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The true economic value of supply-side energy storage in the smart grid environment – The case of Korea

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ABSTRACT

With the rapid increase in variable renewable sources in the power system, storage capacity is being considered as an effective solution, because its flexible charging-discharging characteristics enable the reduction of the variability of these sources. However, the value of energy storage has been estimated mostly based on arbitrage benefit, and this does not reflect the true contribution of energy storage to the power system, especially when it is integrated with high levels of wind generation. This study analyzes a more complete set of contributions made by energy storage toward reducing the total cost of supplying electricity to customers. A simulation based on a stochastic form of multi-period Security-Constrained Optimal Power Flow (SCOPF) is used to reflect the stochastic characteristics of wind resources. The results show that in addition to the arbitrage benefit, energy storage can generate an additional economic value by 1) reducing the variability of wind generation; 2) adopting more wind generation that is otherwise wasted because of high variability, and 3) lowering the peak capacity needed to meet system adequacy. Moreover, the results indicate that the benefit of energy storage is larger with higher wind generation capacity.

1. Introduction

In the conventional power system, electricity should be produced at the time of consumption, and the processes of production and consumption should be simultaneous. Otherwise, electricity that is generated will be wasted. This is the main cause for inefficiency in power systems because they should maintain a large generation capacity to meet high electricity demand occurring in short peak periods, typically on hot summer days. For this reason, the efficiency of the US power system is known to be approximately only at 40%, according to the EIA (2012), and many natural gas(NG) power plants designed to meet the peak-hour demand only operate for less than 100 h out of 8760 operation hours per year. This means that most of the equipment installed to cover the peak demand remains turned off, for about 99% of the time.

Energy Storage Systems (ESS) are often considered as key components in enhancing the efficiency of the conventional power systems, as they can decouple the consumption of electricity from its production. ESS can significantly increase the efficiency of a power system by lowering the electricity demand at the peak hours, by moving the energy production required for peak demand to the off-peak hours. Pumped hydroelectric storage has been used in traditional power systems, but it cannot be widely used as a general solution, because it requires special geographical conditions that enable the use of potential energy stored in water. As an alternative, electrochemical energy storage, such as lithium-ion batteries (LIB), is actively being considered. Due to recent cost decreases in LIBs, many power system operators in various countries, including Korea, are considering the use of LIB in supplying electricity.

In addition to lowering peak electricity demand, ESS is a principal component that increases the efficiency of the non-dispatchable renewable sources, such as wind and solar power. Despite their benefits in reducing CO_2 emissions and lowering marginal cost of producing electricity, wind and solar power generation seriously undermine the reliability of power systems due to their inherent variability and uncertainty. Regarding the impact of wind generation on operating cost or CO_2 cost, the following literature provides empirical evidence. Valentino et al. (2012) focused on the environmental impact of incorporating wind power generation in the power system, using a model with unit commitment and economic dispatch, and shows that increased cycling and start-ups of thermal power plants due to variable wind generation, causes a negative impact on emission reduction. Ortega-Vazquez and Kirschen (2010) quantified the impact of wind power generation on operating cost, separately for startup cost,

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dispatch cost, CO_2 cost and the expected cost of outages. In addition, Hitaj (2013) analyzed key components that promote the deployment of wind power generation in the US and found that improving physical access of wind power generation to the grid, as well as providing financial support, are important.

Regarding the effectiveness of storage capacity in integrating wind power generation in the power system, studies such as Nyamdash et al. (2010) and Cavallo (2007) show that ESS is effective in improving the efficiency and reliability of variable renewable generation, especially wind generation, by mitigating its variability by storing excess energy that is not immediately consumed. Also, Zhao et al. (2015) analyzes ESS technologies and their potential in wind power integration and reviewed the planning problems in ESS adoption, including the selection of the ESS type, optimal location and size.

However, the active deployment of lithium-ion storage in the power system is still limited, because its cost is still considered higher than the profit it can achieve. The major benefit of using ESS in the current power system is profit from arbitrage, which is to buy electricity when it is cheap, and to sell it back to the grid when it becomes expensive. However, many studies, such as Walawalkar et al. (2007), Sioshansi (2009), Drury et al. (2011) and Bradbury et al. (2014), estimated that profit achieved only through arbitrage cannot validate the cost effectiveness of ESS.

As an alternative to the supply-side ESS which is designated only for supporting the grid operation, deferrable demand, such as electric vehicle and thermal storage for cooling which are demand-side storages, have been studied for cost validity (Short and Denholm, 2006; Sioshansi et al., 2009; Jeon et al., 2015a). Deferrable demand is considered cheaper, because the cost of energy storage can be shared between providing the service for its own purpose and supporting the grid. However, even though the profit of deferrable demand surpasses its cost, it faces two barriers for active deployment, namely, to develop a rate mechanism that makes customers participate, and to create a management scheme that can control the distributed resources.

Supply-side storage is easier to deploy and manage in the power system, if it is cost effective, because, similar to a conventional generator, it can be installed with large capacities, and directly accessed by the system operator. Hence, the deployment of supply-side storage will be more massive and prompt, as soon as it achieves economic viability.

In this study, we estimated the true value of the supply-side lithium-ion storage by assessing all aspects of contributions that storage offers in lowering the cost of supplying electricity to customers. As part of our methodology, we used the stochastic form of the Multi-Period Security-constraint Optimal Power Flow (MPSOPF) method to analyze the power system in Jeju Island in South Korea which has high penetration of wind capacity. We applied the time-series econometric method to develop a wind generation forecasting model for four actual wind farms in Jeju Island. The rest of the paper can be summarized as follows. First, we estimated the cost of wind variability that the power system must bear due to decrease in system reliability under different wind penetration levels. Second, we estimated the impact of lithium-ion storage in mitigating wind variability and lowering peak demand under different wind penetration levels. Third, we evaluated the true benefit of having lithium-ion storage coupled with high wind capacity by analyzing its contributions in moving peak demand to off-peak hours, mitigating wind variability and lowering peak demand. Finally, this paper proposed a reasonable cost scheme that reflects all the ESS contributions in improving the efficiency of the power system.

2. Model specifications

2.1. Model of the power system network

a) Specifications of MPSOPF

This study employed a stochastic form of security-constraint optimal power flow (SCOPF) model named Multi-Period SuperOPF (MPSOPF). This power system optimization platform was developed according to the architecture of MATPOWER (Zimmerman et al., 2011). The objective function of MPSOPF (Eq. (1)) is used to minimize the expected system cost including the generation cost and to consider the cost of a set of stochastic scenarios for wind generation and a set of contingency scenarios for a 24-h horizon in a day-ahead planning scheme. This power system optimization is conducted within constraints, such as the given load pattern for 24 h, physical restrictions of the generator, network restrictions, stochastic features of the wind generation and contingency scenarios.

$$\begin{aligned}
&\min_{G_{itsk},\quad R_{itsk},\quad LNS_{jtsk}} \sum_{t\in \mathrm{T}} \sum_{s\in \mathrm{S}} \sum_{k\in \mathrm{K}} \pi_{tsk}\{ \sum_{i\in I} [C_{G_i}(G_{itsk}) + Inc_{its}^{+}(G_{itsk} - G_{itc})^{+} \\
&+ \quad Dec_{its}^{-}(G_{itc} - G_{itsk})^{+}] + \sum_{j\in J} VOLL_j LNS(G_{tsk}, \quad R_{tsk})_{jtsk}\} \\
&+ \quad \sum_{t\in T} \rho_t \sum_{i\in I} \left[C_{R_{it}}^{+}(R_{it}^{+}) + C_{R_{it}}^{-}(R_{it}^{-}) + C_{L_{it}}^{+}(L_{it}^{+})\right. \\
&\left.+ C_{L_{it}}^{-}(L_{it}^{-})\right] + \quad \sum_{t\in T} \rho_t \sum_{s_2\in S^t} \sum_{s_1\in S^{t-1}} \sum_{i\in I^{ts2}} [Rp_{it}^{+}\left(G_{its_2} - G_{its_1}\right)^{+} \\
&+ Rp_{it}^{-}\left(G_{its_2} - G_{its_1}\right)^{+} + \quad f_s(p_{sc}, \quad p_{sd})]
\end{aligned} \tag{1}$$

MPSOPF has three important features that differentiate it from the other SCOPF models. First, it allows the stochastic characteristics of the wind generation and load to be represented in the model as a form of multiple scenarios with transition probability; therefore, it allows the analysis of the power system with respect to the uncertainty that faces the system operator in the day-ahead planning. Second, it endogenously determines the amount of optimal hourly reserve needed to maintain the system reliability, as well as the amount of energy for each generator simultaneously. In MPSOPF, the reserve consists of load-following reserve and contingency reserve. Third, as indicated by the model name, it allows the simulation of the power system in a multi-period scheme, typically for 24-h, which is essential in assessing the decision of ESS charging and discharging in the power system. This is not a trivial issue, since it considers the uncertainty the system operator faces to determine the proper level of energy storage to maximize the profit through arbitrage and through mitigating the wind variability. Nomenclature for Eq. (1) is included in the Appendix A, and detailed information regarding MPSOPF can be found in Zimmerman and Murillo-Sanchez (2013)[1]

a) Specifications of Jeju power system network

Fig. 1 shows the Jeju power system network constructed based on MPSOPF. Jeju Island is located in the Southwest area of the Korean peninsula, and its size is approximately half of Long Island. The population size is about 0.6 million, and its peak electricity demand was approximately 715 MW in 2015. The conditions of Jeju Island are suitable for conducting a proper power system network test. Its system size is approximately 1 GW, which is appropriate for the academic study, and the island is considered a smart grid test-bed in South Korea. It has a very high wind generation capacity and other new technologies employed, such as electric vehicles; in addition, smart metering and demand response are being rapidly incorporated. Jeju power system shown in Fig. 1 consists of 16 buses, 29 transmission lines, eight conventional power plants, and four wind farms. Detailed information of the power system is summarized in Table 1.

Table 2 shows the information of four wind farms in Jeju Island. The installed wind capacity in Jeju Island is 156.3 MW as of 2015, which represents approximately 21.9% of the peak demand. This wind capacity is projected to an increase to reach 597.3 MW in 2020, which would represent approximately 83.5% of the peak demand. Hence, it is

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[1] Zimmerman, Ray and Murillo-Sanchez Carlos, “Multi-Period SuperOPF User's Manual”, 2013.