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Editorial

Control of Energy Storage

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Received: 30 May 2017; Accepted: 10 July 2017; Published: 16 July 2017

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1. Introduction

In the attempt to tackle the issue of climate change, governments across the world have agreed to set global carbon reduction targets. For instance, the UK has agreed to reduce the green house gas emissions by 80% of 1990 levels by 2050 [1]. In the pursuit of the carbon reduction, there has been a continuous shift towards the de-carbonisation of major infrastructures such as transport and energy, and an uptake of renewable power generation.

An increasing proportion of renewable energy introduces new challenges for the transmission and distribution system operators. The intermittent nature of the renewable energy resources impacts their power output, causing imbalance in supply and demand across the power system. Since the proportion of inverter-fed generation is also likely to increase, the natural inertia of the system would reduce. This in turn causes the grid's frequency to become less stable and deviate from its target more rapidly than in the present day.

Electrification of major infrastructures will cause an additional demand for electricity, which could potentially coincide with existing demand peaks. Furthering this peak demand imposes additional strain on the distribution network, which pushes both its thermal limits and its voltage constraints.

Energy storage is often viewed as a silver bullet to buffer the differences between the demand and supply. Additionally, it can improve network operation. With advancements in energy storage technologies, today's catalogue of energy storage systems offers a wide range of applications to choose from, where all yield some benefit at different levels throughout the entire network.

The collection of manuscripts in this editorial provides an insight into some of the cutting edge research on the control of energy storage for power systems.

2. Short Review of the Contributions in This Issue

The special issue of the MPDI *Energies* on "Control of Energy Storage" is focused on the control methods of energy storage for a range of applications and degrees of complexity. Specifically, the this special issue addresses the following topics:

- Control of energy storage.
- Energy storage systems for transport.
- Energy storage systems for grid support.
- Intelligent coordination of storage elements in the grid at micro and macro levels.
- Monitoring, modelling, and other performance assessment methodologies for the control of energy storage.
- Explorations of the future of energy storage systems and associated control problems.

The success of energy storage relies on the inclusion of the technical constraints and economic feasibility into the control strategies for the energy storage applications. The research articles included in this special issue cover the full range of aspects for the energy storage applications: from energy storage technology modelling for more predictable performance in real-life applications to micro and macro control strategies for energy storage in power systems of a range of sizes.

2.1. Modelling

Telaretti et al. [2] developed a multi-vector model for energy storage operation taking into account technical, economic, and financial aspects. Along with the model, the paper proposes an energy storage scheduling strategy designed to maximise the profit for the energy storage owner by providing price arbitrage services subject to the technical constraints of the energy storage system (e.g., rating, efficiency, and depth-of-discharge). The performance of the proposed strategy was assessed in a simulation of three energy storage technologies: lithium-ion (Li-ion), sodium-sulfur (NaS), and lead acid.

Looking into more detailed modelling, the performance and lifespan of modern battery chemistries depend on the internal temperature and the voltages on individual cells during the operation. Gao et al. [3] proposed a thermal model and equivalent circuit of a $LiFePO_4$ battery to accurately estimate the state-of-charge and temperature of the battery during operation. The proposed model have been validated on experimental results and shown to have high accuracy cell voltage estimation on a multi-cell $LiFePO_4$ battery.

2.2. Automotive Industry

Energy storage application in automotive industry is presented with unique operational conditions. Bruen et al. [4] presented a study on the effect of vibration on the lifespan and performance of nickel manganese cobalt oxide (NMC) Li-ion batteries, commonly found in electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEV). The results of the study were used to develop an equivalent circuit model for the cells and provide recommendation on the battery management strategies.

Moving on to control strategies for energy storage integrated into power systems, three research articles addressed the application of energy storage for improving the performance and economic efficiency of transport systems. Pietrosanti et al. [5] proposed a power management strategy for the control of a flywheel energy storage system on a rubber tyre gantry crane. A power management strategy was proposed in order to reduce the overall cost of energy that is required to operate the gantry crane. This strategy balances the power demands for container lifting operations, and the recovered energy when lowering the same. Due to the random duration of each such operation, the developed power management strategy was implemented using statistical load distributions. Numerical calculations using MATLAB/Simulink models of the required systems show increased energy savings and reduced peak power demand with respect to current control strategies.

Lin et al. [6] proposed a control strategy for super-capacitor installation to recover breaking energy fromurban rail trains. Introducing variable thresholds for the wayside energy storage system allowed the recuperation to make best use of the train's breaking *V-I* characteristics. Using a dual-loop control method enabled the authors to achieve the best energy-saving effect, which was verified through simulations and an experimental test on the Batong Line of the Beijing subway, using 200 kW wayside supercapacitor energy storage prototypes. Xia et al. [7] proposed a solution for super-capacitor sizing, placement, and control strategy for improving the efficiency of a metro line and improving voltage profile. The proposed solution is based on a novel optimisation method, combining genetic algorithms and simulation platform of an urban rail power system, including network, train, and energy storage system modelling.

2.3. Network Support

Energy storage also has potential to perform energy management and network support in standalone or grid-connected electricity distribution system—microgrids. Zangs et al. [8] proposed an improvement on the additive increase multiplicative decrease (AIMD) algorithm for enabling voltage support services from distributed energy storage devices in a low-voltage distribution network.

The improved algorithm—AIMD+—uses local voltage measurements against location-adjusted thresholds to improve voltage and thermal constraints on the network whilst providing more equal energy storage utilisation.

Nguyen et al. [9] proposed a model predictive control (MPC) system for power control of battery energy storage systems (BESS) in a micro-grid environment. Two variations of MPC—the proposed purely predictive power control and predictive current control with proportional-integral (PI)—are compared against the traditional PI control technique for BESS inverter control. The performance of the control techniques was assessed using MATLAB/Simulink models of a microgrid with a mix of generation sources, two energy storage systems, and a lump load, both in grid-connected and islanded modes. Results showed that MPC-based power control methods are best applied for BESS applications in power import/export control and frequency regulation in a microgrid, and the predictive current with inner PI control loop is more suitable BESS control for smoothing the wind power fluctuations.

Chae et al. [10] highlighted the difference between simulated and actual performance of islanded power systems. Authors presented results from economic feasibility studies of typical island power systems and microgrid island power systems. A representative model of a typical island power system supplied with diesel generators was assessed in a feasibility study tool called HOMER. The results of the study showed that the most economical operational costs remained the same—between 20% and 70% of energy supplied from renewable resources. Study of a planned power system on the test island showed that 91% of the energy will be supplied from the renewable resources, giving an 81% reduction in average fuel consumption. The real operational data showed the 82% of the energy was supplied from renewable resources, achieving fuel consumption savings of 80%. Discussion by the authors highlights the differences between the feasibility study against the actual observations and the effect of microgrid operation on the power quality and operational efficiency of the power system.

2.4. Demand-Side Management

One of the fundamental functions of energy storage is to shift energy usage in time. Demand-side management (DSM) can be viewed as equivalent to energy storage: the energy usage by a controllable load is managed with an aim to minimise the impact on the network (e.g., supply unbalance, frequency regulation, or network support) whilst maintaining the required function of the load for the benefit of the consumer.

Gelazanskas and Gamage [11] proposed a method for scheduling of domestic hot water heaters to compensate for the errors in day-ahead wind generation forecasts. The control system schedules the heating periods every 5 min for the next 12 h to adjust the demand to fill the gap or absorb the excess in supply. An artificial neural network is used to predict the loading of the water heater, allowing the heating periods to be scheduled without causing discomfort to the user. Results showed that the forecasting of energy usage by water heaters combined with scheduling lowers the energy requirement for hot water preparation and reduces the imbalance in supply for wind power generation.

On a larger scale, Kies et al. [12] addressed the issue of demand and supply unbalance in a simplified model of a fully renewable European power system by investigating the impact of DSM on the need for backup generation. Authors use ten years of weather and historical data to perform power flow analysis of several combinations of scenarios for transmission links capacities and distribution of generation capacity across Europe to assess DSM as an energy storage equivalent.

2.5. Frequency Regulation

Imbalance in supply and generation at the grid level causes deviation of frequency from the statutory range. Excess power generation allows the speed of rotating machines (e.g., steam turbines on coal and gas power plants) to increase, which in turn increases the grid frequency. Similarly, lack of supply leads to a decrease in frequency. Significant deviation from the statutory limits could lead to blackouts, as the generation plants and loads will be disconnected from the network by frequency-sensitive relays. Large-scale energy storage devices or coordinated behaviour of multiple small-scale energy storage devices could provide frequency regulation services to assist with maintaining the frequency within the nominal range.

Fu et al. [13] proposed a distributed control algorithm for the coordination of frequency regulation provided by multiple distributed resources. The algorithm uses an agent-based consensus control protocol, where each agent represents a system component capable of providing active power support and, through communication, aims to converge to a new common frequency state. Gatta et al. [14] present an application of $LiFePO_4$ BESS for primary frequency control. Electrical-thermal circuit models were developed for evaluation purposes, taking into account the cycle-life and auxiliary energy consumption. Numerical simulations then showed the trade-off between expected lifetime and overall system efficiency when performing droop controlled frequency control. Yang et al. [15] presented an optimal scheduling algorithm for an energy storage device providing frequency regulation service. The control algorithm uses particle swarm optimisation to compensate for the errors in state of charge estimation and adjust the operation of the energy storage device to maximise profit whilst ensuring availability for the automatic generation control signal.

3. Conclusions

The research articles in the special issue on "Control of Energy Storage" presented contributions from micro to macro scale of energy storage applications. Several works presented models for the prediction of performance and lifespan of the selected energy storage technologies. Control techniques for energy storage applications in transport and microgrid were presented, focusing on improvement of operation efficiency and power quality. On the larger scale, three articles addressed the aspects of frequency regulation provided by energy storage and demand response systems.

The collection of the research articles included in this special issue have demonstrated the wide range applications for energy storage and the role of modelling in delivering effective control systems for energy storage. Energy storage is expected to play an important role in keeping the lights on in the future low-carbon electricity networks. Further integration of renewable generation and low carbon technologies would require greater flexibility from the energy consumers and producers to ensure balance of supply and demand. Energy storage deployed throughout the network levels has the potential to provide the required flexibility and support network operation.

Acknowledgments: The authors are grateful to the MDPI Publisher and the members of the editorial team of "*Energies*" for the invitation to act as guest editors for the special issue.

Author Contributions: Timur Yunusov and Maximilian J. Zangs have reviewed the works included in the MDPI special issue on Control of Energy Storage and wrote the editorial. William Holderbaum is the academic editor for the special issue and have guided and reviewed the writing of the editorial.

Conflicts of Interest: The authors declare no conflict of interest.

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