OPERATING THE WORLD'S LARGEST LEAD/ACID BATTERY ENERGY STORAGE SYSTEM

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Introduction

Southern California Edison Company is now operating the world's largest battery energy storage system — a 10 MW/40 MW h Facility located at its Chino 220 kV Substation, 50 miles east of Los Angeles. A two-year program started after completion of the Facility in July, 1988. Edison began the project in August, 1986. The Electric Power Research Institute (EPRI) and the International Lead Zinc Research Organization, Inc. (ILZRO) are project participants supplying the 10 MW Power-Conditioning System and 2000 tons of lead for the batteries, respectively.

Faced with a changing electric-system operating environment, Edison plans to enhance its flexibility by the development of energy storage options for energy management. These will allow storage of low-cost, off-peak energy to meet peak-demand periods — displacing costly oil and gas fuels. Energy from third-party co-generators and small power producers would be managed more effectively. In addition, Edison's system generating plants can be operated more efficiently by not being constrained by electric system requirements, such as up/down ramping and minimum loading conditions.

Battery energy-storage systems are particularly advantageous because of their modular design, short construction lead-time, and negligible environmental impact. Because of the battery's extremely fast response, the energy storage system can function as an excellent spinning-reserve source. Edison's Chino Battery Facility will also meet local peaking requirements that can defer transmission/distribution equipment requirements. These and other benefits are based on many studies of battery energy-storage systems [1, 2].

As shown in the battery energy-storage diagram, Fig. 1 [1], stored energy from the battery is fed into the Chino 12 kV distribution feeder. This reduces the demand on the 66 kV/12 kV transformer, which has been operating near its capacity during peak-demand periods. This is shown in Fig. 2 for a typical cycle of the battery operation during a 24-h period.

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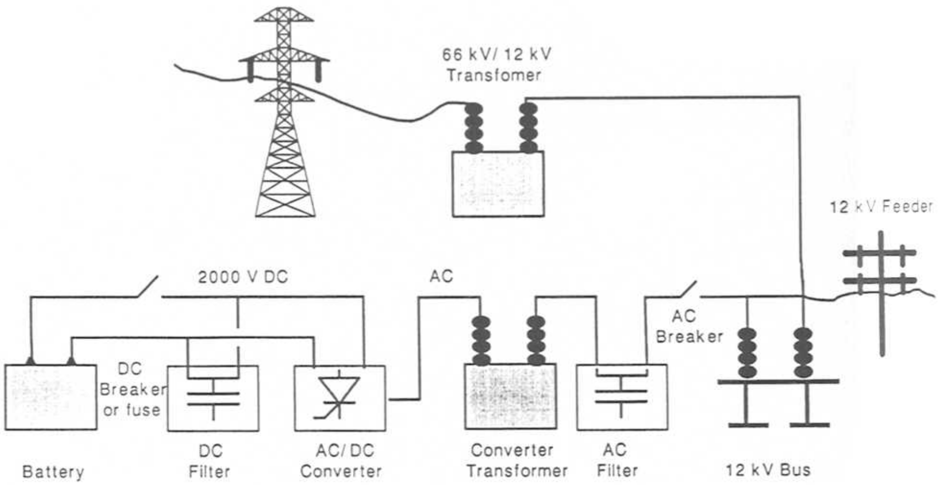

Fig. 1. Chino 10 MW lead/acid battery energy-storage diagram.

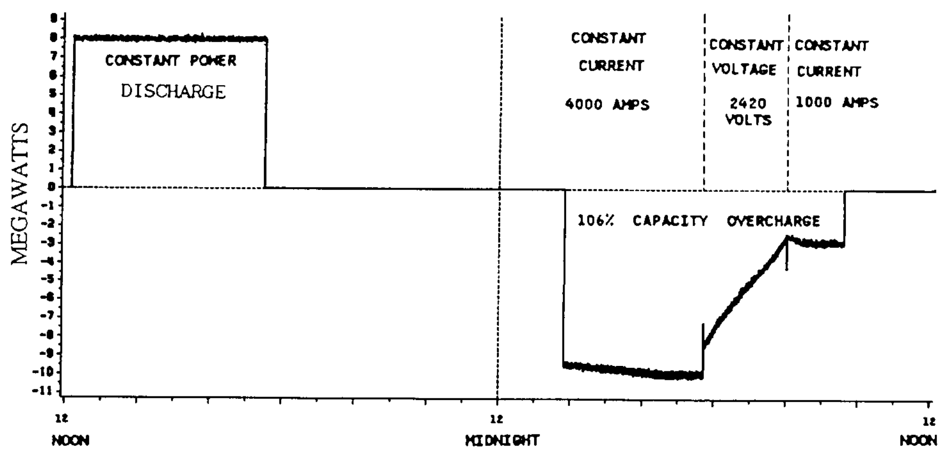

Fig. 2. Typical discharge–charge power cycle of the Chino 10 MW lead/acid battery.

Description

Physically, the plant [3] consists of two large, parallel buildings that house the batteries and which are joined by a common converter/control building in the centre (Fig. 3). The Chino 12 kV a.c. switchrack is located to the left of the two battery buildings.

Battery energy storage system

The Exide Corporation supplied the battery energy-storage system which comprises 8256 individual, large, lead/acid battery cells specifically designed for deep-discharge capability (Tables 1 and 2). Each 2 V cell has a

Fig. 3. Aerial view of Chino 10 MW lead/acid battery energy storage project.

nominal storage capacity of 5 kW h at the $C/4$ rate. The system is currently designed to supply 10 MW of power for 4 h, or 40 MW h of energy: enough to supply the needs of 5000 customers. Exide has warranted the life of the cells for a minimum of 2000 charge/discharge operations. This translates into a life of about eight years before battery replacement becomes necessary. Accelerated tests of similar cells at the Argonne National Laboratories, however, indicate that the batteries could last up to 4000 cycles.

The basic battery unit is a module of six cells (Table 3) connected in series and installed in two-tier racks to form rows, as shown in Fig. 4. When

TABLE 1

Cell design features for 10 MW 40 MW h battery

Rated capacity	3250 A h, 650 A (5 h); 795 A (4 h)
Energy capacity	5.0 kW h (4 h)
Positive plates	Pb–Sb grid, 17 plates
Negative plates	Pb–Ca grid, 18 plates
Separator system (on positives)	non-woven glass absorber mat perforated PVC retainer microporous rubber separator
Acid specific gravity	1.28 - 1.29 (top of charge)
Terminal posts	lead-plated copper
Sediment space	1.3 in.
Cell jar material	SAN
Cell cover material	PVC
Cover-to-jar seal	structural adhesive

TABLE 2

Materials for 10 MW 40 MW h battery

Material	Unit	Total required
Cells, 6 kW h	each	8256
Lead	metric tons	1560
Copper, intercells & posts	metric tons	30
Steel, racks & trays	metric tons	153
Plastic (SAN, PVC PP)	metric tons	90
Sulphuric acid, 1.285 sp. gr.	metric tons	480
Microporous separators	each	280704
Bolts (intercell, racks, trays)	each	139600
Cable, 4/0	feet	6048

TABLE 3

10 MW 40 MW h lead/acid battery

Six-cell module dimensions, weight, and ratings.

Characteristic	Unit	Cell	Module
Length	In	16.6	53.0
Width	In	15.1	36.0
Height (over case)	In	23.6	31.2
Height (overall)	In	27.0	34.8
Volume	ft^3	3.42	34.5
Footprint	ft^2	1.67	13.3
Weight	lbs	580	3650
Energy output, $C/4$ rate	kW h	6.2	37.2
Energy density (weight)	W h lb^{-1}	10.7	10.2
Energy density (volume)	W h in^{-3}	1.05	0.62

bolted on the cantilever rack, the rack braces and rigid trays assure a row assembly capable of meeting Zone 4 seismic shock and vibration. Individual cells are supported horizontally and vertically in each module tray. There are 16 rows per building with four rows forming one 2000 V d.c. string. Eight parallel strings of 1032 cells in series will deliver up to 40 MW h of energy at 10 MW to 80% depth-of-discharge.

Battery accessory features (Table 4) include automatic watering, air agitation of electrolyte, stibine–arsine traps, and flame arresters on each cell as a single assembly, acid sampling tubes, thermocouple wells, and acid-level indicators. Additional details have been previously reported [1, 2].

Power-Conditioning System

The Power-Conditioning System (PCS), manufactured by the General Electric Company under an EPRI contract, is the primary interface between

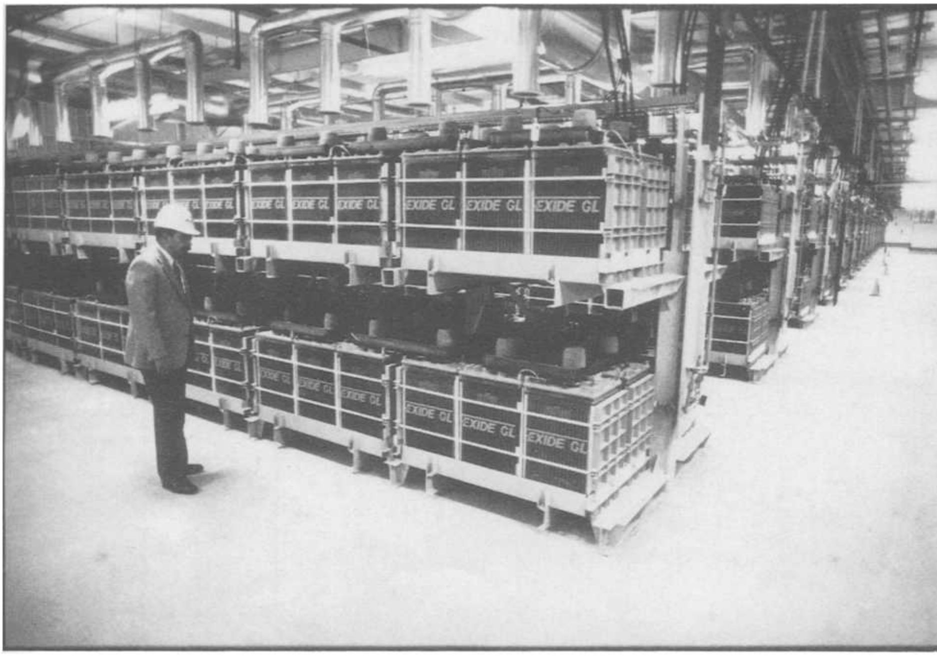

Fig. 4. View of 10 MW lead/acid battery modules of six cells in two-tier racks.

TABLE 4

10 MW 40 MW h lead/acid battery
Accessory features.

	Accessory	Location
1	Automatic watering valve Stibine/arsine trap flame Arrester	each cell
2	Air lift pump	each cell
3	Electrolyte withdrawal tube	each cell
4	Thermocouple well	0.5% of cells
5	Acid level indicator	each cell
6	Intercell connectors	lead-plated copper two per post
7	High voltage protectors	expanded plastic tube around each two intercell connectors
8	Intermodule cables	minimum 2 each (4/0 2000 V cable)
9	Lugs on cables	4.0 long barrel compression type (2000 V rating)

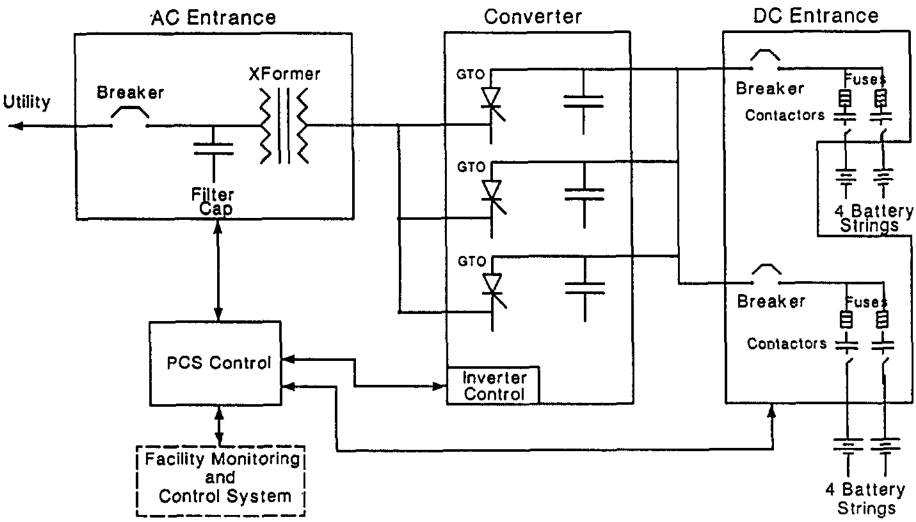

Fig. 5. Power-conditioning system layout for Chino 10 MW battery energy storage project.

the battery system and the Edison grid. The PCS converts d.c. power of the batteries to a.c. power for the Edison system and *vice versa*. The PCS and its associated control systems are the heart of the Chino Facility; monitoring and controlling all functions of the battery system such as ramp-up rates, charging voltage, and power level. Figure 5 shows a block diagram of the PCS and associated equipment.

Because of its unique design, the converter can function independently as a synchronous generator to maintain a power factor of unity. It is also designed to produce very clean and high-quality power while maintaining a 97%, one-way efficiency at full load. The 18-pulse converter is a self-commutated, Gate-Turn-Off (GTO) voltage source, stepped-wave design which means it can behave independently as a synchronous generator to maintain unity power factor. A summary of the major performance characteristics of the PCS is shown in Table 5.

The d.c. entrance equipment consists of two, 3000 A, 3000 V d.c. high-speed breakers, eight, 900 d.c. ampere no-load break battery string contactors, fuses, and disconnect switches. The PCS control system is a microprocessor-based interface to the PCS with pre-programmed algorithms for charging and discharging operations. The control system communicates with the Facility Monitoring and Control Systems (FMCS) via a distributed network interface for reporting over 100 system status parameters. It also provides commands for real and reactive power to the converter control and receives diagnostics from it for transmittal to the FMCS.

The a.c. entrance equipment includes 12 kV vacuum switchgear, nine, single-phase transformers, one, three-phase neutral transformer, filter capacitors, surge arresters, and a.c. protection relays.

TABLE 5

Major power-conditioning system characteristics

Power	
real	10 MW, charge/discharge
reactive	10 MV A, leading/lagging
Efficiency	97% one way
Harmonic voltage	3% total, 1.5% any single frequency
Ripple voltage	
d.c. to battery	1.5% RMS voltage
Response	16 ms
Voltage input range	
nominal	2112 V d.c.
maximum	2860 V d.c.
minimum	1750 V d.c.

Facility Monitoring and Control System (FMCS)

The Westinghouse Corporation was contracted by Edison to supply the FMCS. The microprocessor-based control system provides complete facility supervisory control and data acquisition. The FMCS is interconnected with the PCS control system via a single RS-232 communication cable and one hard-wired contact to enable the facility to be operated from either the PCS or the FMCS control console. Two control consoles and an engineer's console are provided. One of the control consoles is located in the Chino Substation operator's control room for remote operation and status monitoring.

The FMCS is pre-programmed with a typical load curve for automatic control of the battery discharge rate but can be modified readily from the engineer's console to allow for different discharge patterns. Reactive power output is also programmed into the FMCS.

The Historical Storage and Retrieval System (HSR) is the component of the FMCS that records data on facility operations to allow analysis of performance and economics. Analogue inputs are scanned at one-second intervals and stored in the data acquisition system (DAS) at pre-defined intervals of one, ten, or sixty seconds if they have exceeded deadband limits. Digital points are recorded with one-second resolution if states have changed. A modem is also connected to the data highway to facilitate on-line data reduction and data access from a remote personal computer located at Edison's main offices.

Research test program

During the two-year testing period, the Chino Battery Facility will accomplish several major objectives. First, the Facility will demonstrate the compatibility and reliability of the system to manage loads effectively on a daily basis. The system will undergo a series of tests to assess its capabilities under actual operating conditions in various modes, such as load levelling, spinning reserve, load following, up/down ramping, and voltage/frequency control. Other studies will be conducted to determine optimum operating procedures, system efficiency, battery cell performance, and battery system thermal behavior. The initial three months of the Two-Year Test Plan were formulated to characterize operating parameters, such as discharge voltage and current levels, and subsequently to establish benchmark performance curves for later comparison. These initial operating tests will also be used to establish baseline operation of the Facility at selected times.

Second, the Chino Facility will provide actual operation and maintenance (O&M) costs, and such information will be used to develop improved O&M procedures to lower costs. Finally, it is the objective of the project's participants to transfer the information gained on this first-of-a-kind demonstration to electric utilities and other parties interested in applying battery energy storage for energy management purposes. Activities during the two-year program will be monitored and a summary report written by an Engineer-of-Record, provided under an EPRI contract with United Engineers & Constructors.

Initial operating results

Once construction of the Facility had begun, the work of installing and pre-testing the equipment progressed satisfactorily and on schedule. As each battery string was electrically connected to the bus and inverter/control equipment, it was partially cycled through charge, discharge, and equalization until all cells appeared to be at equal capacity. This sequential procedure was necessary because the cells had been manufactured over a year's duration and were on different periods of float charge during storage before shipment.

By the end of June, 1988, it was possible to begin cycling all eight strings in parallel, first at reduced power and time, and gradually to full power. During this period, it was observed that 27 cells suffered reversal prior to the strings reaching 80% depth-of-discharge. These were identified quickly with an infrared scanner and were either replaced or closely monitored while being brought back to full capacity. After a few cycles in which the capacity of 40 MW h was discharged into the PCS, the battery appeared to have reached about a 50 MW h capacity, based on an end voltage well above the 1.75 V/cell cut-off.

August was the first month of testing, in accordance with the Two-Year Test Program. During the subsequent months, there were several control system trips for various reasons, but these could be categorized as program software glitches, or electronic hardware failures. On two separate occasions, four GTO thyristors failed for not totally understood reasons to date. A total of four man-weeks was expended to water the lead/acid batteries.

TABLE 6

Battery and system efficiencies in two test cycles

	Test no.	Power (a.c.) (MW)	Energy (d.c.) (MW h)	Capacity (d.c.) (kA h)	Energy (a.c.) (MW h)	Energy (a.c.) auxiliaries	Efficiency[b] (a.c.) plant
Discharge	33	8.2	43.3	20.8	42.8		
Charge	33	[a]	52.5	22.05	54.1	4.60	
Eff. (%)			82.5	94.3	79.1		72.9
Discharge	34	8.2	43.4	20.8	42.9		
Charge	34	[a]	56.2	23.0	58.2	4.80	
Eff. (%)			77.2	90.4	73.7		68.1

[a] Charge method is CC/CV/CC. Initial power in both charges was 7.5 - 8.0 MW. Also, note, coulombic overcharge was 106% and 111%, respectively. It appears that 106% will be normal, but occasional equalization will be necessary throughout life.
[b] See text for formula.

Another major disturbance was the failure of a battery string fuse bank, but this was attributed to a defective fuse.

These events have caused the Facility to be unavailable for about four weeks, delaying the Two-Year Test Program for one month. Power, energy, and efficiency in two successive cycles are listed in Table 6. The a.c. plant efficiency is the ratio of a.c. energy out to the sum of a.c. energy in and a.c. energy for auxiliaries. In the first cycle, a 105% recharge (A h) is considered normal, and in the second cycle, the 111% recharge is excessive.

The 10 MW battery resistance at full state of charge was calculated to be 0.025 Ω, using the $\Delta V/\Delta I$ method of estimation, over a range of discharge power levels from 1 to 10 MW. The string average is then 0.20 Ω and the single cell value is 194 μΩ, including all inter-module connectors and string end-cables. Exide data on single cells, by the same method during both charge and discharge, averaged 140 μΩ post-to-post. The difference in these two measurements implies that resistance of the module connections in a string is about 50 μΩ.

The a.c. impedance of the Exide cells has been measured. Using a Keithley Model 503 milliohmmeter with a 40 Hz square wave, a value of 220 μΩ was obtained. Using a newly designed meter developed for utility lead/acid stationary batteries (with a 1 A, 25 Hz sine-wave signal applied to subrows of 33 cells in series), values around 100 μΩ post-to-post were measured. Studies will continue for possible correlation of impedance and capacity throughout life cycling of the battery.

Conclusions

The Chino 10 MW Battery Energy Storage Facility has been operating under a two-year test plan since July, 1988, when construction and start-up were completed. Initial operating performance is considered satisfactory, in spite of unexpected operating disturbances.

Under a formulated test plan, it is expected to demonstrate and quantify the costs, benefit, and performance of the Chino Battery Facility within a two-year period. In addition, operating, maintenance, and safety procedures will be developed and documented as the test program progresses.

The Facility has already demonstrated its unique load-levelling capability that can defer or replace costly peaking generation capacity.

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