Evaluation and Simulation of Energy Storage Systems
Applied for Large Pulsed Load

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Abstract: Fusion power plant which will be a prospective generating system in the middle of 21st century, and ITER which is a representative of fusion experimental devices consume large amount of pulsed power and cause rapid power fluctuations when the systems are operated with controlling plasma current inside the reactor. As effective countermeasures to solve these problems, adoption of energy storage systems such as flywheel motor generator and the SMES are considered. These energy storage systems have the characteristics of increasing energy losses during holding the stored energy.

The SMES is superior to the other energy storage systems in views of rapid charging and discharging energy, and high efficiency of energy storage. It has been developed to manufacture large scale SMES and to reduce its initial cost. The flywheel motor generator was already applied for large pulsed loads by means of storing kinetic energy. It is broadly utilized in view of its large scaled capacity and reliability, while it has comparatively high mechanical loss compared with SMES.

For optimal system used in large pulsed power load, it is desirable to take into account a total evaluation involving these initial cost and performance. In this paper we propose the evaluation method and discuss the simulation result by using the flywheel motor generator and SMES for the pulsed power load.

Keywords: SMES, flywheel motor generator, large pulsed load, evaluation, simulation

1. INTRODUCTION
This paper describes evaluation method and simulation results of energy storage system applied for large pulsed power, such as fusion experimental devices and fusion power plants, which require huge amount of power and rapid power flow from utility power source at the beginning of operation. These power consumptions cause power fluctuation and frequency deviation, one of countermeasures to suppress the instability is application of energy storage systems as intermediate buffer between utility power source and large pulsed load.

One of typical storage system for this purpose is flywheel generator motor (FWMG) which has been applied for some fusion experimental devices in worldwide. FWMG has features of good reliability and availability as large capacity device, although it has comparatively high mechanical loss.

On the other hand, recent progress of superconducting technology makes SMES prospecting energy storage system, which has the features of high storage efficiency and rapid energy transfer.

In this paper simulations of energy storage systems for large pulsed power were conducted in two cases; Case-1: SMES and Case-2: SMES-FWMG combination and evaluations of them were discussed.

2. ENERGY STORAGE SYSTEM
The connection of the energy storage system simulated with a large pulsed power system is shown in Fig.1. The large pulsed power load is connected parallel with utility power source, SMES and FWMG. In this paper following two cases had been investigated.

Case-1: SMES
Case-2: SMES and FWMG

Fig.1. Connection of energy storage system

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3. POWER CONTROL

3.1. Control method

SMES absorbs active power deviation of load by mean of compensating the difference between present and moving weighted average values of pulsed power load. The initial charging of SMES is assumed to be done before the simulation cycle. The SMES cannot be affected by the small power as 10MW.

FWMG will discharge active power according to programmed sequence receiving the signals from the load. Every charging of FWMG is assumed to be done in the preparation period of the operation in the simulation cycle.

Basic control algorithm of active power compensating of Case 2 is shown in Fig.2.

3.2. Simulation conditions

As the simulation model for large pulsed load, a mock up data processed from the typical active load curve of ITER [1] is used. The plot of this model is shown in Fig.3.

One cycle of this model is 1800 seconds, and the data are used in each second. The active peak is 284[MW], the maximum positive change rate of active power is 188[MW/s] and the maximum negative one is 228[MW/s]. The target maximum change rate of utility power source for active power fluctuation is restricted in around ±30[MW/s].

The available energy rates for the SMES and the FWMG are assumed 80 and 60 %, respectively.

3.3. Simulation results

Simulation results are shown in Table 1. In Case 1, the SMES needs 200MW of capacity, and 2.88GJ of stored energy. In Case 2, the SMES needs 200MW of capacity, 1.38GJ of stored energy, and the FWMG needs 61MW (76MVA) of capacity and 7.00GJ of stored energy.

4. EVALUATION

4.1. Economic evaluation

Economic estimation of the SMES was carried out by using the data of Japanese national project phase-II[2]. The estimated cost of the SMES for load fluctuation compensation will be realized about ¥200,000/kW including installation cost and total operating cost for 30 years. The specification of the SMES was 100MW output, 1.8GJ of available energy and 2.2GJ of stored energy. It was assumed that 46% of initial cost was concerned with the electric equipment and 54% of initial cost was concerned with superconducting coils and refrigerators.

In this estimation of the SMES simulated, it is assumed that the electric equipment’s cost is proportional to output of the electric equipment, and the cost of superconducting coils including refrigerators is proportional to around 2/3 power of the stored energy.

Table 1 Results of simulation and cost estimation

<table>
<thead>
<tr>
<th>Item</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>System</td>
<td>SMES</td>
<td>SMES + FWMG</td>
</tr>
<tr>
<td>Capacity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output</td>
<td>200[MW]</td>
<td>SMES 200[MW]</td>
</tr>
<tr>
<td></td>
<td>FWMG 61[MW]</td>
<td>76[MVA]</td>
</tr>
<tr>
<td>Stored energy</td>
<td>2.88[GJ]</td>
<td>SMES 1.38[GJ]</td>
</tr>
<tr>
<td>Available energy</td>
<td>2.30[GJ]</td>
<td>SMES 1.10[GJ]</td>
</tr>
<tr>
<td>Performance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power fluctuation of utility power source</td>
<td>+32[MW/s]</td>
<td>+34[MW/s]</td>
</tr>
<tr>
<td></td>
<td>-30[MW/s]</td>
<td>-30[MW/s]</td>
</tr>
<tr>
<td>Storage Index</td>
<td>SI=0.926</td>
<td>SMES SI=0.921</td>
</tr>
<tr>
<td></td>
<td>FWMG SI=0.869</td>
<td>Total SI=0.888</td>
</tr>
<tr>
<td>Cost estimation</td>
<td>32.4[G ¥ ]</td>
<td>SMES 26.2[G ¥ ]</td>
</tr>
<tr>
<td></td>
<td>FWMG 7.6[G ¥ ]</td>
<td>Total 33.8[G ¥ ]</td>
</tr>
</tbody>
</table>

Economic estimation of the FWMG was calculated using the cost per unit of ¥100,000/kVA. The estimation results of energy storage system are as follows. Case-1 is 32.4 G ¥, while Case-2 is 33.8 G ¥. Composing hybrid system, it’s available to reduce SMES’s stored energy and its cost. The total cost of Case-1 is a little cheaper than that of Case-2, but almost they are in the
same range.

4.2. Performance evaluation

Restriction of rapid power change and storage efficiency during storage cycle are important in application of energy storage systems in large pulsed load. For example the maximum change rate of active power and the minimum duration time of the ITER typical load is up to 200MW/s and 1800 seconds, respectively [1]. It is too huge power change demand and too long time compared with the existing facilities.

4.2.1. Power fluctuation

Concerning restriction of rapid power fluctuation, which are limited as the operational conditions in Case-1 and Case-2, the target of the change rate of the utility power is around 30MW. Shown in Table 1, the power change rate results of the utility power source are layed around the same restricted value in Case-1 and Case-2.

4.2.2. Storage efficiency

For evaluating storage efficiency during the storage cycle we propose a storage index for the energy storage system such as SMES, FWMG and so on. It is useful to grasp briefly the tendencies related with total storage efficiency of each system or combination system. This index obtained by calculation is approximate value, but we can get it easily in the simulation.

Especially the operational loss of the FWMG varies on its rotating speed. Wind loss, which is major part of mechanical loss of FWMG, is proportional to rotating speed cubed. Stored energy of the FWMG is proportional to its rotating speed squared. So the main part of FWMG’s loss is assumed to be proportional to 1.5 power of its stored energy. The more stored energy generates the more energy loss, and the storage efficiency is a function of depth ratio of stored energy.

$$SI = \frac{S_i}{P_i}$$  \hspace{1cm} (1)

4.2.2.2. Storage holding factor

The storage holding unit factor $f(d)$ is similar to a remaining ratio of the stored energy during the unit time $I=1$ (simulation step). When the total storage holding factor at the end of repetition cycle is described as $F(d)$, the storage holding unit factor $f(d)$ is estimated as follows.

$$f(d) = 1 - (1 - F(d)) / M$$ \hspace{1cm} (2)

$d$: charging ratio of stored energy
$M$: total steps of simulation
(1800 in this simulation)

In this simulation, the storage holding factor $F_{SM}(d)$ of the SMES is assumed to be a constant value (0.90) under the condition of holding initial stock without input and output during repetition cycle. And also $f_{SM}(d)$ is assumed to be a constant, and $d$ is charging ratio of stored energy.

The storage holding factor $F_{FW}(d)$ of FWMG is also assumed to be a value (0.80) under the condition of holding initial stock of full charging ratio ($d=1.0$) of stored energy without input and output during repetition cycle. And $F_{FW}(d)$ is assumed to be a function of $d$ as following expression.

$$F_{FW}(d) = 1 - [ (1 - F_{FW}(d)) / m ] (ad^{1.5} + bd + c) \hspace{1cm} (4)$$

$a$: ratio of wind loss proportional to $d^{1.5}$
$b$: ratio of bearing loss proportional to $d$
$c$: ratio of other constant loss
(0.35 in this simulation)

If numerical value of $SI$ of SMES is bigger than 0.9, it indicates that charging and discharging of stored energy are performed with less holding losses and less holding time, and that good storing performance conducted. About FWMG it can be evaluated like same as SMES. Numerical value bigger than 0.8, it indicates that good storing performance conducted.

5. DISCUSSION

Using simulation conditions for large pulsed load, two cases of energy storage system are simulated. The results are indicated in Table 1. Two type of energy system have similar results at the point of economic evaluation.

One of important power performances, the maximum power change rate of utility power source is restricted in the target value of 30[MW/s]. The storage index $SI$, which is related to the storage efficiency, is also important in the case of the huge power demand and the long duration time. The total $SI$ of Case-1 was 0.926, the total $SI$ of Case-2 is 0.888, which is 0.038 lower than that of Case-1. Because Case-2 is composed of the SMES and the FWMG, it results in improvement up to 0.888 by av-
ranging a part $SI$ of FWMG: 0.869 and a part $SI$ of SMES: 0.921. It indicates that SMES performs effectively to FWMG. Both storage holding factor of SMES and FWMG were tentative value, so it needs further investigation.

6. CONCLUSION

Two cases of the energy storage system are simulated for the large pulsed load. Case-1 has only the SMES system and Case-2 has hybrid system composed of the SMES and the FWMG. We propose the storage index related to the storage efficiency in performance evaluation.

In economic evaluation, the cost of the Case-1 is a little cheaper than that of the Case-2. However, both of them are similar in the cost. It is needed to estimate further in detail.

In performance evaluation, Case-1 and Case-2 achieve good restriction of power fluctuation, the storage index of the Case-1 is better than that of the Case-2 at the point of storage efficiency. It is also needed to investigate in detail for the storage index estimation.

REFERENCES