Saving Energy and Uninterruptible Power System for Large Scale Research Facility

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Abstract: Large Scale Research Facility such as J-PARC is faced on a budgetary deficit and also environmental concerns. Then, affordable and sustainable energy supply should be considered to continue and develop the big science. Magnets of the synchrotron are excited by a pulse operation power supply, and then the load fluctuation should be a severe problem. An energy storage system, such as superconducting magnetic energy storage (SMES), flywheel generator so far are expected to protect the load fluctuation and the instantaneous voltage drop. The author has investigated about the application to the particle accelerator power supply of SMES. The resent status and the future energy storage systems for large-scale research facilities, especially a particle accelerator facility, are described in this paper. This engineering technique is effective for office buildings and hospitals so far. Feasibility of the sustainable energy supply will be discussed.

Keywords: Sustainable energy supply, Large-scale research facility, Accelerator power supplies, Power compensation, Superconducting magnet energy storage circular particle accelerator.

1. INTRODUCTION

At the age of Sir Rutherford's famous experiment, every nuclear scientist deeply desired the particle accelerators, even if it is very low energy and low intensity. It should improve a very poor and inefficient way of nuclear scattering experiment [1]. More than one hundred years after that, accelerators have been developed historically to provide higher beam energy and beam intensity, and extended to collider machines. However, synchrotrons are operated with a pulse mode and accelerated beam is extracted to use not only elementary particle and nuclear physics experiment but also another several fields such as material science and medical treatment.

Especially, small-scale and low-priced accelerator facilities have been widely equipped for condensed matter physics and medical use following development of the accelerator technologies. Many medical accelerator facilities have been constructed and planned in the world.

In case of large synchrotrons such as the J-PARC main ring, the CERN-PS and the BNL-AGS, the large electric power swing is generated and electric disturbances occur in connected power networks. In such case some electric power compensation devices have to be installed. Further, peak power is several tens or a hundred MW. Especially after the biggest earthquake 2011.3.11, which has never experienced in recent Japan history and severe nuclear reactor accident, a power saving should become to an important problem.

Power supplies for larger accelerators are usually connected to their own dedicated power stations in order to suppress disturbances to networks. Some compensation is required for suppression of the load fluctuation due to large power swing caused by the facilities. The investigation has been carried out for the power compensation such as direct network connection, kinetic energy storage system, magnetic energy storage system and capacitive energy storage system so far [2, 3]. Table **1** shows the electrical power equipment of typical large synchrotrons.

2. RESEARCH DEVELOPMENT AT THE KEK

At the past KEK 12GeV-PS main ring magnet power supply, the thyristor rectifiers directly to the electrical network, that is, the ring magnet power converters (23.6MVA), the thyristor controlled reactor (TCR) type reactive power compensator systems (20 MVar lag for fundamental) and the harmonic filter banks (20 MVar lead) [4]. Research developments for the stable and reliable magnet power supply had been made efforts. The improved negative feedback loop of TCR [5] copes with three-phase unbalance and uncharacteristic ripples was reduced [4].

On the other hand, research of the SMES was performed in 1970's [6]. At the KEK, small scale SMES experiment was done in order to transfer the energy between superconducting coil and accelerator magnets

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Table 1: Electrical Power Equipment for Typical Large Synchrotrons

	KEK-PS	J-PARC	CERN-PS	BNL-AGS
Repetition (s)	2.2-4.0	3.64	2.5	1.4 -3.0
P_{total} (MW)	23.6	105	40	5/70
V_{prim} (kV)	154/66/6.6	66/22/6.6	130/18	138/69/13.6
Compensator	20 MVA SVC	Capacitor	7 MW-motor/90 MVA-FW (233 MJ) => 18.5MJ capacitors	9 MJ MG (34 MJ MG) => 12.6 MJ
Comments	Shut down in 2006	Phase II	Injector for LHC	Injector for RHIC

SVC: Static Var Compensator.

[7, 8], but it did not continue until 2000's. As a case of the 50 GeV main ring magnet power system of the Japan Hadron Project (JHF), the total peak active power becomes about 80 MW [9]. The fluctuation of active-power produce serious effects on power systems of the installation site of the magnet power supply, even if the reactive power is compensated. Hence, installation of a large-capacity energy storage system to the magnet power supply is necessary.

For the JHF, doubly-fed FW generating system was proposed [10] and continued to J-PARC, but there was no budget to construct it and extend to phase II of J-PARC plan. We have performed to research the application of FW and SMES to realize the stable power supply. The related research has been done in collaboration with the power electronics laboratory at Okayama University for FW [2] and RSMES (Research Association of Superconducting Magnetic Energy Storage) for SMES system [3].

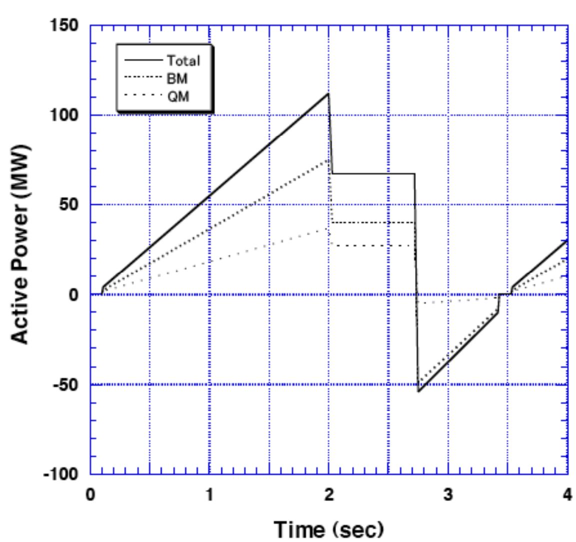

Figure 1: The pattern of the active power of the MR at the 50 GeV operation. The solid line is for the total required active power, and the dotted lines are for the dipole magnet (BM) and quadrupole magnet (QM), respectively.

Figure **1** shows the pattern of active power for J-PARC main ring magnet and Table **2** shows the candidate system of the power compensators for J-PARC.

At this present, J-PARC MR power supply equipped the capacitor storage system for rapid cycle operation of 30GeV. [11]. Table **3** shows the history of the studies for energy storage system at the KEK. The author also proposed the sustainable power system for the accelerator magnet power supply in 1998 and several workshops were organized [12].

3. RESEARCH STATUS OVER THE WORLD

The CERN-PS was the first large accelerator, which has been operated since 1959 and will be continue to the injector for LHC (Large Hadron Collider). The maximum active power varies 40 MW from plus to minus was not acceptable to the electrical network, and then a Motor-Generator (MG) was mounted as kinetic energy storage. However, this has reached the end of life. CERN has decided to replace it and many R&D was done to find new solutions [13] and at this present the capacitive energy storage system is constructed and under operation [14]. That is, DC/DC converters transfer the energy from the storage capacitors to the magnets. BNL-AGS, which mounted MG, is faced on the similar status and they also study to find solutions [15].

4. STATUS OF THE ENERGY STORAGE SYSTEM IN JAPAN

a) Superconducting Magnetic Energy Storage

The application of SMES to power compensation for these large experimental facilities are now practical

Table 2: Power Compensators and their Applications

Apparatus	Characteristics	Results	
		Facility	Capacity
FWG	Fast response Repetitive Stress Maintenance	Keihin El. Express Railway Okinawa Electric Power Fusion: JT-60 (Accelerator: J-PARC)	25 kWh 200 MJ 1300 MJ
SMES	Fast response High efficiency AC loss	Accelerator: BNL NSLS UPS: Sharp Kameyama Plant El. Power: National project Kyushu Electric Power (Accelerator: J-PARC)	2.4 MJ 10 MJ 20 MJ 3.6 MJ
Capacitor (EDLC)	Fast response Small & med. size Repetitive life	UPS: Sharp Kameyama Plant (Accelerators: BNL-AGS, CERN-PS) HEV truck	200kVA 50 – 500 kW ~100,000
Battery	Small & med. size Repetitive Life Maintenance	HEV truck	50 – 500 kW ~1,000

The parentheses indicate under investigation.
The italic words mean shortcomings.

Table 3: Hiistory of the Studies for the Energy Storage System at the Kek

1970's	・100KJ SMES Experiment.
	・3MJ SMES Coil Design.
	・Collaboration with Wisconsin University.
1997-2002	・Visit to ROTES at Okinawa.
KEK Director Support	・75KW-FW experiment.
Japan Society for the	・Collaboration with Okayama University.
Promotion of Science	
2003-2006	・Studies of SMES for J-PARC 50GeV-PS.
Collaboration with	・Studies of SMES for Medical Accelerator.
Univ. & RASMES	・10KJ-SMES simulations Experiment.
At this Present	・POP Experiment of Capacitor System.
	・Studies of SMES for 30GeV Rapid Cycle
	Operation of J-PARC PS.

thanks to the recent technological developments. Although these studies have been done, an application for the real accelerator has not realized. However, a national project to develop SMES has been carried out for the application to compensate the load fluctuation of power networks by New Energy and Industrial Technology Development Organization (NEDO) in Japan [16]. By this project, a 20MJ SMES test module was constructed and successfully tested by connection to a practical power network with small hydroelectric power stations and a metal rolling factory at the Furukawa Nikko Company. The test showed that the SMES system is very effective for stabilizing voltage and frequency fluctuations of power networks [17].

SMESs for protection of the instantaneous voltage drop, that is, UPS-SMES, are realized in several industries and laboratories such as Sharp Kameyama Factory [18] and National Institute for Fusion Science [19] so far. Moreover, the project has also investigated cost reduction of SMES for the purposes with the conclusion that the SMES system should be sufficiently cost effective [16].

The energy for compensation over 60 MW is estimated as around 30 MJ. If it is assumed that 30% of the stored energy in a SMES system is used, the SMES system of 100 MJ is necessary. My collaborators and I designed two types of SMES coils: one is a simple solenoid type and the other is a Force Balanced Coil (FBC) type [3]. The capacity of the system is 100 MJ/55 MW. We propose that the system configuration with six SMESs units are connected at the dc side of the each six power supplies. The simulation was carried out to confirm the sufficiently precise controllability of the magnet currents required for the accelerator performance [3].

The designed 100 MJ/55 MW SMES coils with the solenoid and the FBC types are shown in Tables **4**. We have varied the maximum field from 5 to 10 T. The coil sizes are almost same in the two types. However, in case of the FBC type the structural materials can be reduce to one-third and the allowed current density becomes almost 5 times larger than those of the solenoid type. The required amount of superconductor will be 1.6 times that of the coil of the solenoid type.

b) Flywheel and Others

FW system is also realized to compensate the load fluctuation of power networks which facility is named ROTES [20] and Keihin Kyuko railway company (Keikyu) [21]. Attention has been paid to a FW energy storage system based on a doubly-fed induction machine for the purpose of power conditioning. It is also referred to as an "adjustable speed rotary condenser" capable of both active-power control and reactive-power control, in contrast with a conventional "synchronous speed rotary condenser" capable of only reactive power control.

FW systems to protect the instantaneous voltage drop are operating in many industries and laboratories [22]. On the JT-60 project, 400MJ energy transfer experiment was performed between JT-60 superconducting coil and FW [22]. A FW with superconducting magnetic bearings is under studied [23].

The capacitor system for the UPS is also adopted to protect the instantaneous voltage drop at the Sharp Kameyama Factory. These facilities mounted various energy storage systems are shown in Fig.2.

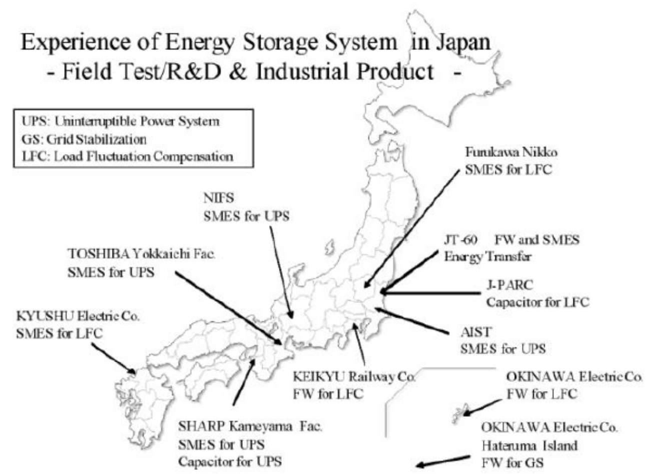

Figure 2: Energy storage sytem in Japan.

c) Application for the Small Accelerators

Many medical accelerator facilities have been constructed and planned in the worldwide. More than 20 facilities are operated, under construction, and planned in Japan. These facilities are almost composed of synchrotrons with pulse operation. Although the storage ring for the synchrotron orbital radiation is not pulse operation, the instantaneous voltage drop would be severe problem. In case of

Table 4: Parameters of 100 MJ/ 55 MW SMES

Type	FORCE-BALANCED COIL				Solenoid		
Maximum field (T)	5.0	7.0	10.0		5.0	7.0	10.0
Coil OD (m)	4.6	3.7	2.9		3.8	3.1	2.4
Height (m)	0.92	0.73	0.58		1.0	0.77	0.61
IS ($\times 10^8$ Am)	1.2	1.1	0.95		0.73	0.65	0.58
Length of 10 kA conductor (km)	12	11	9.5		7.3	6.5	5.8
M_{st} (ton)	1.0	1.0	1.0		2.8	2.8	2.8
J_{allow} ($\times 10^8$ A/m^2)	1.6	1.5	1.3		0.35	0.31	0.28

small-scale accelerators, electric power is supplied from general commercial lines and compensation devices are also desirable even though the power fluctuations are small. In addition, it is expected that the operation cost may be reduced by the associated reduction in power compensation. Then, application of energy storage system should be desired and was studied and discussed with the Hyogo Ion Beam Medical Center, Gunma University Heavy Ion Medical Center, SAGA Heavy Ion Medical Accelerator in Tosu and Nagoya University Synchrotron radiation Research center for the model cases [3]. At this present, Yamagata University hospital is proposing the charged particle therapy facility with saving electricity and is under deliberations [24].

5. ENERGY SAVING AND EFFICIENT OPERATION

At the 12GeV-PS operation, the main ring power supply was stopped afternoon to save the power and average the daily peak power, and re-started at the evening. At the Hyogo Ion Beam Medical Center, machine operation is well controlled to save the power [3]. Gunma University Heavy Ion Medical Center is proposing and under discussion including the stable power supply system for whole hospital facility.

A co-generation system (CGS) has been adopted at the RIKEN RIBF in order to increase the overall efficiency [25]. A gas turbine generates electricity and a hot exhaust from the turbine makes chilled water for cooling the equipment and air-conditioning the entire facility. Carbon dioxide and Nitrogen oxide gas emissions are also reduced by the CGS operation.

Mega-solar and wind power generation should be applied to accelerator power supply, even if these are too small to operate the magnet power supply, but effective for auxiliary power sources as air conditioner, cooling water system so far and this will give the contribution to reduce the total power of facility. For example, the incineration facility in Tsukuba-city, which is in the neighborhood KEK, generates the electric power of 3 MW and cooperation with such facility was also proposed. Spread of CGS for the large experiment facility should be strongly desired.

CERN organized the workshop “Energy for Sustainable Science” on 2011 [26] and second and third workshops were opened, 23-25 October 2013 and 29-30 October 2015, respectively [27].

SUMMARY

Status of the research and development for the energy storage systems and sustainable energy power sources are reviewed. As the first large scale energy storage system, CERN demonstrated the energy transfer between the magnets and capacitor banks and take a minimum required electric power and compensate the fluctuation of power network. At the J-PARC, similar small case system is under going for 30GeV operation [11]. One of the reasons of which CERN rejected the SMES is no industrial product above 100kJ, but a few tens MJ SMESs are realized in Japan [18].

Large-scale research facilities all over the world are faced on a budgetary deficit and also environmental concerns. Then we have to make mid- and long-term strategies for the future reliable, affordable and sustainable energy supply, particularly after 2011.3.11 these are strongly desired. We proposed the stable power system even if under sever confusion by a big earthquake accident.

In order to realize the future ILC project, it is important of best practice on the energy efficiency and optimization.

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