Optimal Control of Energy Storage Devices for Future Power Grids and Electric Vehicles

次世代の電力網および電気自動車のためのエネルギー貯蔵装置の最適制御

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Two challenges of modern power systems are the increasing integration of renewable energy sources and the increasing use of electric vehicles. A key enabling technology related to both these challenges is energy storage. However, the field of energy storage itself poses significant research questions, ranging from the search for new and better materials to advanced control algorithms. The research reported herein explores new approaches for optimal control of storage devices. One paper studies the optimal energy management strategy in complex networks with storage devices. Two other papers introduce the “shortest path” optimization technique. These concepts allow simple planning of the stored energy, and enables reliable and efficient operation of power systems and electric vehicles.

最近のパワーシステムでは，再生可能エネルギー源との統合拡大と電気自動車の導入拡大という二つの課題があるが，これら二つの課題のいずれにも有効な解決策がエネルギー貯蔵技術である。しかしながらエネルギー貯蔵技術自体の分野においても，新素材開発・材料改良から先端的な制御アルゴリズムにおよぶ重要な課題を解決しなければならない。本論文で紹介する研究は貯蔵素子の最適制御への新たな研究手法を開拓するものである。貯蔵デバイスからなる複雑なネットワークにおけるエネルギー管理の最適化に関する論文1件と，他に「最短経路法」による最適解法について解説する論文2件を示そう。これらの概念によってエネルギー貯蔵システムの設計が簡素化され，電力供給システムと電気自動車を高信頼性かつ高効率で運転することが可能となる。

Introduction

Over the past few years storage technologies are slowly emerging as an essential component of modern power systems. Batteries in particular are being used in increasing numbers both in electric vehicles and in conjunction with renewable energy systems, due to their falling costs. A key question is what will be the main function of storage systems, since they may be used for different tasks such as reducing the peak power generation, shifting energy from one time to another, regulating the frequency, stabilizing voltages, or trading energy.

Another question is how to locate energy storage devices in the grid, and how to organize energy storage systems on a large scale. Two leading concepts are the decentralized approach, which calls for numerous distributed storage systems, and the centralized approach, in which relatively large storage devices are located in key points within the grid. Decentralized storage systems will be probably owned by private consumers and operated for maximal profits, whereas centralized storage systems will be probably owned by the utility, and operated to stabilize the power system as a whole. Each of these approaches has advantages and disadvantages. For instance, while the first approach enables high modularity and flexibility, the second offers the advantages of scale, and allows tight control by the system operator. The future is wide open, and these issues are currently far from being resolved.

One of the primary drivers for the growing interest in storage systems is the increasing use of renewable energy sources. A common claim is that renewable sources such as wind and solar are intermittent and unreliable, and thus require storage systems to be useful in a utility system. To address this challenge one idea is to use storage devices for energy balancing: surplus energy is stored when the power demand is low, and used later when "the wind is not blowing, or the sun is not shining". A common claim is that storage systems are crucial if the penetration level of renewable sources exceeds a certain threshold. This threshold however depend on many factors, vary from one system to another, and is currently not sufficiently well understood. On shorter time scales, fast reacting storage devices are crucial for frequency and angle stability. Since renewable energy sources and other power electronics based devices have little inertia, they may jeopardize the grid stability and overall dynamic behavior. This problem may be mitigated by fast reacting storage systems that are installed alongside low-inertia sources.

A well known challenge is how to optimally control storage devices to maximize the efficiency or reliability of a power system. As an example, for a grid-connected storage device the objective is usually to minimize the total cost, the total fuel consumption, or the peak of the generated power, while operating the device within its limits. The problem in this case is to decide how much energy should be stored, and when to store it. Such optimal control problems are generally hard to solve due to their high numeric complexity, and since in order to find an optimal solution one has to compute the stored energy at each and every point in time. In addition such optimization problems are usually not convex, either since the objective function is not convex, or since it is not defined over a complex set. As a result gradient-based optimization methods are usually inefficient, and tend to converge to local minima.

The dynamics and operating limits of the storage device may also complicate the solution process. For instance, in simple problems an optimal solution may be found according to Pontryagin's minimum principle. This approach often yields solutions that can be implemented in real-time, but may be inefficient for complex constraints or dynamic equations. In addition, dynamic programming algorithms can typically locate a globally optimal solution, but can practically handle only a limited number of state variables. In peak-shaving or energy shifting applications load forecasting may also pose a major challenge. While several works avoid this problem by assuming that the load may be estimated with sufficient accuracy, others propose optimal solutions which also forecast the load.

Integration of Storage Devices in Modern Power Systems - a Short Introduction

Currently two grand challenges in the power system field are the increasing integration of renewable energy sources and the increasing use of electric vehicles. It is well known within the power system community that a key enabling technology related to both these challenges is energy storage. However, the field of energy storage itself poses significant research questions, ranging from the search for new and better materials to advanced management and control algorithms.

Storage devices come in various sizes and serve different needs. For instance, the term grid-scale energy storage encompasses a number of different technologies such as pumped hydroelectric storage, compressed air storage, batteries, flywheels, superconducting magnetic energy storage, and super-capacitors. These technologies are also characterized by many different parameters such as capacity, energy density, power density, efficiency, lifetime, cost, etc. Common energy storage technologies include:

- *Mechanical:* hydroelectric energy storage (pumped storage)1, flywheels, compressed air, thermal storage;
- *Electrochemical:* rechargeable batteries, flow batteries, fuel cells;
- *Electrical:* capacitors, inductors, superconducting magnetic coils.

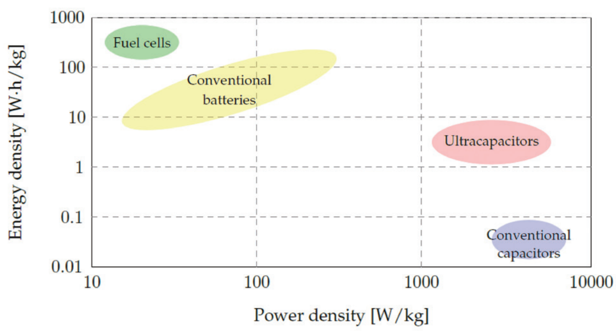


Figure 1 Energy density vs. power density

Storage devices with high power density are crucial for stability of electric power systems. A classic example is the kinetic energy stored in the rotors of synchronous generators. This kinetic energy supports instantaneous changes in the load, and is essential for regulating the grid frequency. Today, one possible challenge associated with renewable energy integration is the low rotational inertia of renewable energy sources, which in several cases may lead to stability problems. To address this challenge the total system inertia may be increased by means of additional storage devices.

On the other hand, storage devices with high capacity are mostly used for energy shifting and energy balancing.

The main idea is to store surplus energy at times when the power demand is low, and then to use it when the main source cannot supply the energy needed, or when generation is more difficult or expensive. Typical applications in power systems include:

- **Energy balancing, Load leveling, or Peak shaving**. In electric power systems the load is constantly varying. Storage devices may be used to shift generation from times of peak load to off-peak hours. This lowers the peak of the generated power, and improves the overall system efficiency.
- **Renewable energy integration**. Renewable sources provide variable power that is not always matched to the load. If the energy generated by renewable sources cannot be consumed immediately it can be stored and used later. Energy storage technologies seem to be essential for large-scale integration of renewable sources.
- **Energy trading**. Storage devices enable to buy energy at a low price, and then to sell this energy at a higher price. In addition to generating profit this also helps to match the power supply to the power demand, and stabilizes the energy cost.
- **Emergency preparedness**. Storage devices may supply energy in case of a malfunction in the generation or transmission systems. This function is vital for sensitive facilities such as hospitals, military bases, etc.

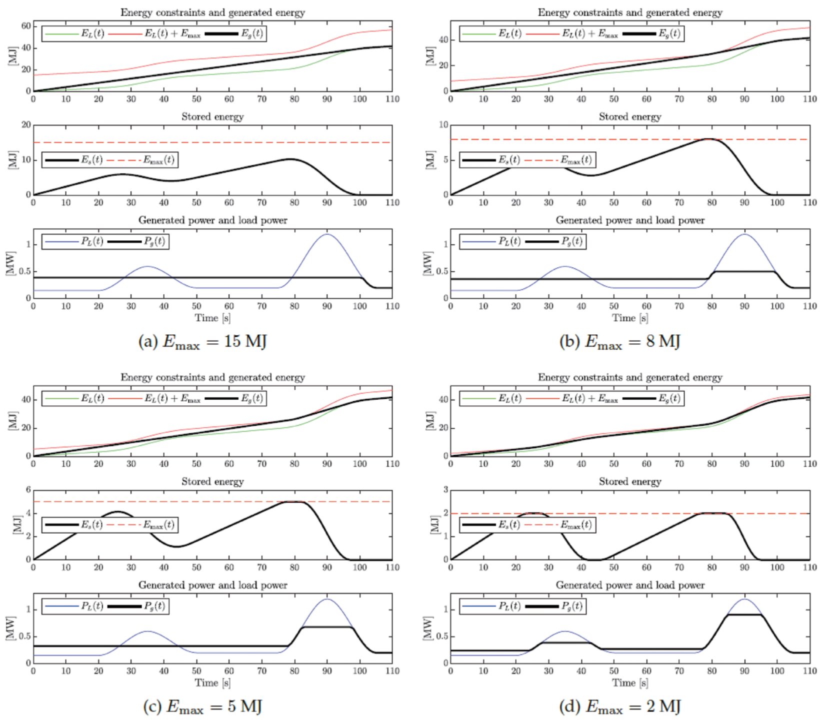
New Approaches for Managing Storage Systems in Future Grids

The research reported herein explores new approaches for large-scale utilization of energy storage devices in power grids, and the impact of these devices on possible integration of renewable and distributed sources of energy. Consider a general system consisting of generators, storage devices and loads, in which the generated power can be controlled. In such a system it is necessary to decide at every moment how much energy should be generated, and how much energy should be stored. The best mix is found by solving an optimization problem, in which the objective is to maximize the efficiency or to minimize the overall cost.

Paper[1] studies the optimal energy management strategy in complex networks with storage devices. The solution is based on dynamic programming, and utilizes the Bellman equation. This paper received considerable attention in the power systems community since it is the first paper showing the optimal energy management strategy for a storage device in a complex power network. The main idea is to view the energy stored in the device as a resource that should be optimally distributed within different time slots and throughout the network. This view enables to formulate the optimal control problem as an allocation problem, which is naturally solved using dynamic programming. Still a major challenge is how to handle the nonlinear power flow equations describing the grid. The paper shows an efficient numerical technique to do so for one or two storage devices.

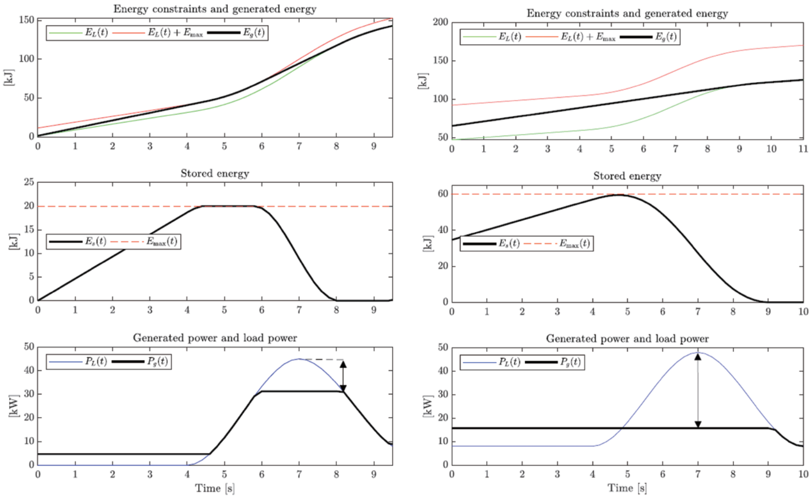
Papers[2, 3] explore the usage of storage devices for energy shifting and energy balancing. The main contribution of these works is the "shortest path" optimization technique: the optimal generated energy must follow the shortest path within two bounds set by the load profile, and the device capacity. This concept eventually allows simple planning of the optimal generated energy, and enables designers to estimate the required storage capacity for a specific application based on a graphical design procedure. Examples are shown in the following figures.

The optimal generated energy is the shortest path between the bounds, and the generated power is "as constant as possible". This intuitive result shows that for high capacity values the generated power is approximately equal to the average load, and for low capacity values it is



(a) $E_{max} = 15$ MJ (b) $E_{max} = 8$ MJ (c) $E_{max} = 5$ MJ (d) $E_{max} = 2$ MJ

Figure 2 The optimal generated energy $Eg(t)$ is the **shortest path** between the bounds, and the generated power $Pg(t)$ is "as constant as possible". For high capacity values $Pg(t)$ is approximately equal to the average load, and for low capacity values $Pg(t) \approx PL(t)$.



(a) Low capacity, high peak power (b) High capacity, low peak power

Figure 3 Optimal peak shaving strategy in a hybrid electric vehicle.

approximately equal to the load. Therefore, the shortest path method allows simple planning of the optimal generated energy, and enables designers to estimate the size of the storage device for a specific application. Paper[3] in the list above provides an optimal energy management strategy that minimizes the peak of the generated energy. The solution stems from the shortest path principle, as illustrated in the following figure:

We are currently trying to extend these results by showing how the shortest path idea relates to Pontryagin's minimum principle. Such a link may be theoretically interesting since it may demonstrate that the intuitive shortest path method can be extended to handle more complex systems. Another possible result is a low-complexity algorithm for calculating the shortest path when considering the uncertainty in the load profile.

Conclusions

A well-known challenge is how to optimally control storage devices to maximize the efficiency or reliability of a power system. As an example, for a grid-connected storage device the objective is usually to minimize the total cost, the total fuel consumption, or the peak of the generated power, while operating the device within its limits. The problem in this case is to decide how much energy should be stored, and when to store it. Such optimal control problems are generally hard to solve due to their high numeric complexity, and since in order to find an optimal solution one has to compute the stored energy at each and every point in time.

The overall aim of the reported research is to better understand management strategies of storage devices in autonomous systems and in future grids. Two obvious applications are the ability to integrated renewable energy sources into existing power grids, where storage is expected to be a key technology, and to enable improved energy management in electric vehicles. Paper[1] studies the optimal energy management strategy in complex networks with storage devices. The solution is based on dynamic programming, and shows an optimal energy management strategy for a storage device in a complex power network. The main idea is to view the energy stored in the device as a resource that should be optimally distributed within different time slots and throughout the network. Papers[2, 3] explore the usage of storage devices for energy shifting and energy balancing. The main contribution of these works is the "shortest path" optimization technique: the optimal generated energy must follow the shortest path within two bounds set by the load profile, and the device capacity. This concept eventually allows simple planning of the optimal generated energy, and enables designers to estimate the required storage capacity for a specific application based on a graphical design procedure.

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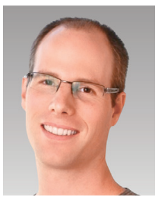

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