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Economic Analysis for Possibility of Hybrid Energy Storage Systems Application to Frequency Control in Power System

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Abstract: Battery energy storage system (BESS) is focused in Smart Grid among the currently available energy storage solutions. Furthermore, Hybrid Energy Storage Systems (HESS) composed of two different kinds of battery is also studied to achieve better performance and lower cost than single kind battery system. As the possible business case for battery storage is provision of ancillary service, this paper focuses on HESS application to frequency control in power system. This paper shows possibility of HESS applied to frequency control through the economic analysis of HESS capacity combination.

Keywords: Power system, frequency control, energy storage, battery, economic analysis

1. INTRODUCTION

The increase of renewable energy resources and their intermittent characteristics of generation need to restructure frequency control using energy storage technologies as well as utilizing the traditional generation such as thermal and hydro generation plants. Battery energy storage system (BESS) is focused among the available energy storage solutions such as pumped hydro storage, compressed air energy storage (CAES), flywheels, etc. due to the current technology innovation and cost reduction of BESS.

There are many kinds of battery which have different characteristics such as energy storage density, charge/ discharge rate, life cycle, cost, etc. Those characteristics are surveyed by Joseph et al. (2006) and Sparacino et al. (2012). Charge/discharge rate is kW performance per kWh while the battery is charged or discharged. C-rate is usually used instead of charge/discharge rate in BESS application. C-rate originally specifies charge/discharge currents (A) compared to its storage capacity (Ah) and 1C, for example, charges from empty to full in one hour or discharges from full to empty in one hour, and 5C takes 1/5 hour.

Cost is shown per kWh in general. When the necessary kW is given for battery, for example, the necessary capacity (kWh) is derived from C-rate and then the necessary cost is counted on that capacity. Therefore, in battery characteristics mentioned in the above, C-rate and cost including life cycle are the most important to be considered for BESS's application to power system.

Some battery has high C-rate which is available for rapid charge/discharge but it is expensive. The other battery has low C-rate but it is cheap. When the both needs of charge/discharge performance and cost should be required, it comes to the idea of combination of two different batteries.

From the above point of view, several researchers have been studying Hybrid Energy Storage System (HESS) application to power system. HESS application to Wind farm or to Microgrids has been studied by Li at al. (2008), Hongxin et al. (2010), and Etxeberria et al. (2010) in order to mitigate generation fluctuation of renewable energy resources. Liu et al. (2010) have also studied HESS control strategies. Their basic ideas are to take the each advantage of two different batteries where the slow fluctuation is controlled by low C-rate battery and high C-rate battery compensates for the rest of fluctuation. Although their aim is to achieve two needs of charge/discharge performance and cost, the cost issue has not been evaluated explicitly.

As battery is now not cheap itself, BESS business case has been discussed regarding its application to power system. Then they conclude that its possible business case is application to ancillary service, that is frequency control, and Oudalov et al. (2007) and Borsche et al. (2013) present BESS's performance and economic usefulness for frequency control. HESS can also be applied to frequency control. However, HESS's application to this issue has not been studied yet.

In Japan, it is reported that the target cycle zone of frequency control is from 1 minute cycle to 20 minutes cycle of load variation and the load variation has characteristics of normal distribution by Special Committee for Survey of Load Frequency Control in Normal and Emergency Conditions in Power System (2002).

This paper shows possibility of HESS's application to frequency control for the same load characteristics in Japan. The necessary battery cost is evaluated analytically and explicitly and then the economically optimal capacity combination is indicated. This paper presents the important characteristics of battery for HESS application at first and then introduces the load variation of frequency control in Japan. HESS is modelled for frequency control and the economic simulation analysis results are mentioned in this paper to show the possibility.

2. BATTERY CHARACTERISTICS

2.1 General

There are many kinds of battery which have different characteristics of,

- Energy storage density
- C-rate
- Energy efficiency
- Life cycle
- Cost

from the viewpoint of their application to power system. Energy storage density indicates kWh/volume and bigger energy density battery occupies less space. Regarding C-rate, higher C-rate battery charges or discharges more kW with less kWh capacity. Energy efficiency is a conversion rate from charged power to discharged power. Life cycle corresponds to longevity and it shows a number of how many times the battery can repeat the process of charge and discharge while it is operated under its specified performance.

As mentioned before, the most important factors of characteristics are C-rate and cost with life cycle. Popular batteries are categorized into three groups as shown in Table 1 in terms of C-rate, cost per kWh. Advanced lead-acid is higher C-rate and better life cycle than traditional lead-acid. Lithium-ion capacitor has been developed currently and it has better performance than EDLC (Electric Double Layer Capacitor).

Table 1. Main battery characteristics comparison

Category	Battery	C-rate	Cost per kWh
A	Advanced lead-acid NaS Redox flow	Small	Not expensive
B	Lithium-ion	Medium	Medium
C	EDLC Lithium-ion Capacitor	Big	Expensive

In the past, HESS composed of Redox flow and EDLC has been studied for fluctuation mitigation where Redox flow plays a role for slow fluctuation and EDLC for fast fluctuation because that approach takes advantage of each battery's C-rate and cost.

2.2 Life Cycle

Life cycle is changed according to Depth of Discharge (DOD), which is percentage of capacity used for charge/discharge in the total capacity of battery. Smaller DOD usage makes the life cycle bigger, bigger DOD usage makes it smaller, and each battery has its own DOD-life cycle characteristics.

The actual relation between DOD and life cycle is referred to as being a smooth curve as shown by Liu et al. (2010). Fig. 1 shows the image of curve in that paper.

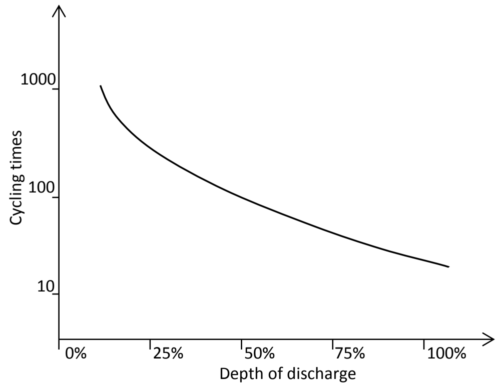


Fig. 1. Image of relation between DOD and life cycle by Liu et al. (2010).

2.3 HESS Applied to Frequency Control

In this paper, three batteries from each category in Table 1 are evaluated for HESS composition, advanced lead-acid battery from category A, Lithium-ion from category B, and Lithium-ion capacitor from category C because lead-acid battery is said to be the most promising business case of ancillary service by Oudalov et al. (2007), Lithium-ion battery has been developed most innovatively, and Lithium-ion capacitor is a prospective one in this application. Table 2 shows each battery's characteristics used in this evaluation.

Table 2. Battery's characteristics data used in analysis (1$=100Yen)

Factor	Advanced Lead-acid	Lithium-ion	Lithium-ion capacitor
C-rate	1.0 C	3.0 C	300.0 C
DOD-life cycle	7500 cycles at DOD 30% 4500 cycles at DOD 70%	10000 cycles at DOD 70% 6000 cycles at DOD 100%	not related to DOD 1,000,000 cycles
Energy efficiency	85%	90%	95%
Cost	250$/kWh	1,000$/kWh	68,000$/kWh

In frequency control, advanced lead-acid battery and lithium-ion are applied to control relatively long cycle of load variation, and their lack of regulation is compensated by lithium-ion capacitor which controls relatively short cycle of load variation.

3. LOAD CHARACTERISTICS FOR FREQUENCY CONTROL

Committee of IEEJ (The Institute of Electrical Engineering of Japan), Special Committee for Survey of Load Frequency Control in Normal and Emergency Conditions in Power System (2002), issued their technical report after they had surveyed and analysed nine utilities' frequency control conditions in Japan. In the report, they mention that the target cycle zone of frequency control is from 1 minute cycle to 20 minutes cycle of load variation and that the relationship between load demand and its standard deviation (SD) of less than 20 minutes cycle load variation is the followings and Fig. 2.

$$\sigma_D = \gamma\sqrt{P} \quad (1)$$

σ_D: SD of less than 20 minutes cycle load variation,

γ: constant, P: Load demand

γ depends on the utility and load curve time zone, but it ranges from 0.2 to 0.7.

In addition to that, they analyse the following each SD according to the cycle of load variation.

$\sigma_{D10\text{-}20}$: SD of 10 -20 minutes cycle load variation

$\sigma_{D3\text{-}10}$: SD of 3 -10 minutes cycle load variation

$\sigma_{D1\text{-}3}$: SD of 1 -3 minutes cycle load variation

They report that $\sigma_{D10\text{-}20}$, $\sigma_{D3\text{-}10}$, and $\sigma_{D1\text{-}3}$ are around 1/2 of σ_D respectively. As the each load variation is presented by the cycle curve of its cycle time and SD, the each energy (MWh) corresponds to the area of cycle curve.

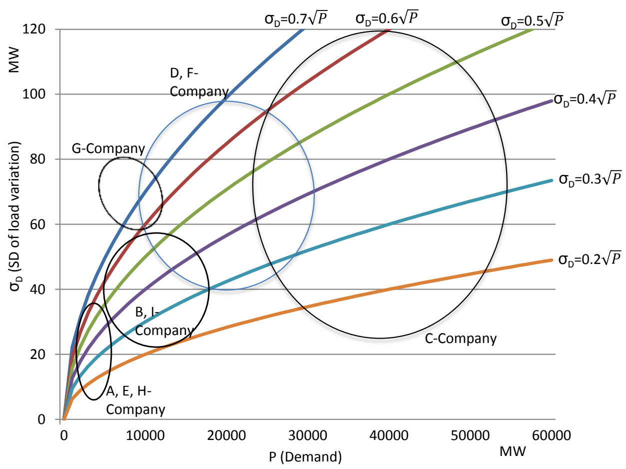


Fig. 2. Load variation characteristics for frequency control.

4. ECONOMIC ANALYSIS OF HESS FOR FREQUENCY CONTROL

4.1 Load Variation Modelling

From the load variation characteristics in Japan mentioned in the above, the following parameters in (1) are used in the economic analysis simulation in this paper (Table 3).

Table 3. Parameters for analysis

Parameter	Value
P (Load Demand)	10,000MW
γ (Constant)	0.4
σ_D	40MW
$\sigma_{D10\text{-}20}$	20MW
$\sigma_{D3\text{-}10}$	20MW
$\sigma_{D1\text{-}3}$	20MW

4.2 HESS Composition

The following two types of HESS are the target of analysis.

- Advanced lead-acid battery and lithium-ion capacitor
- Lithium-ion and lithium-ion capacitor

Low C-rate battery, Advanced lead-acid battery and Lithium-ion, covers relatively long cycle of load variation and high C-rate battery, Lithium-ion capacitor, compensates for the rest of load variation. In the former HESS, for example, advanced-lead battery is used to control some of $\sigma_{D10\text{-}20}$ and lithium-ion capacitor controls the rest of $\sigma_{D10\text{-}20}$, $\sigma_{D3\text{-}10}$, and $\sigma_{D1\text{-}3}$.

In this paper, in order to present those batteries shortly, “Battery1” is used instead of advanced lead-acid battery or lithium-ion battery, “Battery2” instead of lithium-ion capacitor in the below.

It is assumed that HESS covers 3 x σ of load variation, that is, necessary output (MW) or capacity (MWh) of battery to control 3 x $\sigma_{D10\text{-}20}$, 3 x $\sigma_{D3\text{-}10}$, and 3 x $\sigma_{D1\text{-}3}$ is provided. It is also necessary to take energy efficiency of battery into account for capacity (MWh) of battery.

Although the relationship between DOD and life cycle is mentioned in 2.2, DOD-life cycle is here dealt with approximately as linear relation derived from Table 2. Fig. 3 shows the relation used in this paper.

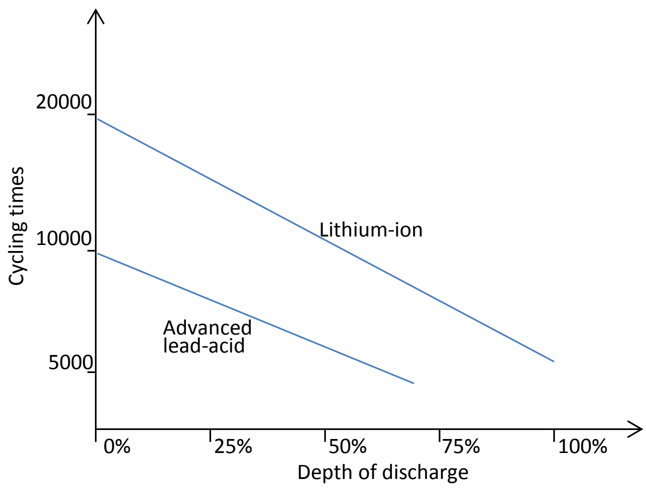


Fig. 3. DOD-life cycle in analysis.

4.3 Economic Simulation

In order to evaluate the possibility of HESS applied to frequency control, several approximation models are used in this paper.

(1) Cycle of load variation

As there are three cycle zones of load variation for frequency control mentioned in the above, those zones are presented as their average cycle in this simulation. Therefore, 15minutes cycle is represented for 10-20 minutes cycle, 6.5minutes cycle for 3-10 minutes cycle, 2 minutes cycle for 1-3minutes cycle.

(2) Cycle curve of load variation

Triangular wave is presented as the load variation curve. Therefore, 10-20 minutes cycle load variation, for example, is simulated as upside-triangular and downside-triangular forms, each of which has base length of a half of 15 minutes and the height of σ_{D10-20}.

(3) Normal distribution of load variation

As load variation has characteristics of normal distribution such as σ_{D10-20}, its expected value can be presented with probability of normal distribution. In this paper, the expected value is calculated by the summation of three points' probabilities of σ, 2 x σ, and 3 x σ.

(4) Battery rated power and capacity

Although both the rated power (MW) and capacity (MWh) of battery are necessary factors for HESS design, the capacity is derived from the given rated power using C-rate as mentioned before. In this simulation, the rated power of Battery1 is given at first, then the capacity is decided automatically, and Battery1 is assumed to use its capacity as much as possible. Battery2 rated power and capacity are provided to compensate for the control of the rest of load variation.

(5) Simulation steps

The economic analysis is simulated in the following steps.

Battery1:

(Step1) Set Battery1 rated power (MW) = 0MW

(Step2) Calculate Battery1 capacity (MWh) from the rated power, C-rate, and energy efficiency

(Step3) Calculate expected life cycle of Battery1

Using probability of normal distribution, the expected life cycle is calculated from each life cycle corresponding to σ_{D10-20}, 2 x σ_{D10-20}, and 3 x σ_{D10-20}.

At first, the following $DOD_{1\sigma}$, $DOD_{2\sigma}$, and $DOD_{3\sigma}$ are found.

- Battery1 capacity used for σ_{D10-20} and its $DOD_{1\sigma}$
- Battery1 capacity used for 2 x σ_{D10-20} and its $DOD_{2\sigma}$
- Battery1 capacity used for 3 x σ_{D10-20} and its $DOD_{3\sigma}$

Then each life cycle from $DOD_{1\sigma}$, $DOD_{2\sigma}$, or $DOD_{3\sigma}$ is counted respectively with DOD-life cycle characteristics. At last, the expected life cycle is calculated from the summation of $DOD_{1\sigma}$, $DOD_{2\sigma}$, and $DOD_{3\sigma}$ with their probabilities.

(Step4) Calculate expected length of life (year) from the expected life cycle

(Step5) Count Battery1 cost by Battery1 capacity of (Step2)

(Step6) Calculate Battery1 cost/year (M$/year) from cost and expected length of year

Battery2:

(Step7) Calculate necessary Battery2 rated power (MW) = 3 x σ_D – [Battery1 rated power]

(Step8) Calculate necessary Battery2 capacity (MWh) in two ways.

- Battery2 capacity (MWh) is calculated from the rated power of (Step7), C-rate, and energy efficiency
- Battery2 capacity (MWh) = MWh of [3 x σ_{D10-20} + 3 x σ_{D3-10} + 3 x σ_{D1-3}] – [Battery1 capacity]

Then each capacity is compared and the bigger capacity becomes the necessary Battery2 capacity.

(Step9) Count Battery2 cost by Battery2 capacity

(Step10) Calculate expected life cycle from the shortest cycle

(Step11) Calculate expected length of life (year) from the expected life cycle

(Step12) Calculate Battery2 cost/year (M$/year) from cost and expected length of year

HESS (Battery1 + Battery2):

(Step13) Sum up (Step6) Battery1 cost/year (M$/year) and (Step12) Battery2 cost/year (M$/year) and introduce the total expected cost/year (M$/year)

(Step14) Increase Battery1 rated power by +1MW

(Step15) Return to (Step2) if Battery1 rated power is less than 3 x σ_{D10-20}, or end this process if not

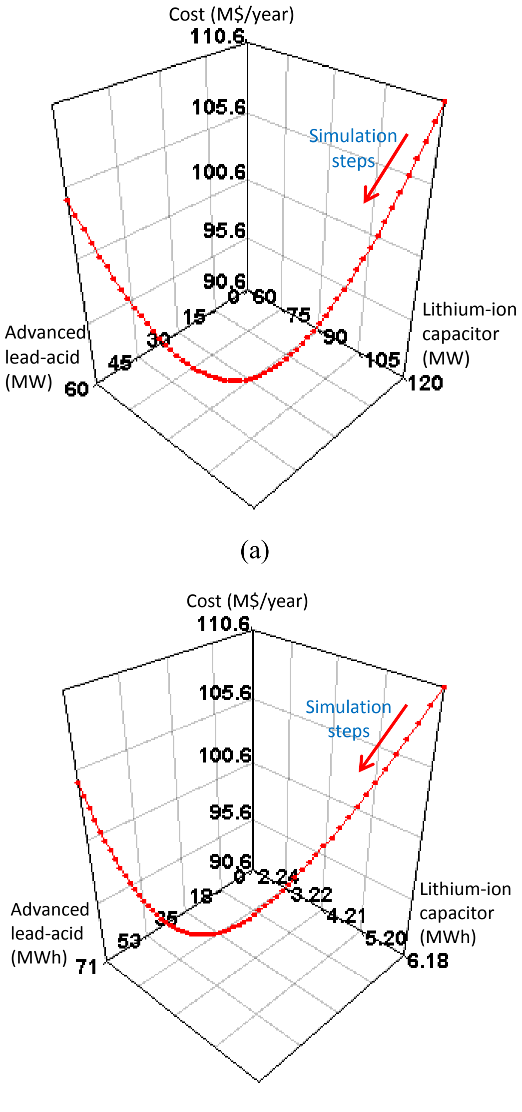
Those steps can find the economically optimal combination of HESS capacity.

4.4 Simulation Results

(1) Battery1: advanced lead-acid battery, Battery2: lithium-ion capacitor

Fig. 4 (a) shows the results of simulation steps and it has the lowest expected cost/year in the rated power (MW) combination of Battery1 and Battery2. Fig 4 (b) also shows expected cost/year and their capacity (MWh) combination calculated from the rated power.

When Battery1 rated power is 0MW at (Step1) and necessary Battery2 rated power is 120MW, which comes from 3 x σ_D, necessary Battery2 capacity is around 6.18MWh which is MWh of [3 x σ_{D10-20} + 3 x σ_{D3-10} + 3 x σ_{D1-3}]. And the Battery2 cost is around 420M$ from the capacity and its longevity is 3.8 years, which comes from 2 minutes cycle charge/discharge on its life-cycle of Table 2. Then the expected cost/year becomes 110.6M$/year. At this capacity combination, as Battery2 needs to supply all the MWh and it is also expensive, the expected cost/year becomes expensive. According to the increase of Battery1 rated power, the expected cost/year decreases gradually as Battery1 supplies MWh as well as MW and Battery2 decreases by that volume.



(a)

(b)

Fig. 4. Economic simulation results for Battery1: advanced lead-acid battery, Battery2: lithium-ion capacitor.

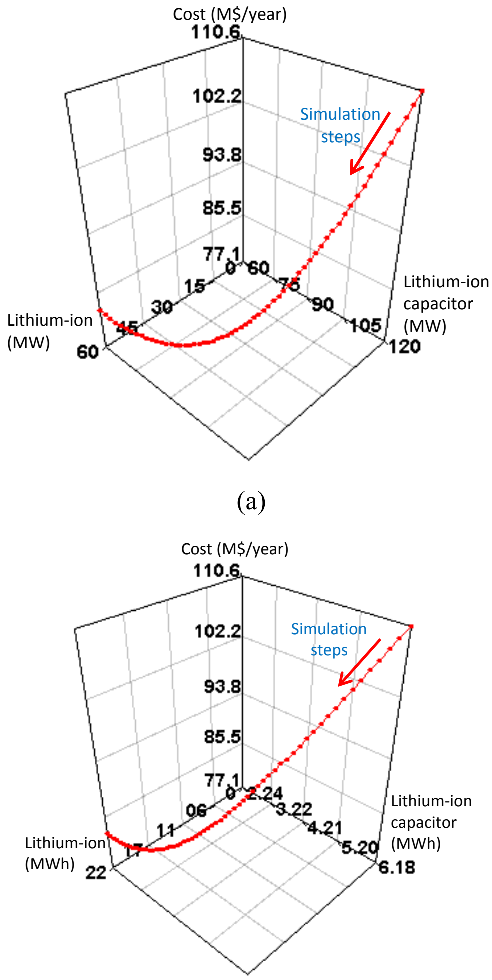
At the lowest point of expected cost/year, where Battery1 is 33MW and battery2 87MW, the expected cost/year becomes 90.6M$/year. When Battery1 rated power increases from that point, the expected cost/year starts increasing because the increase of Battery1 cost of necessary MWh is bigger than the decrease of Battery2 cost of necessary MWh.

When Battery1 rated power is 60MW, where it supplies 3 x σ_{D10-20}, and Battery2 60MW, the expected cost/year becomes 104.8M$/year.

As Battery1 C-rate is 1.0, Fig. 4 (b) shows the similar curve as Fig. 4 (a).

(2) Battery1: lithium-ion, Battery2: lithium-ion capacitor

Fig. 5 (a) and (b) show this case. At the lowest point of expected cost/year, where Battery1 is 43MW and Battery2 77MW, the expected cost/year becomes 77.1M$/year which is lower than (1) lowest expected cost/year. This reason comes from that lithium-ion takes advantage of higher C-rate than advanced lead-acid in this application, which needs relatively big MW compared to necessary MWh, and the necessary MW and cost of lithium-ion make the expected cost/year cheaper.



(a)

(b)

Fig. 5. Economic simulation results for Battery1: lithium-ion, Battery2: lithium-ion capacitor.

4.5 Consideration on Simulation Results

Total expected MWh supplied by HESS charge/discharge, which is MWh of [3 x σ_{D10-20} + 3 x σ_{D3-10} + 3 x σ_{D1-3}], corresponds to 358,146MWh in a year. As the lowest expected cost/year is 77.1M$/year in case of combination of lithium-ion and lithium-ion capacitor, the expected cost of frequency control becomes around 0.22$/kWh.

In this economic simulation, HESS rated power and capacity was considered to cover [3 x σ_{D10-20} + 3 x σ_{D3-10} + 3 x σ_{D1-3}] which is bigger than 3 x σ_D because this simulation assumes the severe case. HESS rated power and capacity, however, would not need such volume in the actual use. This indicates that the cost of HESS could decrease. Apart from that, HESS is always equipped with Power Conditioning System (PCS), transformer, controller, etc. and their cost is not included in the simulation. As the almost cost of HESS comes from battery cost, this simulation deals with only battery cost. The other equipment cost should be included in order to assess HESS cost in detail.

Fig. 6 shows expected DOD in the simulation steps. It indicates that both advanced lead-acid and lithium-ion use very small DOD and they have big charge/discharge margin of MWh. This margin could be used simultaneously for other purpose of energy storage application such as peak shift, for example, which has long cycle characteristics. That additional usage could lead to utilize HESS more economically.

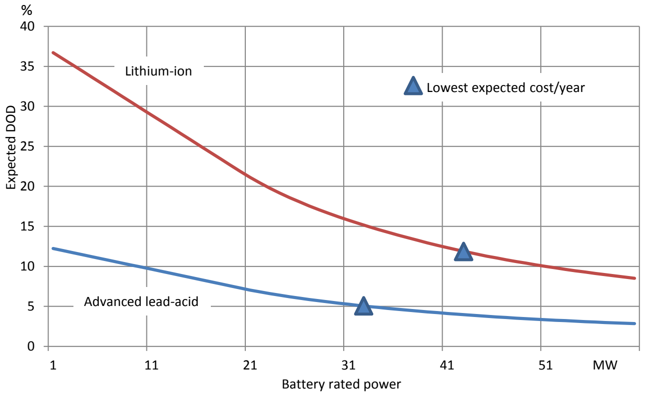


Fig. 6. Expected DOD and rated power of battery in simulation.

5. CONCLUSIONING REMARKS

This paper shows the possibility of HESS application to frequency control in terms of its cost through the economic simulation of HESS battery capacity combination. The simulation results clarify that HESS application is promising rather than only single kind battery application in frequency control field.

In order to establish HESS usefulness, the further work such as HESS evaluation under the dynamic load variation or HESS assessment of the added value by simultaneous additional use is suggested.

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