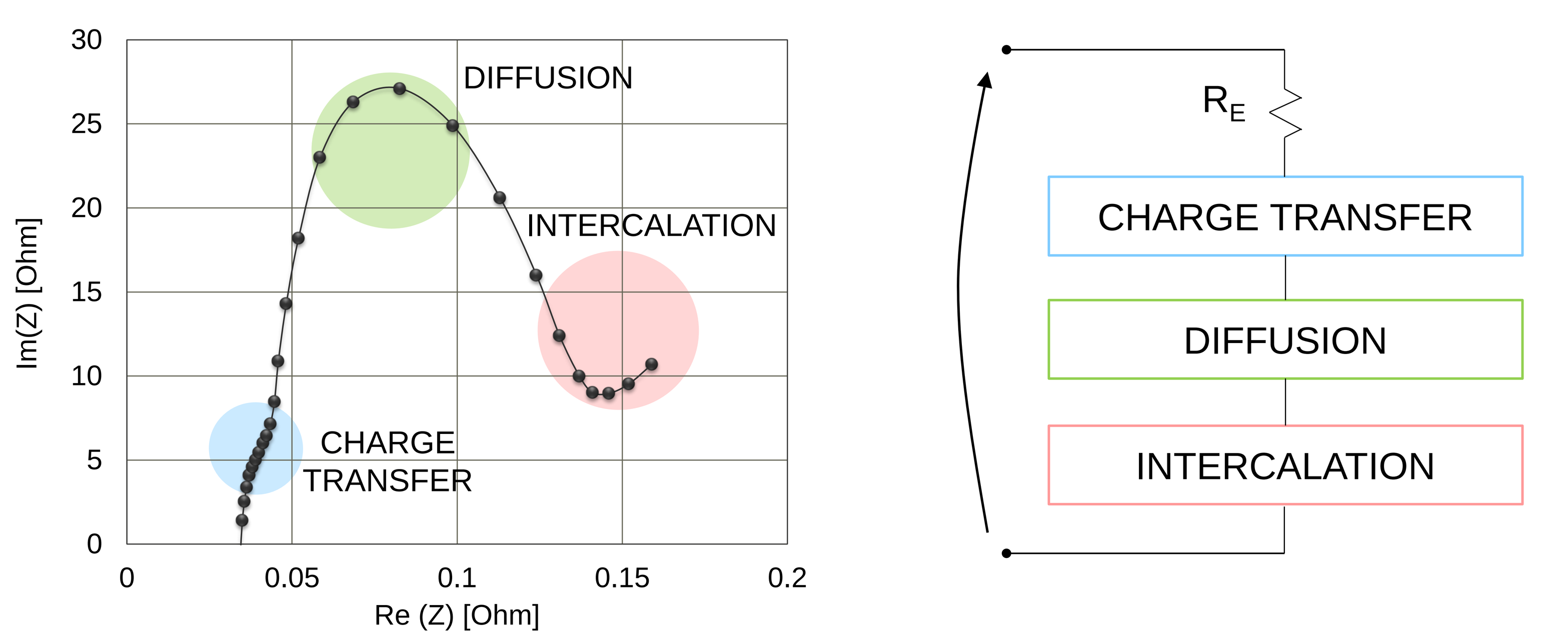


*Figure 1 – EIS measurement of the cell used in the Electrical model and schematic representation of the electrical battery model.*

C. Brivio, V. Musolino, M. Merlo, and C. Ballif, "A physically-based electrical model for lithium-ion cells," IEEE Trans. Energy Convers., p. 1, 2018.
C. Brivio, V. Musolino, P.-. Alet, M. Merlo, A. Hutter, and C. Ballif, "Analysis of lithium-ion cells performance, through novel test protocol for stationary applications," in 2017 6th International Conference on Clean Electrical Power (ICCEP), 2017, pp. 410–415.

## The proposed methodology

The approach developed (Figure 2) includes all the sub-models necessary to simulate the operation of a BESS:

- *The controller model*, where the frequency signal and the battery SoC are elaborated through **specific decision-making rules** to provide droop settings and SoC regulation strategies.
- *The regulation model*, where the droop control curve is defined and the **power set-point for the battery** is calculated.
- *The inverter model* that models the inverter through a simplified equivalent efficiency and response time.
- *The battery model* that includes the ***Empirical***, ***Analytical*** and ***Electrical*** models.

The models and algorithms have been developed in Matlab™ Simulink™. Simulations results are evaluated in term of BESS performance indicators in providing the PCR services. Specifically: the service provision reliability (technical point of view) and the Net Present Value (economic point of view).

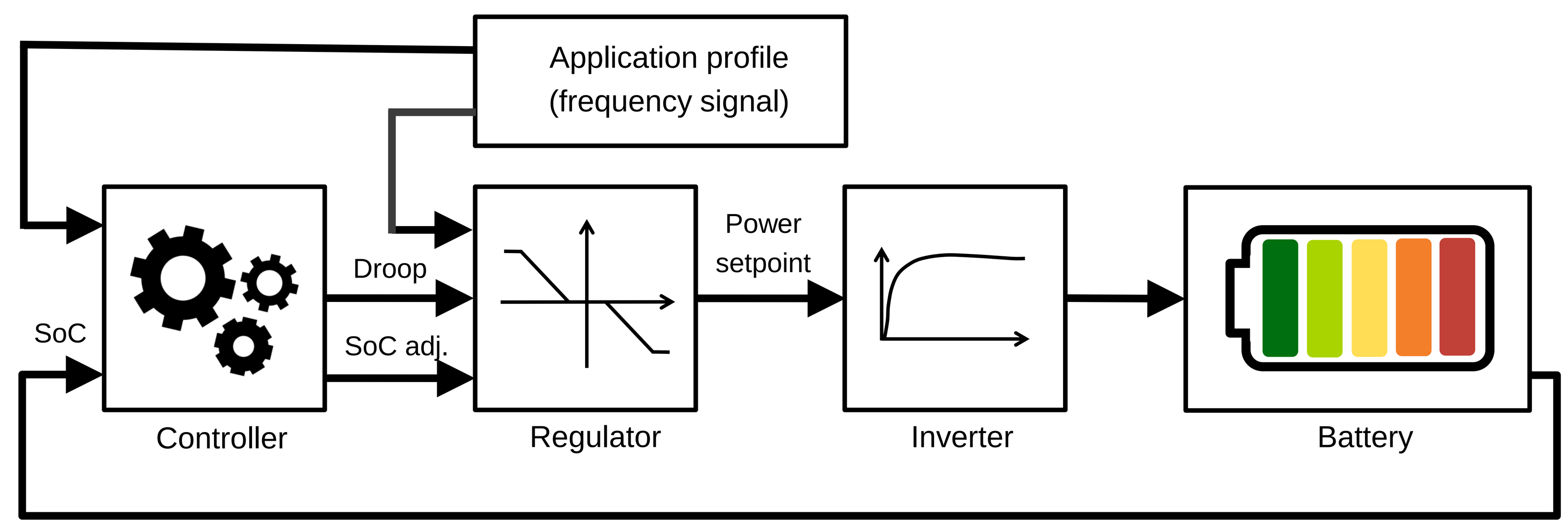


*Figure 2 – Schematic representation of the proposed approach.*

C. Brivio, S. Mandelli, and M. Merlo, "Battery energy storage system for primary control reserve and energy arbitrage," Sustain. Energy, Grids Networks, vol. 6, pp. 152–165, 2016.

## Results: battery models comparison

The case study refers to the Italian regulatory framework; the frequency signal has been measured at Politecnico di Milano in February 2017. Given the not yet complete Italian regulatory framework, the revenue of PCR has been set based on the Central Europe Mechanism. The analysis assumed **five different possible BESS sizes** which have been simulated with the different battery models over **10 years of investment span**.

- Technical results**:** the service provision is highly influenced by the choice of the model. *Empirical* model and *analytical* model show the best values being less severe especially when the battery is undersized. Whilst the *Electrical* model show the lowest (i.e. highest loss of service) because of the additional limitation on the exploitable SoC range due to the voltage limits of the battery.
- Economic results: the NPV is highly influenced by the choice of the model. A very simplified model (*empirical*) would lead to the choice of a 1MWh/1MW BESS which maximize the NPV to 320k€; however, more detailed models suggest to oversize the BESS: 1.2MWh/1MW (*analytical*), 1.5MWh/1MW (*electrical*). This will turn in lower NPV: 200k€ (*analytical, -38%),* 100k€ *(electrical, -69%).* These differences definitely motivate the usage of more precise battery models.
- Computational effort**:** simulation time is highly influenced by the choice of the model. Due to its model complexity, the *Electrical* model requires 50 times more than the *Analytical* and *Empirical.*

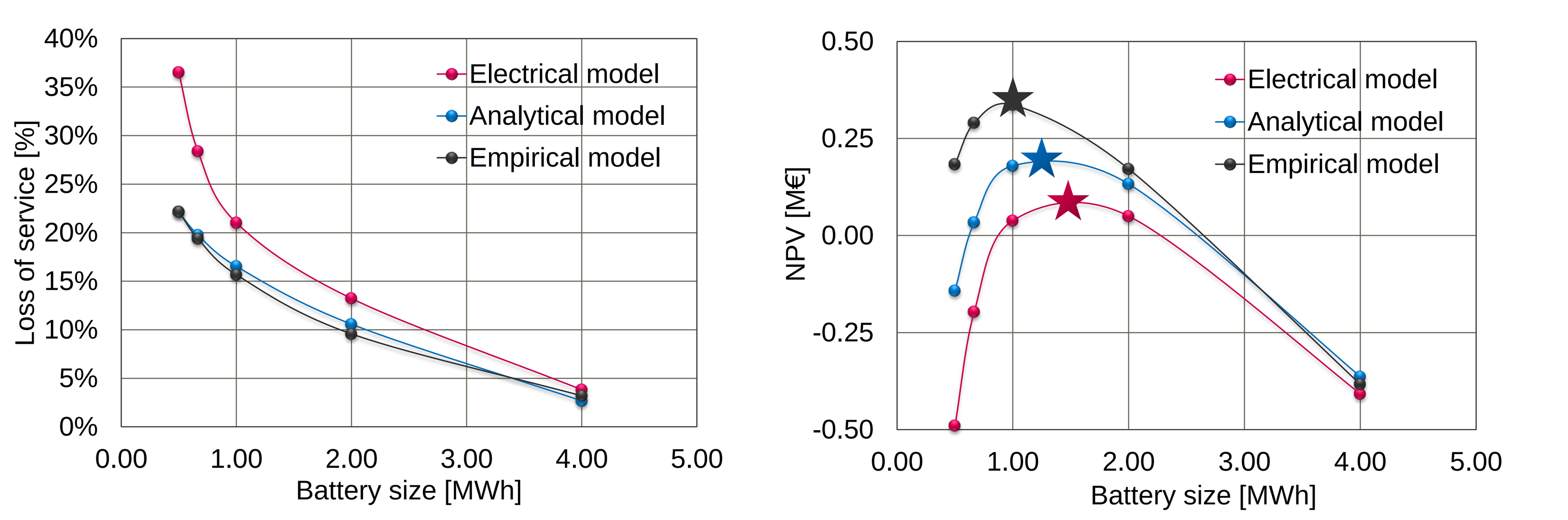


*Figure 3 - Comparison of Empirical, Analytical and Electrical battery models: estimated Loss of service curves as function of the Battery size (MWh) and estimated Net Present Value (NPV) curves with highlighted optimal size (star).*

P. Iurilli, C. Brivio, M. Merlo, "SoC Management in Battery Energy Storage Systems for Primary Control Reserve Provision", Sustainable Energy, Grids and Networks (under review).

## Results: SoC control strategies

Different SoC control strategies have been also investigated to maximize the service provision.

- *Strategy A*: **dead band range** is exploited to bring the SoC to a given SoC target value by absorbing or delivering power.
- *Strategy B*: SoC restoration is done by **interrupting the service provision**. The battery then starts to absorb or release power to reach the pre-defined SoC target. When the restoration ends, the battery re-starts the PCR service provision.
- *Strategy C*: SoC restoration **contemporary to PCR provision**.
- *Strategy D*: **droop angle is modified** (no power set-point is imposed). The controller optimizes droop angle by using a pre-defined droop-map → *droop=f(frequency,SoC).*

On a technical point of view, SoC management strategies increase the service provision performances with respect to the traditional droop control; however, the exploitation of the battery is higher, with higher average C-rate and number of cycles. On an economic point of view, SoC managements strategies cause higher costs related to more frequent battery replacements and, in some cases, they can results a worse investment with respect to the traditional droop control.

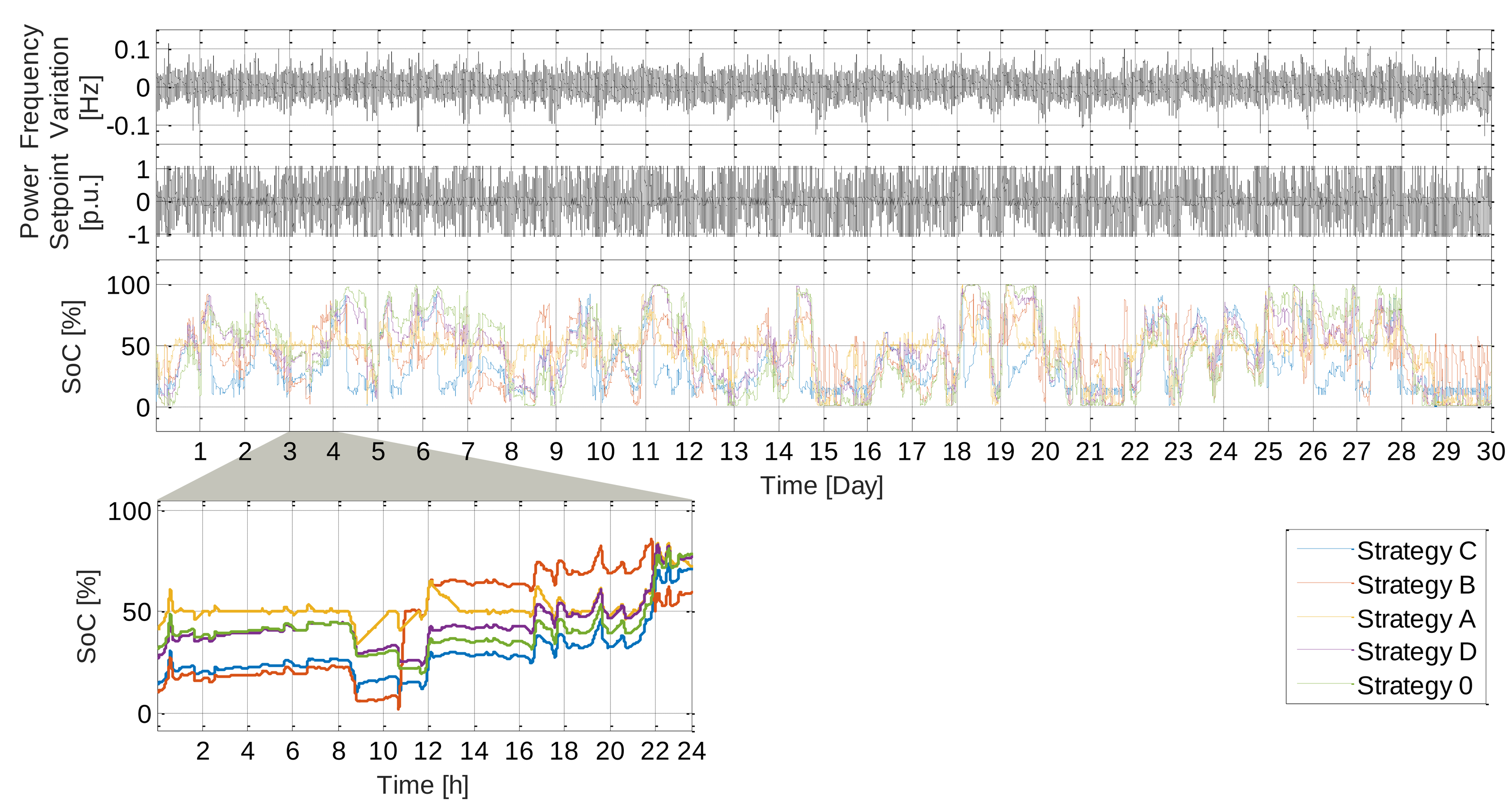


*Figure 4 - 30 days simulations exploiting different SoC control strategies. Frequency variation, Power setpoint requested to provide PCR, SoC profiles of the four different control strategies and reference case (strategy 0).*

P. Iurilli, "Modelling and analysis of battery energy storage system for primary control reserve provision", Master Thesis, Politecnico di Milano, 2017.