Modeling and tasks of dispersed energy storage for secure and optimal operation in distribution system

Tatiana Sokolnikova
Konstantin Suslov

NR Irkutsk State Technical University
Irkutsk, Russia
sokoltvz@gmail.com

Natalia Moskalenko
Christian Klabunde
Przemyslaw Komarnicki

OvGU & Fraunhofer Institute IFF
Magdeburg, Germany
natalia.moskalenko@ovgu.de

***Abstract*—Secure operation of power system is hindered last year essential by different factors like fluctuated renewable generation or wide use of power electronics as well. With increased use of energy storage for smoothing this fluctuation, the costs of these units are decreasing. Because of this fact, these units will be used also for another applications: for technical issues (e.g. power quality improvement), market issues, as well as for the optimal energy management especially in the distribution system.**

In this paper, after an overview of the storage technologies usable in the dispersed manner, the numerical model of storage has been introduced. Taking this model into account, some study cases in which the use of energy storage can be favorable are modeled and results of corresponding computation are presented and discussed. The benefits of energy storage use and current existing obstacles are finally pointed out.

***Index Terms*-- distributed generation, energy storage system, electricity market, optimization, security of power supply**

I. Introduction

The power system changes in the last year rapidly. Firstly continually growing integration of renewable energy sources (RES) into electrical grid leads to uncontrolled fluctuations in power system. Further, the loads become also more nonlinearity by wide using of power electronics [1]. These facts increase the need of the energy storage systems (ESS), which can smooth the energy supply, stabilize the power system and in this case, are one of the most important components for the realization of secure and sustainable future energy supply system [2], [4], [5].

Energy storage systems can be used in all sectors of the power grid. For example, they support big power plants during the scheduled load changes. For the transmission networks, energy storage systems provide:

- electrical power during power outages, and
- system services (e.g. compensation of reactive power for voltage stability or provision of balancing power for frequency stability).

For the distribution networks, the energy storage systems make congestion management possible, help maintain voltage stability and power stability, and make it possible to create virtual power plants. Thus, they can be used for technical and market reasons. On the consumer side, energy storage systems support the security of power supply, which is especially important for critical loads.

The properties of various storage technologies and specific application are e.g.: voltage control [2] power flow management [6], restoration [7], network management [8]and participation in the energy market [9].

In this paper, after an overview of the storage technologies usable in the dispersed manner, the numerical model of storage has been introduced. Taking this model into account, some study cases in which the use of storage could be favorable are modeled and results of corresponding numerical computation have been presented and discussed. The benefits of the storage use and current existing obstacles have been finally pointed out.

II. Use of energy storage in the distribution system - overview of the useful technologies

Energy storage systems can store electricity by changing it into another form of energy: mechanical, magnetic, chemical, electrochemical etc. [10]. Batteries as well as power-to-gas storages store electricity in a chemical form. Diabatic Compressed Air Energy Storage Systems (CAES) and flywheels store it in its mechanical form, while the Adiabatic CAES (ACAES) systems store electricity in thermal and mechanical forms. The electricity can also be stored as magnetic energy if Superconductive Magnetic ESS (SMES)

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are used or as gravitational energy if pumped hydro power systems are chosen.

However, storing electricity in another form is energetically expensive since all of the energy storage processes incur energy losses. Depending on the storage technology, the storage losses can range from 8 % to 55 % of the input electricity [11].

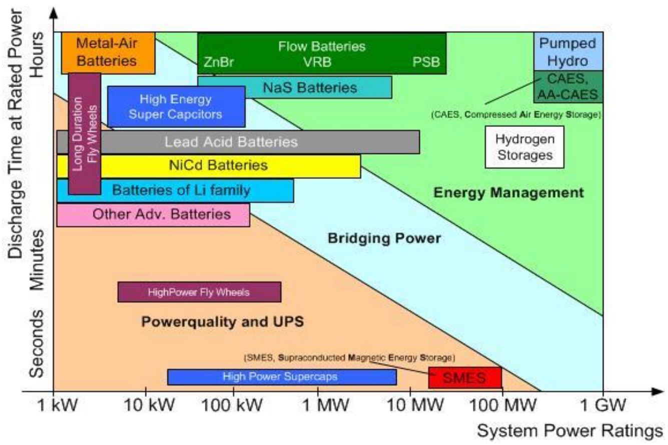

Figure 1. Fields of application of energy storage systems [2].

Energy storage systems can be classified according to a bi-criteria method: the system power rating and the discharge time at rated power. Using this method, three different fields of application can be distinguished: power quality, bridging power and energy management (see Fig.1). In the bridging power applications, ESS are used for switching from one power generator to another. The main purpose is to ensure continuity of power supply. Its usage is in the order of minutes to hours. Usually batteries are used to bridge the power. For energy management purpose the storage systems have to be able to store a high amount of power for long time. The discharge time ranges from a few to many hours. Pumped hydro systems, CAES, hydrogen and batteries are the most used technologies for energy management.

Depending on the storage technology, the investment cost range from few hundred US dollar per kW to more than 8000 US dollars per kW [2], [12].

TABLE I: THE TOTAL INSTALLED TYPES OF STORAGE CAPACITY WORLDWIDE AND THEIR APPLICATION [2]

Technology		Total installed	Size ranges	Potential application
Pumped hydro		110 GW	Up to 2.1 GW	• load leveling • spinning reserve
CAES		477 MW	25 MW – 350 MW	• peak shaving • spinning reserve
Batteries	Lead Acid	125 MW	100 W – 20 MW	• integration with renewables
	Na-S	~ 200 MW		• load leveling
	Redox	38 MW		• peak shaving
	Ni-Cd	26 MW		• spinning reserve
	Li-Ion	~ 517 MW		• power quality
Flywheels			kW scale	• power quality
SMES			10 – 100 MW	• power quality
Supercapacitors			7 - 10 MW	• power quality

Nowadays, as depicted in Table I, the most used ESS technology worldwide is the pumped hydro system. Because there are only two diabatic systems (CAES) in operation, the total amount of installed capacity is low. Among the battery technologies, the Lithium-Ion and Sodium-Sulfur high temperature batteries (NaS) have had a high use recently.

III. MODELLING OF THE ENERGY STORAGE

A general model of an energy storage system is depicted in Fig. 2. Electrical energy generated either through fossil based or through RES based power plants is stored inside a storage medium. As it was discussed above, it can be stored in a different form (like chemical (battery technology), mechanical (compressed air), gravitational (pumped water) or thermal (hot water)) than its generated form. The stored energy is then converted again into electricity when the storage system is discharged. By charging/discharging an energy storage system a part of energy is lost.

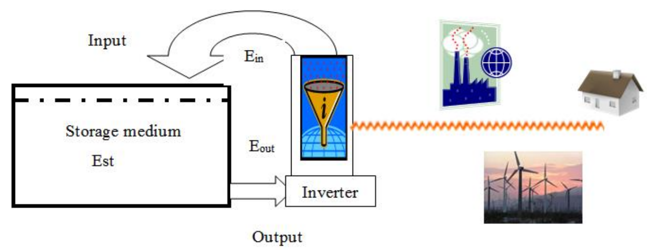

Figure 2. General energy storage model.

Equation 1 describes the energy balance during the charging and discharging phase:

$$\mathrm{E_{out}} = \eta\, \mathrm{E_{in}} \quad \text{and} \quad \mathrm{E}_{out} = \mathrm{E}_{in} - \mathrm{E}_{l} \qquad (1)$$

where:

η – efficiency ($\eta \leq 1$)[-],
E_{out} – discharged Energy [Wh],
E_{in} – charged Energy [Wh],
E_{l} – lost Energy [Wh].

The power of an energy storage system can be distinguished as input power (P_{in}) and output power (P_{out}) (2):

$$\begin{aligned} \mathrm{P_{in}} &\neq \mathrm{P}_{out} \\ \mathrm{P_{in}} &= f(t,n) \\ \mathrm{P_{out}} &= f(t,m) \end{aligned} \qquad (2)$$

where: the input and output power are dependent on time t and other technological parameters given here symbolic as n or m (e.g. temperature, kind of storage etc.).

Storage technologies with high capacity are especially useful for the integration of renewables into the electric power system. From this point of view the pumped water systems, the compressed air energy storage and the H_2-storage are preferable. The first two technologies have reached a technological maturity which makes them more preferable from the economic point of view. However, they require special local arrangements (rivers, mountains, caverns etc.) which may limit their utilization.

The storage systems have different kind of operation. The charging and discharging modes are dependent on the technology and State-of-Change (SoC). Generally the charging process is more time intensive than the discharging one. If the storage process requires a conversion of energy form (e.g. electric energy to chemical energy), the charging process is more complicated and it is also related to thermal behaviors. The battery technology will be explained in more detail as follows. This storage technology may be mainly used in distribution system for technical and market issues and also for small island power systems (micro grid). The thermal state of the battery storage should be supervised and controlled because of the possibility of damage. The charging process is generally provided by two characteristic periods: constant current at the beginning and constant voltage at the end of this process.

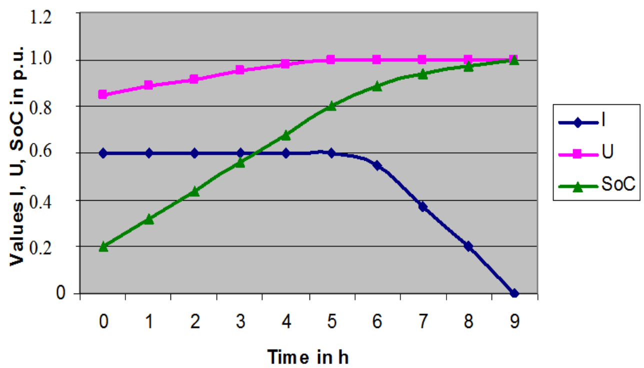

Figure 3. General schema of battery charging process.

In Fig. 3 an example of general charging strategy is given. The Y axis depicts the values of voltage, current and SoC, which are normalized and given as per unit (p.u.) value. The selection of charging current depends on battery technology and the charging time. Generally, a limit of 10 hours is assumed to fully charge a battery. In the first 5 hours the battery is charged with a constant current of 0,6 p.u. When it reaches the nominal voltage (1 p.u.), it is charged at constant nominal voltage. When the SoC reaches the value 1 p.u., the charging current decreases to 0 p.u., and the charging process ends. In reality, it may happen that the battery is charged up to SoC higher than 1 p.u. because of some electrochemical process, which may appear. This aspect is not depicted in the ideal case as shown in Fig. 3.

IV. USE CASES – DISTRIBUTED ENERGY STORAGE IN THE POWER SYSTEM

A. Technical issues (abandon of reinvestment in the network)

The scope of this chapter is to reduce the overloading of electrical equipment (e.g. power cables) with the help of energy storage system. This situation can be relevant, when into existing power grid are integrated additional consumers or generators that can cause the occasional (for example seasonal) consumption peaks, which can exceed the allowed power during only some short periods of the year. Such consumption peaks lead to overloads in the power grid, which can be a matter of cable damage. To avoid such effect, the existing power grid should be improved, i.e. the existing cables should be changed with a cable of bigger cross section. If such overloads appear not permanently but only some times during a year, the power grid extension is not economically beneficial. Another possibility is the demand side management or disconnection of non-critical loads for the periods of high consumption. But in the case, when the consumers are presented mostly with non-controllable or critical loads, such a method can be not useful. That is why the usage of energy storages with appropriative parameters can be good alternative for it.

In this study the electricity load of certain small industrial enterprise is analyzed. The electricity load for the time period of one week, when the peak loads occur, is presented in Fig. 4. The considered load profile has two peak loads periods during the day: from about 09:00 till 13:00 and from 15:00 till 18:00. The basic electricity load is about 110 kW, the peak consumed power of this enterprise is about 420 kW that occurs only during few hours annually. The transmission capacity of the cable is 380 kW. Thus the energy storage with capacity that corresponds to the electricity of the maximal peak loads during one day annually can be used for this purpose. The energy storage needs to have a short reaction time, high efficiency and high energy density. Thus the electrochemical energy storage is chosen for such investigation, namely the lead-acid battery.

The calculation results show that the needed capacity of energy storage is 68 kWh. The other parameters considered for energy storage are: the charging power is 15 kW, discharging power is 38 kW and total efficiency is 0.8. The energy storage in this case is charged during the time of low consumption, from 18:00 till 08:00 and between the periods of peak loads during the day (about 13:00 – 15:00), if the free capacity is available. The charging of the battery together with the main electricity consumption should not exceed a value of transmission capacity of cable. Thus, due to the usage of energy storage, the enterprise receives the additional flexibility as well as reduces the overloads in the grid equipment.

In order to show the economic benefit from usage of energy storage the investment costs analysis is done (see Table II). Thus, it can be seen that even if the lifetime of battery is about 8 years, the investment costs for considered capacity and type of battery are lower in comparison with the power grid extension, even under consideration of 20 years period. It shows that the usage of energy storage for the reducing of occasional overloads in power grid equipment is possible and can be economically profitable, depending on the storage capacity and type.

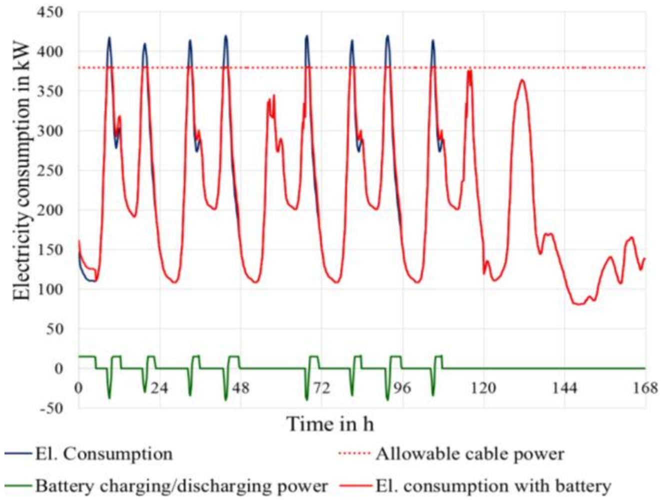

Figure 4. Electricity consumption for considered example.

TABLE II: COMPARISON OF INVESTMENT COSTS FOR ENERGY STORAGE AND POWER GRID EXTENSION [17]

Energy storage costs			**Power grid extension**	
Parameters	*min*	*max*	*Parameters*	*Values*
Lead-acid battery, €/kWh	180	220	Max length of 380kV-cable (low voltage, urban), km	0.7
Inverter costs, €	160		Cable costs, €/km	100000
Other expenses	25 % from the total price		Costs for output feeder panel, €	10000
Lifetime, years	8		Lifetime, years	20
Investment costs, €	**22 770**	**26 132**		**80 000**
Investment costs for 20 years, €/year	**3 415**	**3 919**		**4 000**

B. Market issues (new market design in the distribution)

In the scope of this chapter is explained the support of energy storages during the participation of renewable energy sources at the electricity market. The European Energy Exchange (EEX) in Leipzig is the biggest market place for electricity produced in Germany, where the electricity generated in Germany, France, Switzerland and Austria can be traded. Electricity on the EEX can be traded either on the spot market (EPEX SPOT in Paris) or on the futures markets. The spot market is used as a trading platform for the short-term supplied electricity within 1-2 days: day-ahead and intraday markets. The futures markets provide the contracts for the long-term supply of electricity [13]. In the scope of this paper the participation on the day-ahead market is considered in detail. Thus, the participant determines the bids for power generation and power consumption for each hour of the next day and before 12 o'clock of the contract day [13]. The price estimation for each hour is calculated by the intersection of supply and demand curves [14]. The minimal capacity for the day-ahead market is 0.1 MWh, and the price can vary between -500 €/MWh and 3000 €/MWh [15].

In order to achieve the maximal profit at the day-ahead energy market, it is needed to analyze the electricity price and try to sell electricity during the time of high prices. The fulfillment of this task is especially difficult for renewable energy sources because of their stochastic generation character. Thus, during the period of high price the generated amount of renewable energy can be low. For reduction of such a drawback the energy storage can be used. The main idea of this study is to investigate the influence of energy storage for increasing profit during the participation at the day-ahead electricity market. It will be compared the pa-rticipation at the electricity market with energy storage and without it. The selling of electricity is specified by the actual electricity price. It is profitable to sell the produced electricity only during the periods of high electricity prices and to store it in the energy storage during the periods of low electricity price.

In order to show the influence of energy storage, two simulation scenarios are considered. In the first case is discussed the participation of renewable energy sources at the market without energy storage. In this case, the whole electricity from renewable energy sources is directly sold to the grid independent on the actual electricity price.

In the second case the electricity from renewable energy sources can be stored in the electricity storage – during the periods of low electricity price – if the storage has available capacity for it. When the electricity price is high, the energy both from renewable energy sources and from energy storage is sold to the grid. When the storage is fully charged, but the electricity price is still low, the stored energy will be damped and only produced renewable energy will be sold to the grid. Thus the energy storage provides a higher flexibility of renewable energy usage to achieve the higher profit from the participation on the day-ahead market.

For the simulation the following parameters are used:

- wind turbine with a rated power of 2.05 MW, power coefficient 0.5 and rotor diameter 82 m [16];
- photovoltaic park with rated power of 3 MWp, area of about 21000 m^2 and efficiency 0.12;
- weather data about wind speed and global radiation for June in region Magdeburg, Germany with time interval 1 minute;
- electricity price of day-ahead market for June with time interval 1 hour;
- energy storage is presented with Li-Ion battery, that has a capacity 2 MWh, charging/discharging power corresponds to 2 MW, the total efficiency is 0.9; the initial state of the battery for the first day of consideration is equal to zero.

In considered examples the simulations were carried out for 1 day and for 1 week. The calculation results for the time period of 1 day are shown in Fig. 5. It is assumed, that the accurate forecasting of electricity price is given for the next day. The maximal and minimal values of electricity price are determined for each day.

Because of a very stochastic and strongly variable character of electricity price, an appropriative method for battery scheduling is necessary. Thus, the battery is charged during time periods when the electricity price is not higher than 60 % of minimal value for considered day. The range for battery charging is required to ensure the charging of battery during the low prices. If this range becomes too narrow, it can lead to situation, where the battery is not fully charged, because the majority of electricity price values are much higher than the minimal price for considered day. If the battery is already full, the generated renewable energy is sold to the grid according to the actual electricity price. At the time of maximal price the whole stored energy is discharged along with the actually generated renewable energy and is sold to the power grid. Such a structure provides selling of energy stored in the battery into the grid for high price.

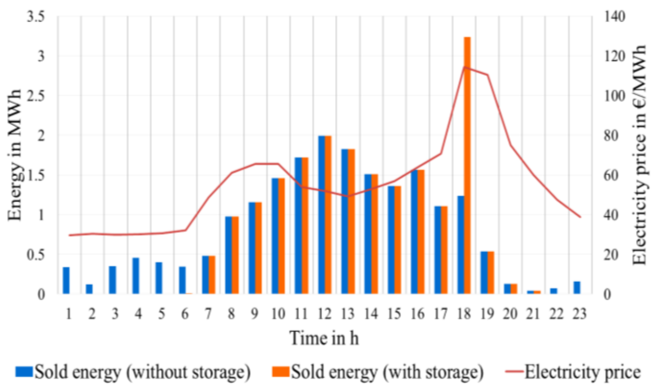

Figure 5. Usage of energy storage for the marketing of renewable energy at the day-ahead energy market.

The results presented in the Table III show the example of calculation for one certain day and one week. The usage of energy storage provides additional flexibility to the operators of renewable energy sources and allows increasing their profit at the day-ahead energy market. Thus the increasing of profit for considered day is 13.66 % and for considered week is 7.26 %. The profit that can be achieved varies strongly depending on the actual renewable energy production, the current electricity price, the price difference for considered day and properties of applied energy storage.

TABLE III: COMPARISON OF PROFIT FROM THE USAGE OF ENERGY STORAGE [17]

	Profit		Delta profit	
	without energy storage, €	*with energy storage, €*	*€*	*%*
for 1 day	1158.15	1316.38	158.23	13.66
for 1 week	6655.75	7139.10	483.35	7.26

V. CONCLUSIONS

This paper presents an analysis of the existing energy storage systems and also presents the comparison of their properties. The main aspects concerning the modelling of energy storage are explained. The usage of energy storage for different purposes is considered. In the first case the energy storage provides the technical issues. It is considered as an alternative to the power grid extension to reduce the overloads in the grid equipment and can be favorable, as shown in the given example. In the second case the energy storage is used to improve the participation of renewable energy sources at the energy market. In the specific situation a benefit for this kind of use can be also reached.

Furthermore detail investigation for other technical issues like voltage stability or reactive power compensation will be done. Especially promising could be a simultaneous use of storage for different technical and marked issues. This required a new, sophisticated concept of EMS system. Such a complicated tool is already not available on the marked and this is currently a mean obstacle in wide use of energy storage. The definition of such a tool and its developing will be also the task of further investigations and works.

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