A Hybrid Energy Storage System Using a Superconducting Magnet and a Secondary Battery

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Abstract --- Energy storage devices with high energy density as well as high power density are expected to be developed from the point of view of compensation of fluctuating load and generated power by distributed generations such as wind turbines, photovoltaic cells and so on. SMES (Superconducting Magnetic Energy Storage) has higher power density than other energy storage methods, and secondary batteries have higher energy density than SMES. The hybrid energy storage device using SMES and secondary batteries is proposed as the energy storage method with higher power and energy density, the sharing method of power reference value for each storage device, simulation and experimental results are presented.

I. INTRODUCTION

An energy storage device with high energy density and high power density is desired for compensation of fluctuating loads and distributed generations such as wind turbines and solar generations, because such fluctuating power may cause disturbances of voltage and frequency of a electric power system. SMES (Superconducting Magnetic Energy Storage) can store the electric energy in the form of magnetic energy, so that the stored energy can be charged and discharged quickly. On the other hand, energy density of SMES is not so high as other devices such as secondary batteries, flywheels and so on. Although there is a study of hybrid energy storage composed of SMES and flywheels, it has rotating mechanical parts in the system[1]. In this study, authors propose a hybrid energy storage system composed of a superconducting magnet and a secondary battery for a energy storage system with high energy and high power density which will be required for the near future distribution system[2].

By using this hybrid configuration, it is possible to expect longer life and higher efficiency for a battery energy storage and cost reduction for a superconducting magnetic energy storage, and to solve the problems of both energy storage systems.

II. CONFIGURATION OF THE HYBRID SYSTEM

Fig.1 shows the configuration of the proposed system. The superconducting magnet (SMES) and the secondary battery are connected together to the common dc link through different type chopper circuit. The key of the system is how to decide the power sharing between the two different type energy storage devices.

Fig.2 shows the scheme for deriving the power reference. When the fluctuating load power or generation power is given to the hybrid energy storage system, the power is shared with the power system, the battery and the superconducting magnet. The power command is decided through the low pass filter and the high pass filter as shown in Fig.2.

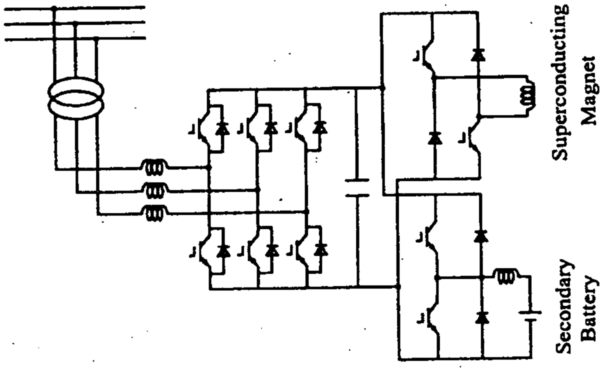

Fig.1. Configuration of the Hybrid Energy Storage System.

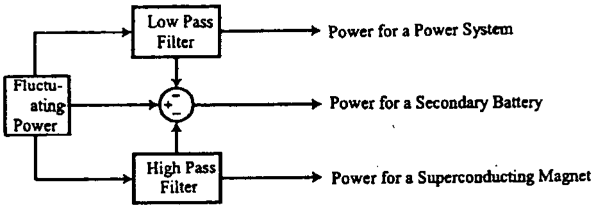

Fig.2. The Scheme to Share Power Fluctuation

III. SIMULATION RESULTS

A. Fundamental Characteristics

Fig.3 shows an example of the power at a railway substation and Fig.4 shows the result of Fourier analysis of the waveform shown in Fig.3. The simulation study was carried out using this waveform. From Fig.4, it is recognized that there is a peak of current magnitude at around 0.004Hz. It is better to compensate the fluctuation of power fluctuation above this frequency by use of SMES, because it requires high power but it does not require large energy capacity to compensate. The high pass filter with cut-off frequency of 0.0016Hz (0.01rad/s) with the first-order characteristics is chosen from the simulation study using the waveform of Fig.3. Then the fluctuation between 0.0016Hz and 0.0003Hz is compensated by the battery, because it requires energy capacity to compensate. The rest of fluctuation is drawn by the power system. As for the low pass filter to separate the power between the battery and the power system, the first-order with the cut-off frequency of 0.000265Hz (0.00167rad/s) were chosen from simulation study.

Fig.5 shows the simulation result of compensation of the fluctuation of the load shown in Fig.3. The fluctuation of the load power is compensated as shown in Fig.5(a). The required power of the secondary battery is much smaller than the required power of the superconducting magnet as shown in Fig.5(b) and (d). The required energy of the superconducting magnet is much smaller than the energy of the secondary battery as shown in Fig.5(c) and (e). From these results, the effect of the hybrid system can be recognized.

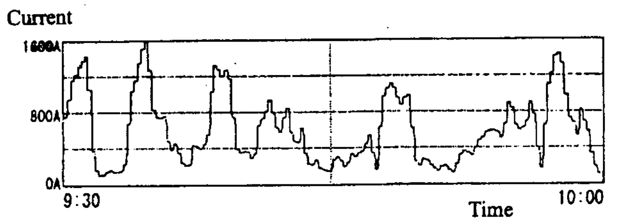

Fig.3. Power Fluctuation at a Railway Substation.

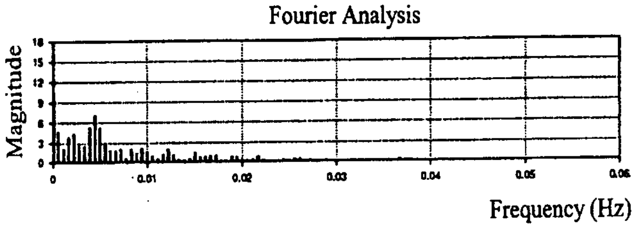

Fig.4. Fourier Analysis of the Waveform of Fig.3.

B. Characteristics for Various Types of Filter

Various types of the high pass filter to separate the power for secondary battery and superconducting magnet was examined using simulation. Table 1 shows the simulation result for various types of the high pass filter. The characteristics of the low pass filter to separate the power between the power system and battery was the first-order with the cut-off frequency of 0.000265Hz (0.00167rad/s) which was same as the simulation result shown in Fig.5.

From the table, the stored energy of SMES can be reduced by the higher order filters, on the other hand, the energy of the battery increases. In Table1, 100% means the energy or power which should be compensated by the energy storage system. If the first-order HPF (High Pass Filter) is used the energy of the secondary battery can be reduced to 71.69% and its power also can be reduced to around 36.8%. As for SMES, the energy is reduced to 35.45%. It means that the power required to compensate is mainly drawn from SMES but the energy of the SMES can be saved due to the energy from battery. On the other hand, if the two series connected first-order HPF, which is the second order filter, is used, the energy of the secondary battery increases to 91.38%. It means that some useless energy transfer between the secondary battery and SMES occurred due to the phase shift of the HPF. The higher the order of the HPF is, the larger the phase shift of the filter is. Hence, the useless energy transfer becomes larger. The same matter can be applied to any types of the HPF. The Chebyshev HPF has the sharpest cut-off characteristics, but the phase shift is largest. So that the useless energy transfer between the secondary battery and SMES becomes largest in case of Chebyshev HPF, as a result the sum of the energy of the secondary battery and SMES is the largest compared with other types of HPF. From the results shown in Table 1, the first-order HPF is the best characteristics.

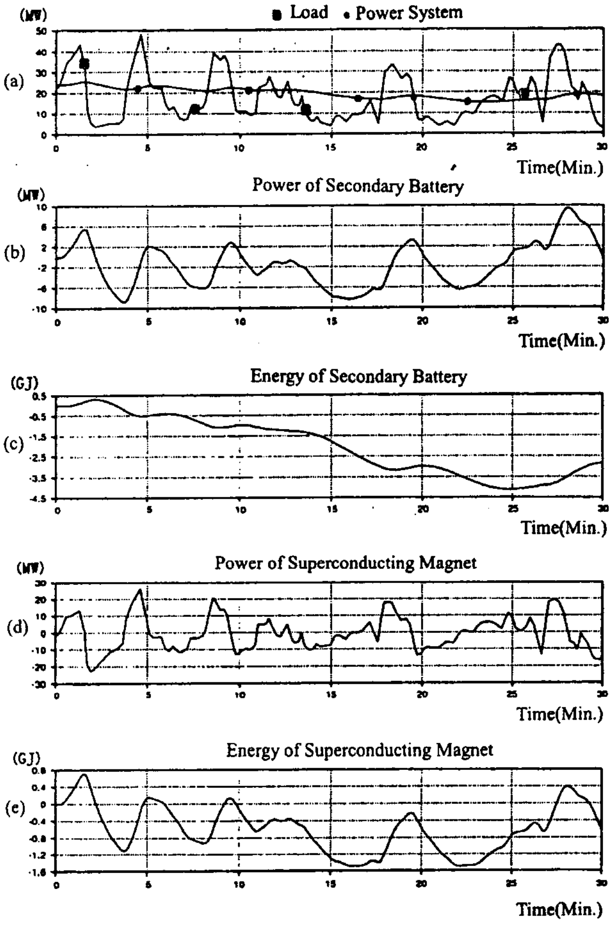

Fig.5. Simulation Result of the Hybrid Storage System.

As for the cut-off frequency of the HPF, it was changed from 0.005rad/s to 0.04 rad/s as shown in Table2. In case of 0.005rad/s, the required energy for SMES is around half of the required energy to compensate and the energy of SMES is relatively large. In case of 0.04rad/s, required energy for SMES is only 13.55%, but the power of the secondary battery is 78.63% and power of the battery is relatively large. Among these results, 0.01rad/s seems to be the best characteristics for the load pattern shown in Fig.3, because of the best sharing of the energy and power between the secondary battery and SMES.

Table1. Required Power and Energy for Secondary Battery and SMES for Various High Pass Filter Characteristics.

	Energy of Secondary Battery	Power of Secondary Battery	Energy of SMES	Power of SMES
First-order	71.69%	36.80%	35.46%	103.45%
Two Series Connected First-order	91.38%	69.50%	35.41%	105.88%
Four Series Connected First-order	96.76%	70.98%	29.68%	103.79%
Second-order Butterworth	86.23%	93.95%	37.25%	98.79%
Second-order Bessel	85.45%	93.96%	40.19%	93.88%
Fourth-order Bessel	89.83%	93.89%	34.55%	118.60%
Fourth-order Butterworth	102.0%	93.85%	30.64%	132.30%
Second-order Chebyshev	87.43%	93.69%	38.04%	107.91%
Fourth-order Chebyshev	110.76%	110.20%	29.83%	141.91%

Table 2. Required Power and Energy for Secondary Battery and SMES for Various Cut-off Frequency of the First-order Filter.

Cut-off Frequency	Energy of Secondary Battery	Power of Secondary Battery	Energy of SMES	Power of SMES
0.005rad/s	52.38%	20.59%	53.74%	105.56%
0.01 rad/s	71.69%	37.35%	35.43%	104.20%
0.02 rad/s	84.40%	58.88%	22.94%	88.53%
0.04 rad/s	92.12%	78.63%	13.55%	83.72%

Fig.6 shows the simulation result of losses of the battery for various cut-off frequency of HPF. The HPF is the first-order HPF used for the simulation of Table2. The higher the cut-off frequency is, the larger the losses of the battery becomes, due to the required power of the battery shown in Table2. The battery model used for this simulation is as shown in Fig.7, in which the internal resistance and the internal voltage are adjusted depending on the remaining energy of the battery. Characteristics of the battery model is as shown in Fig.8, which shows constant current discharging characteristics and agrees with experimental results quite well as shown in Fig.9. In case of 0.01rad/s, losses of the battery can be reduced remarkably due to reduced power for the battery.

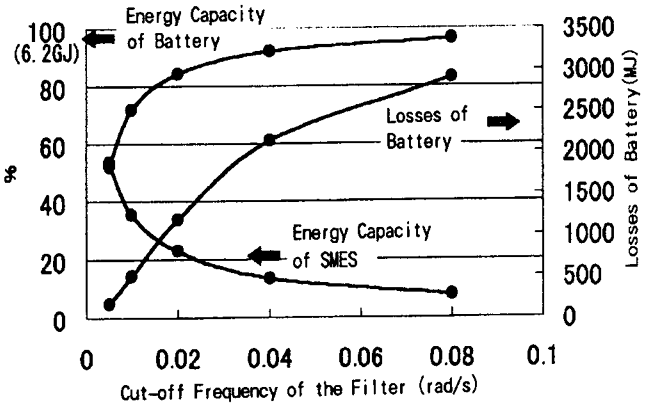

Fig.6. Comparison of Losses by Internal Resistance of the Battery and the Required Capacity of Battery and SMES for Various Cut-off Frequency of the High Pass Filter.

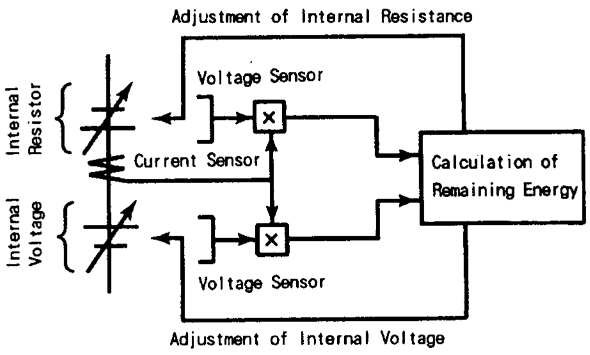

Fig.7. Secondary Battery Model.

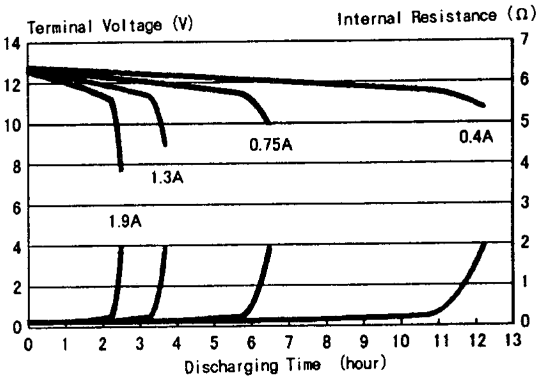

Fig.8. Simulated Characteristics of Constant Current Discharging Using the Battery Model Shown in Fig.7.

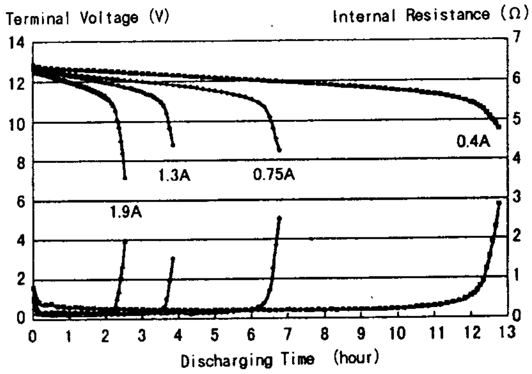

Fig.9. Experimental Characteristics of Constant Current Discharging of a Lead-Acid Battery.

C. Simulation Waveforms

Fig.10 shows simulation circuit of the hybrid energy storage system shown in Fig.1. The simulation circuit was modeled by the DC circuit instead of AC circuit and the choppers were modeled by controlled current or voltage sources instead of the switching circuit for the simplicity and reduction of simulation time.

Fig.11 shows simulated waveform of the hybrid energy storage system using the model shown in Fig.10 and PSCAD/EMTDC software. The inductance of the superconducting magnet is 4H, the DC voltage of the source is 2kV, and the internal voltage of the battery is 1kV for the simulation. The fluctuation of load current can be compensated and the coil current, battery current and battery energy can be simulated as shown in Fig.11. From this figure, it is recognized that the changing of the stored energy of battery is moderate, instead the changing of the superconducting coil current is more frequent.

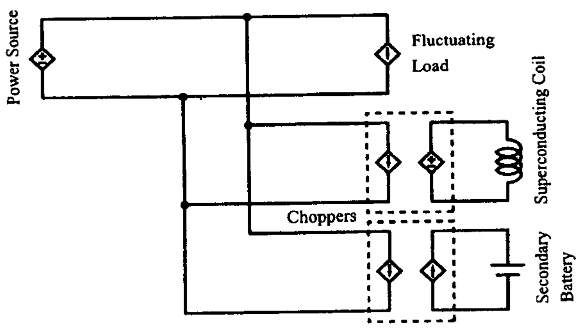

Fig.10 Simulation Circuit of the System.

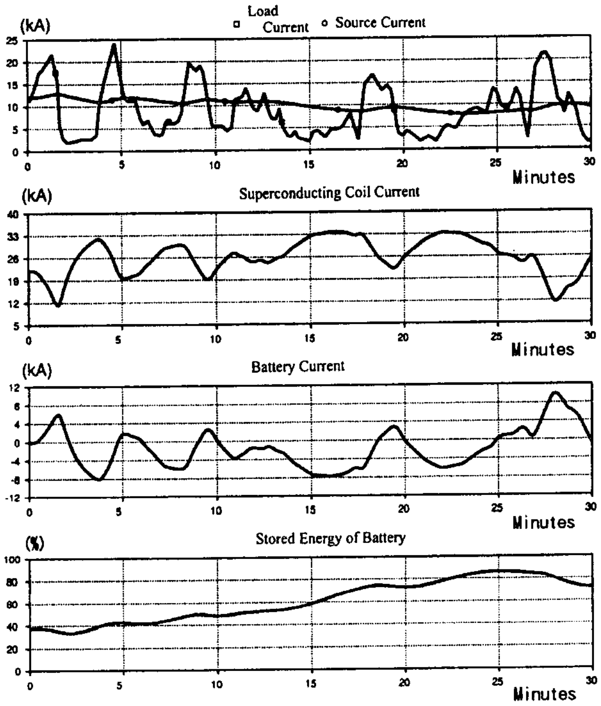

Fig.11. Simulated Waveforms of the Hybrid Energy Storage System.

IV. EXPERIMENTAL RESULTS

Experiment using a 10kJ superconducting magnet and a Lead-Acid battery was carried out. The experimental circuit is shown in Fig.12 and circuit parameters are shown in Table3. The fluctuating load was modeled by the chopper circuit shown in Fig.13. The duty ratio of the IGBT in Fig.13 was controlled in order to produce the load pattern as shown in Fig.3.

Table 3. Parameters of the Experimental System.

DC Voltage	50V
Superconducting Coil	1H, 140A, 10kJ, NbTi
Battery	12V, 160W/10min. Lead-Acid Battery (Two in Series)

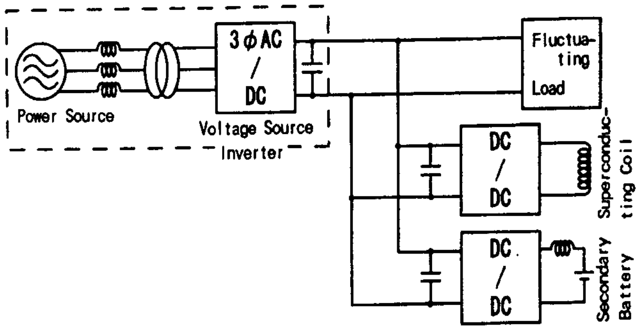

Fig.12. Experimental Circuit.

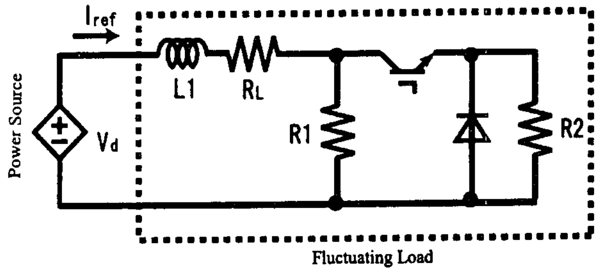

Fig.13. The Circuit for Simulated Fluctuating Load.

Experimental results is shown in Fig.14. In the experiment, the time range was reduced by the factor of 50, which means the thirty minutes in the simulation result corresponds to 36 seconds in the experiment, because of the limited stored energy of the experimental system. The source current means the DC output current of the voltage source inverter in Fig.12. The changing of the load current could be compensated by the combination of the secondary battery and the superconducting coil. From comparison of the chopper current of the battery and superconducting coil, the chopper input current of the superconducting coil is larger and has higher frequency than the battery, which means that the superconducting coil draws more power than battery but the energy is smaller because the frequency is higher. The offset between the reference and output of chopper current of superconducting coil is due to higher losses of the experimental system caused by on-state voltage of IGBTs and wire losses. From this experimental result, the performance of the proposed hybrid system was verified.

V. CONCLUSIONS

The hybrid energy storage system composed of SMES and secondary battery was proposed for the energy storage system with higher power and energy density, its control strategy was studied by simulation and the proposed control method was verified by experimental results.

By using this hybrid configuration, it is possible to expect longer life and higher efficiency for a battery energy storage due to reduced power and less frequent charging and discharging. At the same time, cost reduction of SMES can be expected due to reduced required energy.

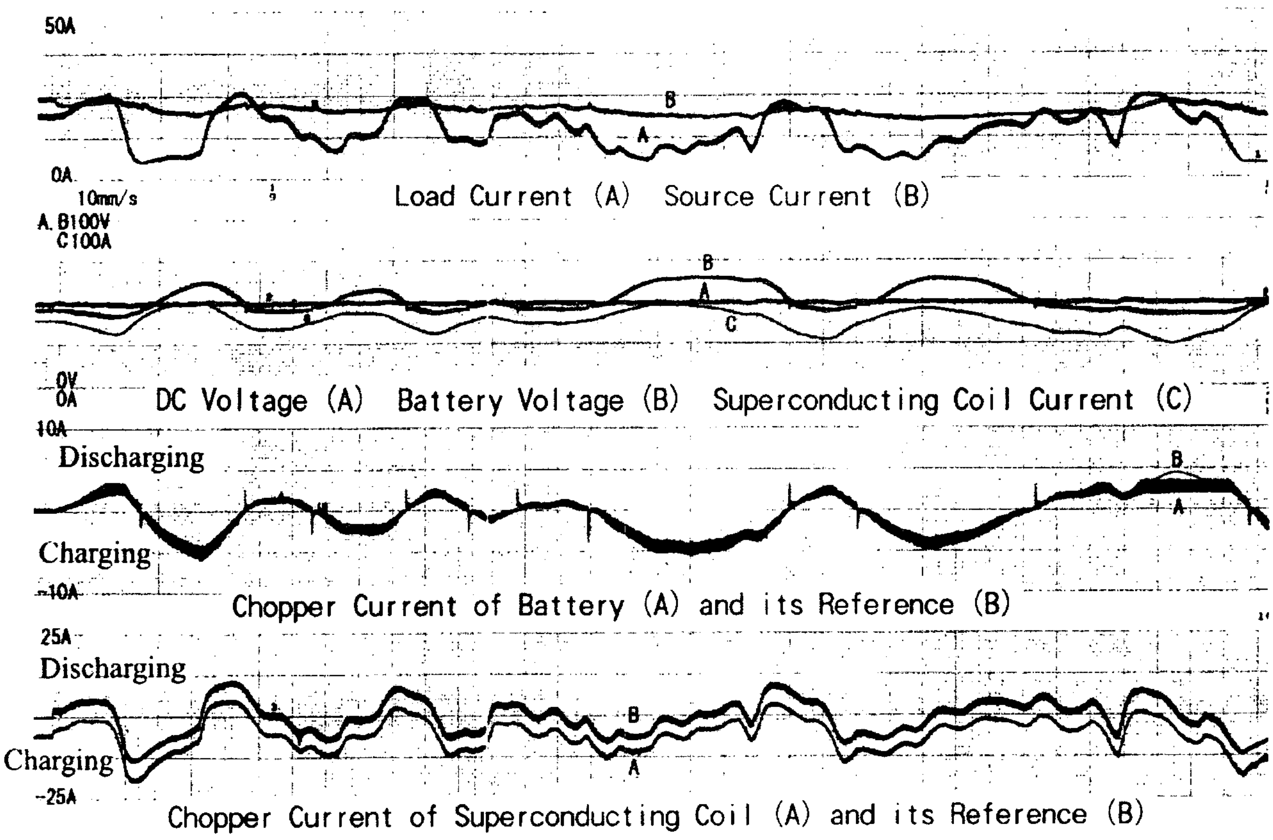

Fig.14. Experimental Results.

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