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Optimized Installation and Operations of Battery Energy Storage System and Electric Double Layer Capacitor Modules for Renewable Energy Based Intermittent Generation

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Abstract – In this paper, a novel approach for optimized installation and operations of battery energy storage system (BESS) and electric double layer capacitor (EDLC) modules for the renewable energy based intermittent generation is presented for them to be connected with an electric power grid. In order to make use of not merely the high energy density of battery but also the high power density of EDLC modules, it is very useful to devise the hybrid system which combines BESS and EDLC modules. The proposed method adopts the linear programming to calculate the optimized capacity as well as the quadratic programming to transmit the optimal operational signals to BESS and EDLC modules. The efficiency of this methodology will be demonstrated in the experimental study with the real data of wind speed in Texas.

Keywords: Battery energy storage system (BESS), Electric double layer capacitor (EDLC) modules, Intermittent generation, Optimization technique

1. Introduction

The proportion of renewable energy and electric vehicles with V2G (Vehicle-to-Grid) capability is expected to spread dramatically as the cost of fossil fuels increases. Although the renewable energy such as wind and solar or V2G generation is one alternative to fossil fuels, it is so intermittent that it cannot always provide power to an electric power grid because it cannot arbitrarily increase its power as a grid's need. As a result, it is especially vulnerable to the reliability of the electric power grid due to its serious volatility. In this context, many reliability councils set the restrictions for the connection between intermittent generation and the electric power grid. For instance, if intermittent generation is more than the demand of grid, it is, to some degree, desirable to save extra power of intermittent generation for the future's demand.

Although a battery energy storage system (BESS) facilitates further storage of the extra power, it is somewhat difficult to charge and discharge in a short time horizon. In other words, it has not high power density but high energy density. In this perspective, an electrical double layer capacitor (EDLC) may be used as a substitute or combination with a battery because an EDLC is able to charge or discharge rapidly and its properties last a lot longer than a battery. By contrast, an EDLC has lower energy density than a battery even if it is typically hundreds of times greater than a conventional electrolytic capacitor.

As mentioned earlier, a battery and an EDLC have their own defects; it is advisable to mix BESS and EDLC modules to make up for the disadvantages and strengthen their advantages. To do this, it is ultimately necessary to calculate the optimum capacity of BESS and EDLC modules according to the size of intermittent generation. In addition, it is also needed to generate control signals for optimal operations of BESS and EDLC modules.

In [1-2], the power operation strategy of BESS and EDLC modules was used for electric vehicles in order to take advantage of energy density of battery and power density of EDLC modules. For the grid connection of the intermittent generation, a predictive control model was suggested in [3].

In this paper, the computation technique for optimized capacity of BESS and EDLC modules for intermittent generation will be explored for their connections with an electric power grid. And then, the optimized operations of the hybrid system which are accurately implemented by the proposed methodology will also be verified.

2. Requirements for Integration into Grid

In order to efficiently integrate intermittent generation into the power grid, the typical requirements associated with the active power must be faithfully observed [4]:

- Ramp rate
- Power curtailment
- Power droop with frequency

The ramp rate of intermittent generation is taken into

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account for satisfying the capacity of frequency regulation. Recommended values of maximum ramp rate for wind farms, which are likely to be connected with the power grid in China, are listed in the following:

Table 1. Wind power grid code in China

Wind Farm Installation Capacity [MW]	10-min Maximum Ramp Rate [MW]	1-min Maximum Ramp Rate [MW]
< 30	20	6
30 - 150	Installation Capacity / 1.5	Installation Capacity / 5
> 150	100	30

Source: Presentation of CEPRI, March 15, 2007.

3. System Configuration

3.1 Overview

It is generally difficult to meet the typical requirements associated with active power when there is only intermittent generation. Accordingly, we fully intend to choose a basic hybrid system consisting of BESS, EDLC modules, and intermittent generation as shown in Fig. 1.

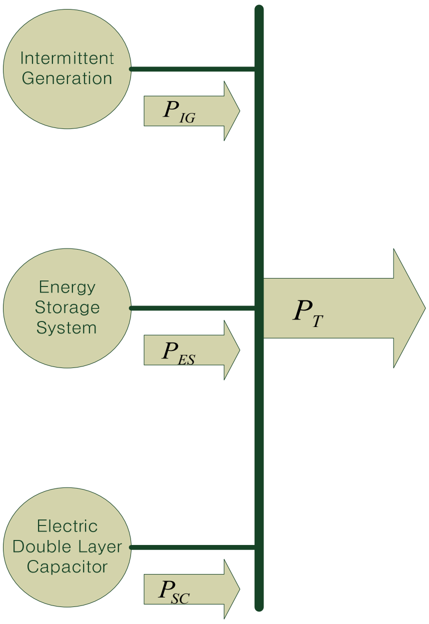

Fig. 1. Hybrid system for intermittent generation

In Fig. 1, P_{IG} [MW] is the output of intermittent generation, P_{ES} [MW] is the output of BESS, P_{SC} [MW] is the output of EDLC modules, and P_T [MW] is the total output of the hybrid system.

The hybrid system utilizes the BESS to deal well with the ramp rate constraint and the EDLC modules to overcome sudden changes in output of intermittent generation considering the life of the energy storage.

3.2 Optimized capacity

In this paper, the computation technique for optimized capacity of BESS and EDLC modules is proposed in order to minimize the installation costs while meeting the grid connection requirements. The objective function of the proposed method is as follows:

$$Min\ C_{ES}E_{ES} + C_{SC}E_{SC} \tag{1}$$

where, C_{ES} and C_{SC} are costs per MWh of the BESS and the EDLC modules, respectively. Here, E_{ES} [MWh] and E_{SC} [MWh] are the energy capacity of the BESS and the EDLC modules, respectively.

Fig. 2 indicates the power and energy capacity of the hybrid system by taking into account the ramp rate constraint when intermittent generation fails to generate electric power. In this case, $P_{IG,\,MAX}$ [MW] is the maximum output of intermittent generation and $P_{T,\,RR}$ [MW/min] is the ramp rate constraint. The *x*-intercept is defined as the time elapsed since the output of the hybrid system fell at the rate of $60{\cdot}P_{T,\,RR}$ [MW/hr] from $P_{IG,\,MAX}$ to the zero.

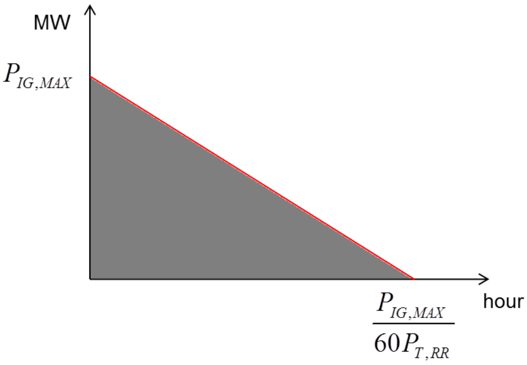

Fig. 2. Power and energy capacity of the hybrid system

In Fig. 2, the power and energy capacity of the hybrid system may be determined as mentioned below:

$$P_{ES,MAX} + P_{SC,MAX} \geq P_{IG,MAX} \tag{2}$$

$$E_{ES} + E_{SC} \geq \frac{1}{2} P_{IG,MAX} \frac{P_{IG,MAX}}{60P_{T,RR}} \tag{3}$$

Most of all, (2) means the restriction for meeting the ramp rate constraint with only the output of BESS and/or EDLC modules when the output of intermittent generation unexpectedly decreases from the maximum value to the zero.

On the other hand, (3) implies the energy capacity of the BESS and EDLC modules needed to respect the ramp rate constraint when the output of the hybrid system reaches the zero at the rate of $60{\cdot}P_{T,\,RR}$ [MW/hr].

Assuming the operations in the middle state of charge

(SOC) range, (3) must be changed to (4):

$$E_{ES}+E_{SC}\geq P_{IG,MAX}\frac{P_{IG,MAX}}{60P_{T,RR}} \tag{4}$$

When half the capacity in BESS and EDLC modules is stored, i.e., at the 50% of SOC, this case calls for the energy capacity twice as much as 100% of SOC.

In fact, the energy capacity is fairly related to the maximum power of energy storage system. The relation between energy capacity and maximum power may be obtained by the energy density and power density of energy storage system. In the same manner, it is true of EDLC modules. This relation is mathematically expressed by:

$$\frac{P_{ES,MAX}}{D_{P,ES}}=\frac{E_{ES}}{D_{E,ES}} \tag{5}$$

$$\frac{P_{SC,MAX}}{D_{P,SC}}=\frac{E_{SC}}{D_{E,SC}} \tag{6}$$

where, $D_{P,ES}$ [MW/kg] and $D_{E,ES}$ [MWh/kg] are the power density and the energy density of the energy storage system, and $D_{P,SC}$ [MW/kg] and $D_{E,SC}$ [MWh/kg] are the power density and the energy density of the EDLC modules, respectively.

Apparently, the minimum costs to install the BESS and EDLC modules may be derived by the linear programming with the inequality constraints in (2) and (4) and the equality constraints in (5) and (6).

4. Optimized Operations of Hybrid System

The battery degradation is relatively infinitesimal in case of low current and low internal resistance. For low current, small current deviation is required and operations in the middle SOC of the battery range is evidently sufficient for low internal resistance. If the voltage of the hybrid system is assumed to be constant, the current deviation is proportional to the power deviation. Therefore, the objective function of the proposed method is divided into two parts, that is, the former is the term to minimize the deviations of real power output and the latter is the term to maintain 50% of SOC.

$$Min\begin{array}{l} w_{ES}(P_{ES}-P_{ES,\text{Prev}})^2+w_{SC}(P_{SC}-P_{SC,\text{Prev}})^2\\ +w_{SOC_{ES}}(SOC_{ES}-50)^2\\ +w_{SOC_{SC}}(SOC_{SC}-50)^2\\ +w_T(P_T-P_{IG,\text{Prev}})^2 \end{array} \tag{7}$$

where, w_{ES} and w_{SC} are weighting factors of power deviations of BESS and EDLC modules, respectively. $w_{SOC^{ES}}$ and $w_{SOC^{SC}}$ are weighting factors to keep 50% of SOC in BESS and EDLC modules, respectively. P_{ES} and P_{SC} are real powers of BESS and EDLC modules, respectively. $P_{ES,Prev}$ and $P_{SC,Prev}$ are real powers at the previous control period of BESS and EDLC modules, respectively. SOC_{ES} [%] and SOC_{SC} [%] are SOCs of BESS and EDLC modules, respectively. Obviously, P_{ES} and P_{SC} are the proposed outputs of the hybrid system. The last term of the objective function allows for the stability of the proposed system. The term relating to the total output of the proposed system and the output of previous intermittent generation provides the reference to the system. Undoubtedly, w_T is a weighting factor of this reference. The total output is described by:

$$P_T-P_{ES}-P_{SC}=P_{IG,\text{Prev}} \tag{8}$$

If the hybrid system is controlled every T seconds, the changes of SOC_{ES} and SOC_{SC} are as follows:

$$SOC_{ES}=SOC_{ES,\text{Prev}}-P_{ES}\frac{T}{3600}\frac{100}{E_{ES}} \tag{9}$$

$$SOC_{SC}=SOC_{SC,\text{Prev}}-P_{SC}\frac{T}{3600}\frac{100}{E_{SC}} \tag{10}$$

where, $SOC_{ES,Prev}$ and $SOC_{SC,Prev}$ are SOCs at the previous control period. Since 1 [MWh] is regarded a unit of energy equivalent to one megawatt of power expended for one hour of time, or 3600 [sec], the amount of energy converted, if work is done at an average rate of P [MW] for T [sec], is $P{\cdot}T/3600$. The changes of SOC are, thus, $P{\cdot}T/3600{\cdot}100/E$ when E is the energy capacity of energy storage systems.

The difference between the previous output and the current output of the hybrid system must be less than the ramp rate constraint.

$$\left|P_T-P_{T,\text{Prev}}\right|\leq P_{T,RR}\frac{T}{60} \tag{11}$$

where, $P_{T,Prev}$ is the total real power output at the previous control period of the hybrid system.

If the 10-minute ramp rate constraint is applied as in China, the output of the hybrid system must be dictated by the following formula.

$$\left|P_T-P_{T,\text{Prev10}}\right|\leq P_{T,10RR} \tag{12}$$

where, $P_{T,Prev10}$ is the total real power output ten minute ago.

Consequently, the proposed operations of the hybrid system can be formulated as the quadratic objective function of (7) with linear constraints in (8) to (11) or (7) to (11) instead of (11) when the 10-minute ramp rate will be, on the contrary, considered.

5. Case Study

The specifications of EDLC modules and BESS are summarized in Table 2, which has been approximately estimated based on the Google search.

Table 2. Specifications of EDLC and BESS

Characteristics	EDLC	BESS
Life Cycle [Cycle]	1,000,000	500
Energy Density [Wh/kg]	3.15	250
Power Density [W/kg]	2,600	340
Installation Cost [$/kWh]	40,000	400

When the maximum power of intermittent generation is supposed to be 200 [MW], the results of the proposed optimization technique are given in Table 3. Total installation cost is approximately 17 million dollars while the cost of BESS without EDLC amounts to 59 million dollars because of the low power density of BESS. Indeed, BESS asks for about 147 [MWh] of energy capacity to cover 200 [MW] of rated power.

Table 3. Results of EDLC and BESS

Characteristics	Hybrid		BESS without EDLC
	EDLC	BESS	
Rated Power [MW]	170.1	29.9	200
Energy Storage [MWh]	0.21	22.01	147
Installation Costs [M$]	17		59

From the wind speed data in Texas for 24 hours on January 1, 2011, the power output of intermittent generation for one day is displayed by Fig. 3. The capacity of wind farms is assumed to be 200 [MW], where wind turbines have 3.5 [m/s] of cut-in wind speed, 14 [m/s] of rated wind speed, and 25 [m/s] of cut-out wind speed [5-6].

In our study, w_{ES}, w_{SC}, $w_{SOC^{ES}}$, $w_{SOC^{SC}}$, and w_T are chosen based on the following condition in terms of not only life cycles of BESS and EDLC modules but stability of control systems:

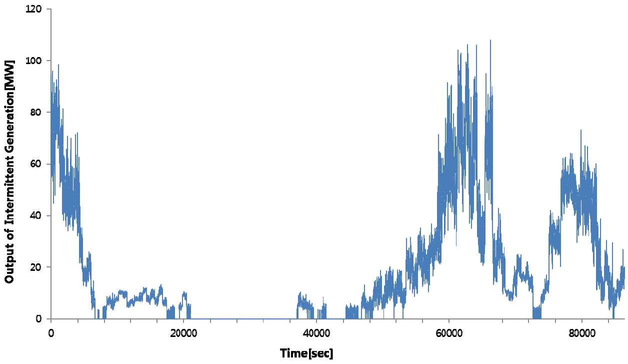

Fig. 3. Output of wind power generation [MW]

$$w_{ES} >> w_{SC},\ w_{SOC^{ES}} >> w_{SOC^{SC}},\ w_{SOC^{ES}} >> w_{ES},\quad w_{ES} < w_T < w_{SOC^{ES}} \tag{13}$$

Our experience shows that the choice of $w_{ES} = 100$, $w_{SC} = 1$, $w_{SOC^{ES}} = 10{,}000$, $w_{SOC^{SC}} = 100$, and $w_T = 1{,}000$ seems very promising among other combinations.

The proposed scheme sends the control signals to the BESS and EDLC modules as described in Fig. 4 and Fig. 5, respectively. When the BESS and the EDLC modules follow the signals of the proposed algorithm, SOCs of both systems are reduced to Figs. 6 and 7.

The battery degradation is mostly the lowest in the operating range close to 50% of SOC. Thus, $w_{SOC^{ES}}$ is quite higher than $w_{SOC^{SC}}$. As a result, SOC of the BESS varies 45% to 52% while SOC of the EDLC modules varies 20% to 70%. Furthermore, for 24 hours since the operations started, both SOCs have still been around 50%.

Moreover, the total output of the proposed hybrid system is portrayed by Fig. 8. The total output of the proposed hybrid system is vividly compared with the wind power generation in Fig. 9. As seen in Fig. 9, from 66,592 [sec] to 66,628 [sec], the wind power generation is changed by 42 [MW], or equivalently 70 [MW/min], which is clearly beyond the ramp rate constraint, while the total output of the proposed hybrid system is changed from 71 [MW] to 53 [MW] by 30 [MW/min], which is absolutely on within the limitation.

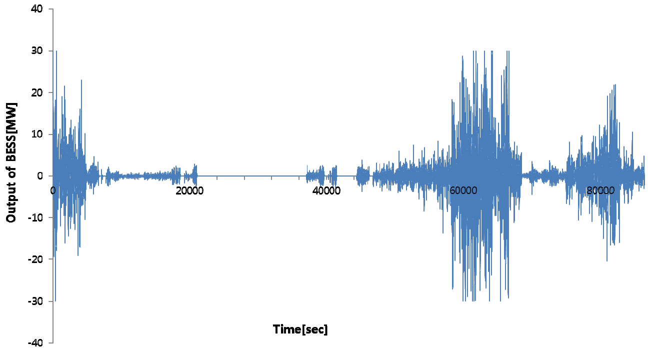

Fig. 4. Output of BESS [MW]

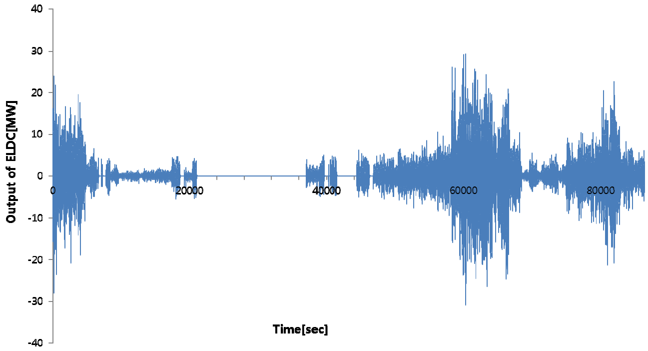

Fig. 5. Output of EDLC [MW]

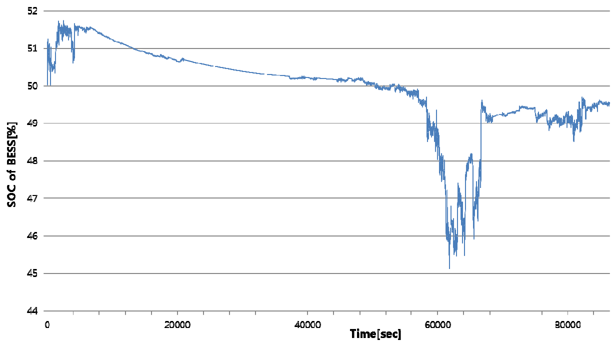

Fig. 6. SOC of BESS [%]

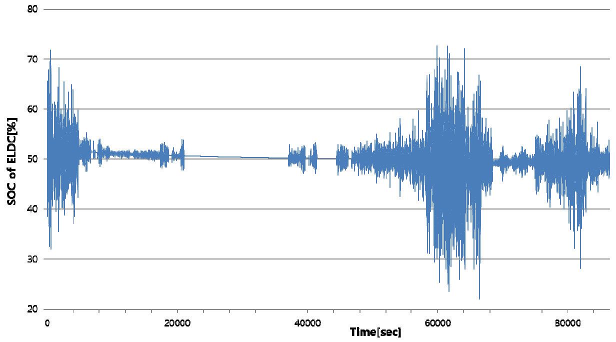

Fig. 7. SOC of EDLC [%]

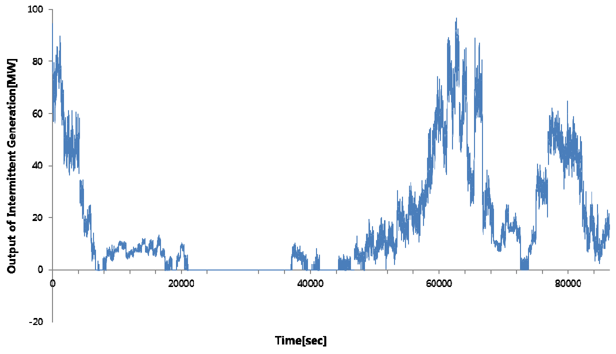

Fig. 8. Total output of the proposed hybrid system [MW]

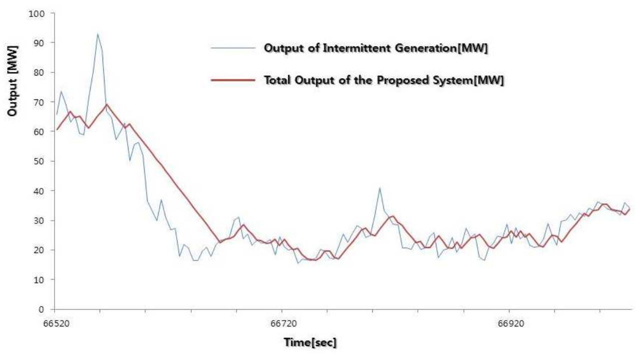

Fig. 9. Comparison between total output and wind power

6. Conclusion

In this paper, the computation technique for optimized capacity of BESS and EDLC modules for intermittent generation has been addressed for their connections with an electric power grid. From the view point of installation costs, the hybrid system has overwhelming advantage over BESS alone while meeting the restrictions for the connection with the power grid. Besides, the foregoing analysis with the wind data from Texas has demonstrated the validity that the optimized operations of the hybrid system might be realized by the proposed algorithm.

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References

[1] Hyunjae Yoo, Seung-Ki Sul, Yongho Park, and Jongchan Jeong, "System Integration and Power-Flow Management for a Series Hybrid Electric Vehicle Using Supercapacitors and Batteries," *IEEE Trans. Industry Applications*, vol. 44, no. 1, pp. 108-114, Feb. 2008.

[2] N. Jinrui, S. Fengchun, and R. Qinglian, "A Study of Energy Management System of Electric Vehicles," *in Proceedings of Vehicle Power and Propulsion Conference*, Windsor, Canada, pp. 1-6, Sep. 2006.

[3] Xiaolei Hu, K. J. Tseng, and M. Srinivasan, "Optimization of Battery Energy Storage System with Super-Capacitor for Renewable Energy Applications," *in Proceedings of 8th International Conference on Power Electronics*, Jeju, Korea, pp. 1552-1557, May 2011.

[4] Zhang Yong, Duan Zhengang, and Liu Xuelian, "Comparison of Grid Code Requirements with Wind Turbine in China and Europe," *in Proceedings of Power and Energy Engineering Conference*, Chengdu, China, pp. 1-4, March 2010.

[5] Christian Eisenhut, Florian Krug, Christian Schram, and Bernd Klöckl, "Wind-Turbine Model for System Simulations Near Cut-In Wind Speed," *IEEE Trans. Energy Conversion*, vol. 22, no. 2, pp. 414-420, June 2007.

[6] Olimpo Anaya-Lara, Nick Jenkins, Janaka Ekanayake, Phill Cartwright, and Mike Hughes, *Wind Energy Generation Modeling and Control*: Wiley, 2009.

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