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On the physical system modelling of energy storages as equivalent circuits with parameter description for variable load demand (Part I)

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A B S T R A C T

Energy storages take a key role in electrical energy balancing in our power grid in respect to the increasing utilization of renewable energies. Assessing the effectiveness of energy storages and finding the optimal use under varying load conditions is essential which requires accurate modelling. This study highlights the equivalent circuit modelling approach for different energy storages. The model parameters R, L, C and U_b define the storage system in question allowing us to analyse storage devices under varying load conditions. Technical assessment criteria (efficiency, response time etc.) of energy storages can also be deducted from these models. Energy storages feature non-linear characteristics which are reflected in variable model parameters.

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1. Introduction

The Smart Grid of the future envisions a reliable, sustainable and environmental friendly power supply. To achieve this goal renewable energy sources, e.g., wind and photovoltaic power will replace fossil fuelled power plants causing greater unpredictable power generation. One way of compensating is balancing any demand and supply mismatch through the use of energy storage systems (ESS). The effectiveness of specific energy storages has been studied for various scenarios in for example wind power integration, load management and power quality etc. [1,2]. The assessment of energy storages to find their optimal use and placement in grid applications is an essential step. This involves the evaluation of technical, economic, environmental and social aspects of the ESS against each other. Multi-criteria selection methods such as Fuzzy Logic and Analytic Hierarchy Process has been suggested as an initial assessment tools [3,4] weighting selected storage parameters against each other. The technical requirements are the first and most important aspects to determine the suitability of ESS. One of the crucial technical requirements is the response time of ESS; or in other words how fast the ESS can adapt to changes of power demand. In practice energy storages are accompanied with ancillary equipment, which are usually subjected to certain technical limitations such as maximum allowed current or maximum motor power. Determining the technical suitability requires in-depth understanding of the technical limits, in this case the physical background and the dynamic behaviour of ESS. Models help to quantify the attributes of physical systems in parameters, allowing us to describe their relations in mathematical expressions. Fortunately, most physical systems exhibit recurrent and similar governing laws, which make it possible to compare different systems through key parameters.

This paper aims to expand the general equivalent circuit model method (ECM) to various ESS to analyse and evaluate them with varying loads. The circuit parameters comprise the physical attributes relevant to the dynamic behaviour, including non-linear effects which we present in the following sections for each of the following storage type (capacitor, flywheel (FESS), battery and pumped hydro station (PHS)). The chosen approach is also modular and compatible with existing storage models. Capacitor and battery models have been investigated extensively to predict the charge/discharge profiles,and the status-of-charge [5]. This paper focuses on the applicability of such models for storage evaluation and expanding equivalent circuit modelling for alternative

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storages. Here, capacitor and battery models serve as reference cases for developing equivalent models for FESS and PHS. Thus, with these models we can deduct the performance of ESS and ascertain technical parameters such as efficiency, response time, storage's capacity etc. under selected conditions. These parameters form the basis of technical criteria for ESS assessment as has been previously suggested in [2–4], making the direct comparison and evaluation of ESS fast and intuitive. The novelty then lies within the application of equivalent circuit modelling for ESS assessment, ultimately leading to an application matrix similar to [2]. Furthermore, these models set the framework for future studies on optimizing ESS for grid applications by finding the optimal parameter settings, which is the main focus of Part II.

In the upcoming sections we will discuss the similarities between different physical systems (Section 2.1) and use that fact to develop a representative electrical circuit model for energy storages with electrical components (Section 2.2). This model should be able to analyse various power demands which is further described under Section 2.3. Section 3 concerns the circuit models for four different ESS types: capacitor, battery, flywheel (FESS), and pumped-hydro storage (PHS), including the description of the relevant circuit components based on the original physical system.

2. Equivalent circuit model

2.1. Analogy of physical systems

All processes involved in physical systems occur with the exchange of energy, including the conversion between different energy types (chemical, thermal, electrical etc.). The capability of a system to perform work to another depends on the energy state both systems exhibit relatively to each other. The way how the systems interact relies on the physical properties which influence the transfer rate of energy [6], e.g., the temperature difference between two objects is the driving force of the energy transfer and vanishes when the temperature difference becomes zero. How fast this process is depends on the boundary separating both systems, i.e. the specific thermal conductivity and geometrical dimensions of the wall. This same fundamental concept of energy transfer allows us to design an unifying model which can describe various physical systems [6].

The equivalent circuit method refers to a theoretical representation of the physical properties of a physical system (electrical, mechanical, thermal etc.), usually to simplify the complex characteristics into more convenient and clearly distinguishable components. This concept has been useful in many engineering areas retaining all physical characteristics in circuit elements (e.g. resistance R, spring constant k etc.) which still describe the system's dynamics accurately [5,6]. All physical systems relate power and energy by the product of their system variables, similar to the power and work done in kinematics ($P = Fv$, $W = \int Fv\, dt$) or electrical systems ($P = UI$, $W = \int UI\, dt$). Note, that the abbreviations of system variables and parameters can be similar, especially in this paper where we compare parameters of different physical systems, e.g., capacitance C and fluid capacitance C_f. Reference [6] denotes the system variables as *effort* (e) and *flow* (f), which represent the extensive (e.g., voltage, force, temperature etc.) and intensive (e.g., current, velocity, heat flow etc.) property, respectively. The analogy can also be found in the governing relations of the system variables as shown in Table 1. The losses and parameter description of the individual systems is summarized in Table 6. The system elements portray the properties of the physical systems, e.g., the electrical resistance limits the electric current passing through a conductor (Ohm's law) which is comparable with friction reducing the velocity of a moving object. Another example is Newton's second law of motion ($F = m\ dv/dt$) which similarly links the relation between the voltage and current of an inductor ($U = L\ dI/dt$). Due to this analogy the parameters in each physical system directly translate to each other (e.g., resistance $R \equiv$ friction B; capacitance $C \equiv$ inverse spring constant 1/k; inductance $L \equiv$ mass m). In circuit theory these elements are usually constant, but this assumption is far from reality as each element can be dependent on further variables, e.g. time or temperature. For example, in fluidic systems the fluid resistance R_f is a function of the flow rate Q, resulting in a non-linear relation ($p = R_f(Q)Q$).

2.2. Mathematical derivations

In this study we focus on the storage media itself (flywheel, electrochemical cell, water reservoir etc.) including the essential components influencing the charging and discharging dynamics. The energy inserted into the ESS will be either stored as kinetic (through an inductance L) or potential energy (through a capacitance C or a voltage source U_{pot}). In the circuit representation the energy storages can either be charged by a voltage or current source, which leaves us with four possible circuits. One circuit with a voltage source is presented in Fig. 1 consisting of two parts: 1a) illustrates the kinetic storage model, whereas 1b) shows the potential storage part. The input to the potential storage model in this case is set by a dependent current source which is determined by the kinetic model. For example, in a pumped-hydro station the

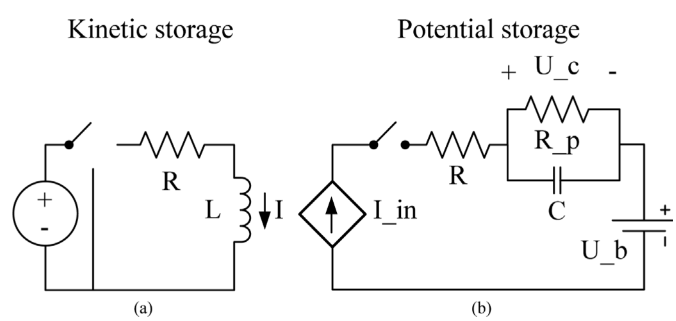

Fig. 1. Equivalent circuit models for kinetic and potential storages with voltage source input. a) kinetic energy storage. b) potential energy storage.

Table 1
Analogy between physical quantities.

	Electrical system (III.1 & III.3)		Mechanical system (rotational) (III.2)		Fluidic system (III.4)	
System variables	Voltage: U	Current: I	Axial torque: τ	Angular velocity: ω	Fluid pressure: p	Fluid flow rate: Q
System parameters	Resistance: R		Rotational damper: B		Fluid resistance: R_f	
	Capacitance: C		Torsional stiffness: k		Fluid reservoir: C_f & pressure tank	
	Inductance: L		Moment of inertia: J		Inertance: L_f	
Governing relations	$\boldsymbol{U = RI}$		$\boldsymbol{\tau = B\omega}$		$\boldsymbol{p = R_f Q}$	
	$\boldsymbol{U = \frac{1}{C}\int Idt}$		$\tau = k\int \omega\ dt$		$\boldsymbol{p = \frac{1}{C_f}\int Qdt}$	
	$\boldsymbol{U = L\frac{dI}{dt}}$		$\tau = J\frac{d\omega}{dt}$		$\boldsymbol{p = L_f\frac{dQ}{dt}}$	

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