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Smart energy storage: Minimizing the required capacity by sequentially switching sections

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ABSTRACT

The problem of minimizing the required capacity of an energy storage by controlled disconnecting and connecting of the energy storage sections to the output line, according to the specified consumption plan, is considered in the article. Energy storages under consideration are the ones in which the energy potential decreases at a rate proportional to the rate of consumption of the stored energy resource and inversely proportional to the storage capacity. Mathematical description of the problem and its solution method are proposed. The method is based on specifying a finite set of moments of time at which the values of the control function can be changed. As result, the problem is reduced to the analysis of a finite set of control law candidates. The proposed method includes techniques that reduce its computational complexity. An example of application of the proposed method to minimizing the required capacity of a compressed air energy storage is provided.

1. Introduction

Among energy storage systems of various physical nature and various principles of action, let's consider those in which the energy potential decreases at a rate proportional to the rate of consumption of the stored energy resource and inversely proportional to the storage capacity. Such energy storages, for example, are capacitors and supercapacitors, compressed gas energy storages, gravity liquid storages (an elevated water tanks, a pumped hydroelectric storages), spring and inertial mechanical energy storages.

Let us assume that the energy storage must provide output energy according to the specified consumption plan, which for each moment of time indicates the planned flow rate and the required energy potential at the energy storage output. Examples of flow rates and energy potentials are: electric current and voltage for capacitors, mass flow rate and pressure of gas or liquid for gas cylinders or elevated water tanks respectively, speed of movement of the output link and the force acting on it for spring accumulators.

The required energy reserve and storage capacity can be reduced if a storage is comprised of isolated sections and only one of the sections is connected to the output line at each time moment. Moreover, the section number for each time moment should be chosen to fulfill the specified plan of energy consumption and to minimize the required storage capacity.

Reduction of the required stored energy and the capacity of such a smart storage is due to possibility of more complete emptying of its sections at time intervals with lower level of required potential (electric voltage, pressure, etc.) and saving only a few high potential sections for high demanding consumption plan intervals.

A more complete emptying of the smart storage compared to the traditional one-part means a decrease of the unused energy remainder. As result, the required energy reserve reduction equals to the sum of the remainders and the energy consumption specified by the consumption plan. Along with the required stored energy, the required energy storage capacity is reduced, which is proportional to the amount of the energy stored.

Let's solve the problem of minimizing the required capacity of the considered class of storages with assumption of reasonable connecting and disconnecting of the energy storage sections to its output line, considering the specified consumption plan.

Minimizing the required energy resource of the storage of the considered class is equivalent to minimizing the required capacity and vice versa. Therefore, the solution of the problem of minimizing the required energy storage capacity simultaneously is the solution of the problem of minimizing the required energy reserve.

The problems of improving energy storages, in particular, optimization of their capacity [14], including the problem of creating smart energy storages [5–8], are actively discussed in the literature.

Paper [1] presents a methodology to evaluate the optimal capacity of a hybrid energy storage system supporting the dispatch of a large-scale photovoltaic power plant. The optimal capacity design is achieved through a comprehensive analysis of the photovoltaic power plant

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performance under numerous hybrid energy storage system capacity scenarios. Article [2] describes the experience of the energy system model application, taking into account the energy storage capacity, spatial distribution and storage dispatch for the optimization of renewable energy systems. In publication [3], the authors present the energy storage capacity optimization strategy for a microgrid with integrated consideration of characteristics of distributed generations, energy storage and loads. The objective of the studies presented in article [4] is to optimize the capacity of storage systems for renewable energy resources, particularly photovoltaic inverters with the capability of reactive power control. To achieve the above objective, the authors propose a hybrid multi-objective sensitivity analysis algorithm that optimizes the capacity of storage systems. Paper [5] presents smart energy storage control strategy to cope with operational uncertainties, such as wind energy and energy price, within the framework of a smart Microgrid. In publication [6] smart energy systems are investigated and comparatively assessed to solve the major global energy-related issues in a sustainable manner. The authors of article [7] assert that in order to determine the least cost solutions of the integration of fluctuating renewable energy sources into the current or a future 100% renewable energy supplies one has to take a Smart Energy Systems approach. Paper [8] makes a review of the scientific literature in a field of smart energy systems. Thereafter it discusses the term Smart Energy Systems with regard to the issues of definition, identification of solutions, modeling, and integration of storage. The authors conclude that the smart energy system concept represents a scientific shift in paradigms away from a single-sector thinking to a coherent energy systems understanding and how to benefit from the integration of all the sectors and infrastructures.

However, despite the considerable interest in the topic of improving energy storages, the problem, formulated and solved in this paper, has not been considered previously. To solve this problem, the article proposes an original approach and demonstrates the efficiency of its application.

The relevance and practical significance of the problem under consideration are due to the fact that minimization of the required capacity of the energy storage, achieved as a result of the application of the proposed approach, allows one to reduce its dimensions, mass and cost.

2. Formulation of the problem

We consider that the energy storage consists of n isolated sections and gives possibility of connecting one of its sections to its power output line (trunk) at the specified moment, disconnecting all other sections from the trunk at the same time.

We assume that functions $p^*(t)$, $g^*(t)$, defining the energy consumption plan, are given for the time interval $t \in [0,T]$. Function $p^*(t)$ indicates the minimum required potential (electric potential, gas or liquid pressure, etc.) for the power output line, and $g^*(t)$ is the flow rate of the energy resource from the energy storage (electric current, a flow rate of gas or liquid, etc.). Consumers of energy get it from the power output line through a stabilizer, reducing the energy potential in the trunk to the level $p^*(t)$ determined by the consumption plan. The energy potential at the trunk $p(t)$ should not be less than $p^*(t)$ value defined by the consumption plan. Therefore, at each moment $t \in [0,T]$, the following condition must be met:

$$p(t) = \Sigma(p_i(t)\ u_i(t)) \ \geq \ p^*(t),\ u_i \in \{0,1\},\ _{i=1,2,\ldots,n,\ \forall t \in [0,T]}, \tag{1}$$

where p_i is the energy potential (electric potential, gas or liquid pressure, etc.) of the i-th section of the energy storage, n is the number of sections, u_i is the "conductivity" of the line from the i-th section of the energy storage to the power output line. The case $u_i = 0$ corresponds to the closing of the line, and the case $u_i = 1$ stands to its opening. Variables u_i constitute the control vector $u = (u_i)$, $i = 1,2,\ldots,n$.

The length of time intervals on which storage sections are used is assumed to be large in comparison with the operation time of the switches used to disconnect and connect sections to the output line. Accordingly, the time for changing the values of the variables u_i is assumed to be sufficiently small.

We assume that the energy potential decrease rate of a section of the energy storage is proportional to the flow rate of the energy resource and is inversely proportional to the capacity of the section. That is:

$$dp_i\ /dt = G_i/C_i,\ _{i=1,2,\ldots,n},\ C_i > 0,\ _{i=1,2,\ldots,n}. \tag{2}$$

where $G_i = g^* \cdot u_i$ is the current consumption of the energy resource from the i-th section, C_i is capacity of the i-th section.

Eq. (2) corresponds, for example, to classical models of the discharge of a capacitor, emptying of a gas cylinder or an elevated water tank, and the discharge of spring and inertia accumulators of mechanical energy. The capacity C_i in Eq. (2) is constant, the physical meaning of which depends on the nature of the processes being modeled. For example, in the case of a capacitor energy storage: C_i is capacitance, p_i is an electric potential, G_i is an electric potential, G_i is an electric current of the i-th section. In case of a gas cylinder energy storage $C_i = W_i/(RT)$, where W_i is the volume of the i-th section, R is the gas constant, and T is the gas temperature. In this case p_i is a pressure, G_i is a mass flow rate. For a spring energy storage $C_i = 1/\eta_i$, where η_i is a spring stiffness, p_i is an elastic force, G_i is a movement speed. In case of an inertial mechanical energy storage, constant C_i is a moment of inertia of a flywheel. In this case p_i is a rotational speed of the flywheel, G_i is a torque moment.

Using formula (2), we assume that the process of discharging the energy storage system is long enough. This eliminates the need for more complex discharge models.

No more than one of energy storage sections can be connected to the power output line at a time. This eliminates useless flow of energy resources from sections with higher potential to other sections (such flow would reduce the ability to service energy demands of the consumption plan intervals with higher potential requirements). It is described by condition:

$$\Sigma u_i(t) \leq 1,\ _{i=1,2,\ldots,n,\ \forall t \in [0,T]}. \tag{3}$$

Energy potential of the energy storage sections can not exceed the specified value p^{max}:

$$p_i(t) \leq p^{max},_{i=1,2,\ldots\ ,n,\ \forall t \in [0,T]}. \tag{4}$$

An indicator of quality, subject to minimization, is the total capacity of the storage sections

$$C = \Sigma C_i,\ _{i=1,2,\ldots,n}. \tag{5}$$

The unknowns are the control law $u(t)$, the capacity of the sections C_i and the initial potentials $p_i(0)$ of each of them.

The problem under consideration is a minimization problem. Its input data are the functions $p^*(t)$, $g^*(t)$, $t \in [0,T]$ defining the energy consumption plan over the time interval $t \in [0,T]$; the number of sections n into which the storage is divided; the maximum permissible initial value of the potential p^{max}. Its output data (optimization variables) are the values of the control variables $u(t)$, the capacities C_i of the sections and the initial potentials $p_i(0)$ in each of them. Constraints that should be met are (1)–(4). Its objective function C is the sum of the capacities C_i of the sections defined by (5).

3. The solution

The problem formulated above can be regarded as a problem of the theory of optimal control. It requires determination of the control law $u(t)$, the parameters of the plant C_i, and the initial values of the state variables $p_i(0)$, delivering a minimum to the quality index (5), taking into account constraints (1–4).