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Optimal energy storage sizing using equivalent circuit modelling for prosumer applications (Part II)

Cong-Toan Pham*, Daniel Månsson

KTH Royal Institute of Technology, Electromagnetic Department, Teknikringen 31, 11428 Stockholm, Sweden

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ABSTRACT

An optimal system design indirectly implies efficient use of available resources, i.e., minimum investment to achieve the desired outcome. An increased demand of energy storages highlights the importance of efficient use and optimal storage sizing. However, the variety of available and newly developed storage technologies complicates decision-making in choosing the appropriate technology to the compatible application. The characterization of storage types extends to the inherent dynamic behavior and technical limitations, which is imperative for storage system design. This paper proposes a brute-force method of optimal storage system sizing based on the equivalent circuit modeling while considering storage's operation constraints. The sizing routine is applied to a set of different energy storage technologies (lead-acid, Li-ion, vanadium-redox flow battery, double-layer capacitor, flywheel) to balance the energy demand of a single-family building supported by a 3.36 $\mathrm{kW_{peak}}$ photovoltaic system. This case focuses on the energy management application of energy storages. Additionally, a suitability index is introduced to determine the applicability of the investigated storages in reference to an ideal case.

1. Introduction

Electrical energy storages currently attract high attention and research interest, not surprising in the face of increasing energy demand coupled with intermittent power generation from renewable energy sources. Safety and supply security of the power grid must be guaranteed, where energy storage system (ESS) fill in the gap if traditional management methods (e.g. curtailment or flexible dispatch via power plants) are costly or fail [1,2]. ESS provide a wide range of services from seasonal bulk storage, customer side load management, integration of renewable energy sources up to short-term power quality applications, to name just a few possibilities [3,6]. Different technologies exists and their application potentials vary among another or need yet to be determined. Then, the main interest lies in grading and finding their suitable working environments. Currently, the distribution of energy storages in real-life application is focused on the battery type systems and pumped hydro storages [4]. Some commercial operational plants for thermal, flywheel or compressed-air energy storages do exist, but their range of application so far is limited to areas with specific requirements, e.g., high power ratings, geographical constraints, weight, etc. Based on the data of existing plants a classification of ESS within their operational limits can be mapped, which provides an overview of the application possibilities [4,5]. Ref. [3] goes one step further in matching the storage's technical characteristics with the requirements of different applications and summarizes their findings in a suitability matrix. Refs. [7,8] continue the idea by introducing a ranking system based on literature surveys among the various storage options. This sets the baseline and mirrors the current achievements in the progress of ESS, but misses on identifying the potentials of newly developed devices or variants of existing ones. A natural approach is to directly test and compare different ESS for any desired scenario (e.g. integration of renewable energies, load management, etc.), which would ideally provide us with the necessary information to evaluate different ESS applicabilities.

In our first paper [10] we introduced a common modeling approach for different ESS types as equivalent circuits, serving as the baseline to analyze and simulate ESS for various cases. From the technical perspective the ESS differ in their physical background and dynamic behavior. Due to design aspects, technical limitations and inertia (e.g. maximum in-/output currents, self-discharge rates, efficiency, etc.) it becomes apparent that ESS react differently to changing demands. Hence, their suitability can be measured by observing their charge and discharge profiles, i.e., how well they can follow a desired in-/output profile. Apart from the transient responses the technical constraints

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* Corresponding author.
E-mail addresses: ctpham@kth.se (C.-T. Pham), daniel.mansson@kth.se (D. Månsson).
URL: https://www.kth.se/profile/ctpham/ (C.-T. Pham).

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Nomenclature

Abbreviations

ESS	energy storage system
ES	energy storage unit
BESS	battery energy storage system
PHS	pumped hydro storage
CAES	compressed air energy storage
SMES	superconducting magnetic energy storage
FES	flyhweel energy storage
DLC	double-layer capacitor
CS	central storage
PTS	power transformation system
CDCS	charge–discharge control system
Lead-acid	lead-acid battery
Li-ion	lithium ion battery
VRB	vanadium-redox battery

Symbols

R_s	inner resistance, friction element
R_p	leakage resistance, charge transfer resistance
C	capacitance, double-layer capacitance, fluid capacitance
L	inductance, moment of inertia, mass, inertance
U_b	open-circuit voltage, pressure gain (through elevation)
U_m	static friction losses (e.g. bearing losses)
U_{in}	source input voltage/torque
I_{in}	source input current
U_{pot}	storage voltage, pressure level (single unit)
I_{kin}	storage current, angular velocity (single unit)
Q_{pot}	storage charge capacity (single unit)
U_{st}	storage system voltage
I_{st}	storage system current
ω	angular resonance frequency
ζ	damping ratio
τ	time-constant
SOC	state-of-charge
Q_{rate}	rated storage capacity
I_{rate}	rated storage current, velocity
U_{rate}	rated storage voltage
Q_{max}	maximum allowed charge capacity
Q_{min}	minimum allowed charge capacity
U_{max}	maximum allowed voltage level
U_{min}	minimum allowed voltage level
I_{max}	maximum allowed current level
I_{min}	minimum allowed current level
$U_{in,max}$	maximum allowed input voltage
$U_{in,min}$	minimum allowed input voltage
$I_{in,max}$	maximum allowed input current
$I_{in,min}$	minimum allowed input current
P_{ref}	reference demand power
P_{st}	storage total in-& output power
C_f	coverage factor (measure of overlap)
η_c, η_d, η_{sd}	efficiency (charge, discharge, idle)
M	number of series connected storage units
N	number of parallel connected storage units
m	flywheel rotor mass
r	flywheel rotor radius
n_{max}	maximum rotor revolutions per minute
n_{min}	minimum rotor revolutions per minute

imposed on a single storage unit narrows its operation range. Designing a multi-storage system of several units compensates for the shortcomings of one unit and naturally raises the question how to appropriately choose and size this system. Considering the aforementioned issues this study proposes a storage sizing routine that includes the storage's basic dynamics and constraints.

This paper is the continuation of [10], applying the equivalent circuit modeling of ESS and, as an example, optimally size them to a grid-connected residential single-family building supported by a 3.36 kW_{peak} photovoltaic system. This application concerns the balancing of the produced solar power and the requested load demand on an hourly basis. Hence, the models presented here are applicable for energy management purposes, but not necessarily usable in power quality assessment. Regardless, we aim to set the framework for analyzing, evaluating, and sizing of different ESS types. The unified modeling approach allows a fast and intuitive way to compare different options.

The upcoming sessions discuss the ESS model framework (2.1), briefly summarizing the basic storage's parameters and constraints (2.2). Moreover, we introduce a system of individual storage units (2.3) and describe the implemented optimization routine (2.4). Finally, we estimate the appropriate storage system size for a case study (single-family building with photovoltaic (PV) system) based on how well the ESS follows the desired demand curve (2.5). Here, Matlab is used as the simulation software [13].

2. Methodology

In this section we focus on the application of the equivalent circuit models of ESS for grid applications. The analogies between the physical quantities (mechanical, electrical, electrochemical, etc.) allows us to describe the physical systems in a common modeling approach [9]. The proposed equivalent circuit features the most important dynamic

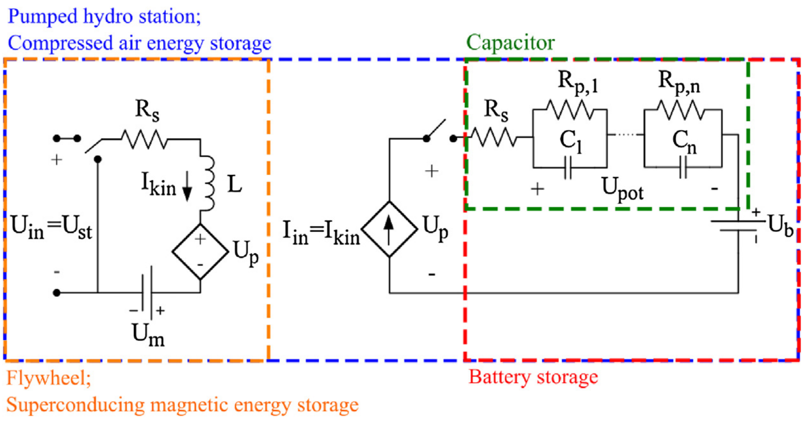

Fig. 1. General equivalent circuit model for energy storage based on [10]. The left circuit represents the kinetic storage part; the right circuit represents the potential storage part. The ESS consider different parts of the circuit, marked in the following colors: red – battery, orange – flyhweel energy storage (FES), superconducting magnetic energy storage (SMES), green – capacitor, double-layer capacitor (DLC), blue – pumped-hydro storage (PHS), compressed air energy storage (CAES). (For interpretation of the references to color in text/this figure legend, the reader is referred to the web version of the article.)