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Design and commissioning of a valve-regulated lead/acid battery energy-storage system for backing up critical environmental loads

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Abstract

Momentary and sustained electrical power interruptions and voltage depressions represent two of the most difficult and important power quality and delivery problems that face many industrial and commercial users. There is a definite need at many industrial processing plants and commercial users of electrical power to have a dependable, efficient and controllable source of real and reactive power that is available instantly to support large electrical loads (greater than 5 MVA), even if the incoming utility a.c. connection is lost. When power is interrupted or lost, the results can be extremely disruptive for critical processes and cause lost production, costly downtime and loss of customer good will, and in certain industries, can lead to environmental damage through the release of toxic emissions into the air. Recently, this challenge was faced by GNB Technologies at its lead reclaiming and smelting facility in Vernon, CA, USA. This study describes a versatile, cost-effective, workable solution to the problem that has resulted in the design and installation of a 5 MVA, 3.5 MWh battery energy storage system (BESS) which provides uninterruptible power to the critical environmental control equipment throughout the plant. The BESS at Vernon provides the required power, combined with both voltage and frequency control, to allow the plant to tolerate disconnection from the utility grid without suffering unacceptable impacts on critical loads. The system also provides the company with a demand-side energy management system for conducting daily peak shaving of energy demand and, thereby, reduces its electrical bills. © 1997 Published by Elsevier Science S.A.

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1. Introduction

Battery energy storage is a technology that can play a flexible, multi-functional role in a wide range of electric utility systems or industrial manufacturing and processing applications. A battery energy storage system (BESS) has the potential to offer electrical utilities and/or their customers an effective tool in helping to manage their electricity generation and delivery needs, provide conservation through energy management, and help solve power-regulation problems [1].

The basic concept of a BESS is to allow the user to store electrical energy for dispatch at a time when its use is more economical, strategic, or efficient. The battery system accepts electricity from the utility grid normally during off-peak hours when the cost of energy is low, stores it in batteries, and returns it to the grid during the peak hours of the day or can supply it to the electrical loads on demand when required, responding very much like an uninterruptible power supply. To perform these functions, numerous components in the system must work together. The primary components are: (i) the power-conditioning system, which interfaces between the utility a.c. and the battery d.c. power where the energy is stored; (ii) the battery system, an assembly of series and parallel strings of typically 2 V lead/acid battery cells, and (iii) the controls and monitoring system.

A new generation of BESSs are now available with power ratings that range from 0.5 MW up to as large as 40 MW. The capacity of the system can be sized to support a few minutes of operation or to operate for hours at maximum power. Sizing of a system is driven by the type of application and how it will be used.

2. Why a BESS at Vernon?

One of the critical processes at the GNB lead reclamation centre is the operation of emission control systems associated with handling lead dust. The plant operates 24 h per day, seven days per week, and produces over 100 000 short tons of reclaimed lead annually. GNB's primary concern is to assure the continual operation of its environ-

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mental control systems during a power interruption or a complete outage. When incoming power is lost, large fan and blower motors (with up to several hundred horse power) stop running and the exhaust emissions from blast and reverberatory furnaces, as well as lead dust generated during-breaking of old spent lead/acid batteries, can escape into the atmosphere.

A cost-effective, workable solution was found by GNB, and resulted in the installation of a BESS which provides uninterruptible power to the critical loads at the plant. Since the critical loads at the plant are not isolated, it is necessary to carry the entire plant load (maximum of 5 MVA) for a short period of time until non-critical loads have been automatically shed immediately following an incident. Plant loading typically peaks at 3.5 MVA with the critical loads totaling about 2.1 MVA. The critical loads are mostly large induction drive 4160 V a.c. motors. It has been established that the plant needs at least 20 min of uninterruptible power to control effectively critical processes for a safe and orderly shutdown, thereby assuring full control of all potential lead emissions.

In November 1995, following 12 months of design and construction, the GNB Vernon BESS facility was commissioned and was placed in service.

3. Vernon BESS description

The primary function of the system is to maintain the critical process loads during outages that result from disturbances external to the plant. To accomplish this, the BESS is installed at the 4160 V level of the plant-power distribution system, in parallel with the existing loads.

The BESS is designed to work with the existing plant-control system to shed automatically all non-critical loads as soon as possible after a power failure. This operation occurs in a matter of seconds and thereby reduces the overall plant loading to approximately 2.8 MVA. The battery capacity has been sized to support this power requirement for up to 1 h. To support all the critical loads, the plant needs at least 20 min for an orderly shutdown. The battery system has been designed with an additional reserve capacity to handle daily peak shaving of 500 kW for 3 h (1.5 MWh). This added feature allows the system to reduce the plant's demand and energy costs. Provision is made in the microprocessor-based controls of the BESS to transfer the plant back (automatically or manual) to the utility feed if utility power is restored within the 1 h operating time frame allotted for supporting the critical loads.

The best way to describe the Vernon BESS facility (Fig. 1) is to list all the major items and components that make up the system (Table 1) and provide a simplified BESS one-line diagram of the installation Fig. 2, Table 2). The entire system, excluding the transformers, harmonic filter bank and coils, and disconnect switch, which are located outside within a fenced-in yard, are enclosed within a building that measures 131 feet long by 25 feet wide. The switch yard area is about 40 feet wide by 50 feet long. The building principally houses the battery strings, power conditioning system, controls and monitoring equipment. The HVAC systems are on the roof.

4. BESS performance criteria at Vernon

There are two types of disturbances that the BESS guards against. These are power interruptions and short-

Fig. 1. Battery energy storage system in Vernon, CA, USA.

Table 1
List of major BESS components

1	A dedicated prefab insulated steel building.
2	A poured, 8 inch (minimum), steel-reinforced concrete foundation and floor.
3	Two strings of valve-regulated lead/acid battery cells, connected in parallel with manual disconnect switches and fuse protection. Each string has 378 2 V modules connected in series and is fused at 4000 A. Each string is split into three sections (252 V each).
4	Battery monitoring control cabinet providing state-of-charge control and peak-shaving control.
5	Personal computer (486/66 MHz) interfaced to the battery monitoring control cabinet for data display, battery maintenance, and data acquisition and storage.
6	A power conditioning system (PCS) which provides bi-directional power conversion between the utility grid and plant substation, a.c. systems and battery d.c. system.
7	Station control for sequencing and control of the power converters.
8	Remote operator's panel located in the plant control center.
9	Fused main BESS disconnect switch.
10	Power factor correction capacitors and harmonic filter to meet *IEEE 519* standard.
11	Relay panel responsible for detecting a utility outage and supervising the operation of the main plant service breaker.
12	Separate PCS and battery room heating, ventilation, and air conditioning unit (HVAC).

circuits. A power interruption is the loss of one or more of the lines that feed the plant. Since the BESS acts as a voltage source in parallel with the load, the load will not experience the interruption and will continue to operate normally. The plant breaker will open based on measured current in balance or reverse power flow.

Short-circuits can occur as phase-to-ground or phase-to-phase and will affect the entire plant. The strategy for

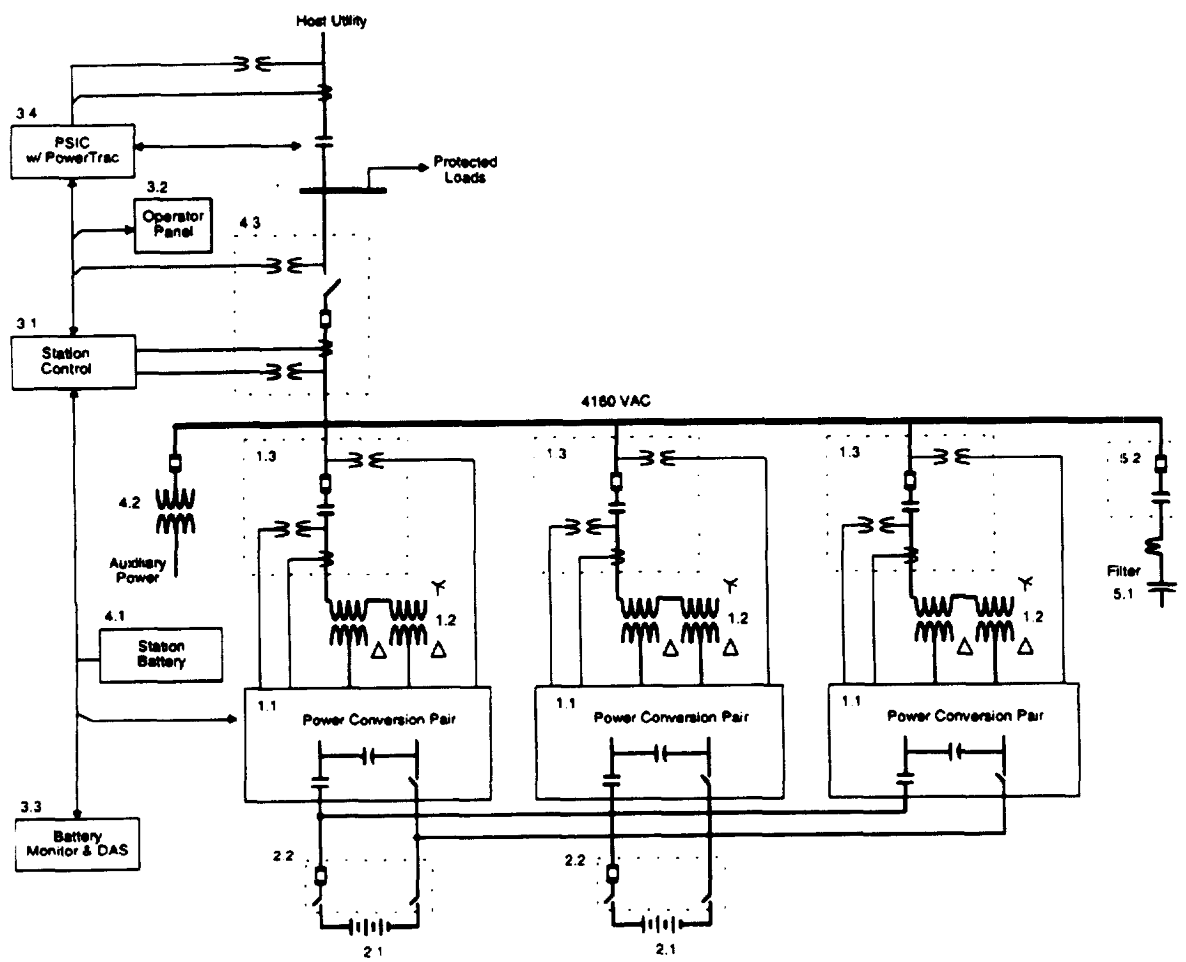

Fig. 2. One-line diagram of the Vernon BESS.

dealing with short-circuits is to isolate the plant from the fault and re-establish voltage to the loads as quickly as possible in less than 200 ms. The BESS is designed to continue to operate through these short-circuits. After the plant breaker is tripped, a signal is sent to the plant PLC to trip non-critical loads and restart some critical loads, if necessary. The BESS can be set to resynchronize automatically and connect to the utility when power is restored, provided the MWh rating of the battery system has not been exceeded.

By design, there are three modes of operation [2]:

1. on utility: defines the normal state when active power for the plant loads is supplied by the utility and the BESS is idle, charging or peak shaving, and managing reactive power for the plant;
2. isolated: defines the emergency state when power for the plant loads is supplied by the BESS and the utility is disconnected, and
3. resynchronizing: defines the process whereby the isolated plant is reconnected to the utility grid.

5. Vernon BESS' rating

The Vernon BESS is designed (Table 3) to operate for up to 10 s at a maximum plant power demand of 5 MVA immediately after a take-over following a loss of utility grid power. Presently, the plant peak demand is about 3.5 MVA and generally ranges between 2.4 and 3.1 MVA. Upon sensing a loss of utility voltage, the BESS automatically controls the following functions:

1. the incoming circuit-breaker is opened;
2. the existing plant-control system has been programmed to shed all but the critical loads (2.1 MVA);
3. the BESS will carry the plant load (up to 2.8 MVA) for up to 1 h or until such time that the utility power has been restored;
4. once the utility feeder voltage is present, the BESS can automatically reconnect (manual reconnect is also available) the isolated plant load with the utility.

Table 2
Description of major components of Vernon BESS. (refer Fig. 2)

Item	Description
1	*BESS power conversion system*
1.1	General Electric PCS 2000
1.2	Zigzag isolation transformer, 0.92 MVA, 522-4270 V a.c.
1.3	Fused contactor with PT's and CT's, Limit amp
2	*Battery system*
2.1	Battery string, 756 V d.c. nominal
3	Control and monitoring equipment
3.1	Station control, sequence logic, outer loop controls
3.2	Operator panel
3.3	Battery monitor and DAS
3.4	PSIC (relay panel) with Power Trac
4	*Auxiliary equipment*
4.1	125 V d.c. station battery with charger
4.2	Auxiliary power transformer
4.3	Fused disconnect switch with PT's and CT's
5	*Harmonic filters* (oil-filled capacitors)
5.1	Common bus filter to meet *IEEE 519* [1]
5.2	Fused contractor

Table 3
Ratings for Vernon BESS

Base voltage at 1.0 pu	4160 Vrms L–L
Frequency	60 Hz
Continuous power rating	3000 kVA
Peak power rating (10 s)	5000 kVA
Nominal current rating	416 A
Nominal d.c. voltage rating	756 V d.c.
Number of series battery strings	2
Nominal battery capacity at the 1 h discharge rate	5000 Ah
Number of power converter pairs (PCP)	3
PCP power output rating	575 V a.c.
PCP d.c. voltage input range	600–900 V d.c.

6. Vernon BESS power conditioning system (PCS)

The PCS part of the BESS consists of a voltage source inverter that is designed to operate as either an inverter when discharging the battery or as a rectifier when charging. The PCS is designed with self-commutating static switches that are capable of supplying the reactive power needs of the Vernon plant. The a.c. waveform has some resultant harmonic content which it filters to meet *IEEE 519* standards.

The building block of the PCS at Vernon is a 6-pulse converter, arranged in pairs to form a 12-pulse power converter module (PCP). A simplified circuit diagram of one PCP is shown in Fig. 3. Each PCP, therefore, forms a 12-pulse bi-directional voltage source using gate-turn-off (GTO) thyristors in the power conversion circuits that make up the converter pair. Each GTO is parallelled by a reverse diode to give the converter the capability of handling power flow in both directions. The d.c. link capacitor bank is necessary to absorb a.c. currents reflected by the converters onto the d.c. bus.

Each 6-pulse converter is connected to a power transformer designed for static converter operation. The connections are arranged to provide an equivalent 12-pulse wave shape when connected to two 6-pulse converters that are operated with firing signals 30 electrical degrees apart.

To assemble the overall power conditioning system, three of the PCPs are connected in parallel to achieve the power rating requirements for the Vernon BESS application. Each PCP is connected to the power system through an a.c. contactor.

The PCP converter hardware line-up is shown in Fig. 4. There are four main cabinets. The two 30″ wide cabinets on the right contain the 6-pulse GTO converters. A 24″ cabinet in the centre contains the d.c. link capacitor bank and protection. The application specific d.c. line panel, 60″ cabinet on the left, contains the d.c. link converter, capaci-

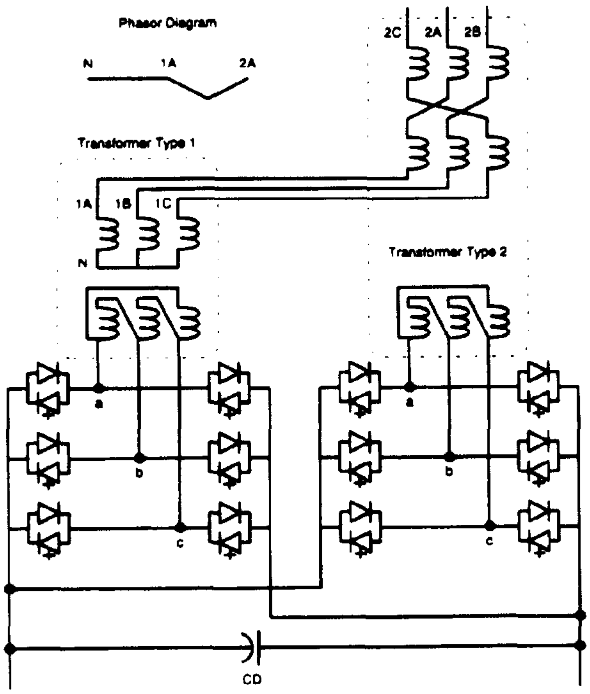

Fig. 3. Outline of a 12-pulse power converter pair.

tor charging circuit. I/O interface, control isolation transformers, contactors, and miscellaneous hardware. (Note: a detailed description of the power converter design is planned for a further publication.)

7. Lead/acid battery system at Vernon BESS

At Vernon, the battery selected and being used is an advanced valve-regulated lead/acid (VRLA) Absolyte* IIP modular battery system manufactured by GNB Technologies.

For more than 100 years, lead/acid batteries have been used for many essential standby and portable-power applications. In the past twenty years, advancements in lead/acid technology and battery construction have lead to the production of large, industrial size, sealed, low-maintenance, VRLA battery cells like the one that is being used in the Vernon BESS application.

The VRLA designed battery cell is completely sealed and employs a pressure-relief safety valve. This electrochemical device operates on the basis of oxygen-recombination technology, uses starved electrolyte absorbed glass mat construction and has no free acid to spill. The cells store energy efficiently, economically and safely, do not require water addition and, during normal charge/discharge operation, do not give off gases as a traditional, flooded, vented lead/acid battery cell can.

By using the VRLA battery at Vernon, the required floor space needed to house the two strings of battery cells was reduced by over 50% as compared with using a flooded battery. Since the VRLA cells are sealed, battery cells are arranged three to a module and stacked one-on-top of each other eight modules high. The battery assembly

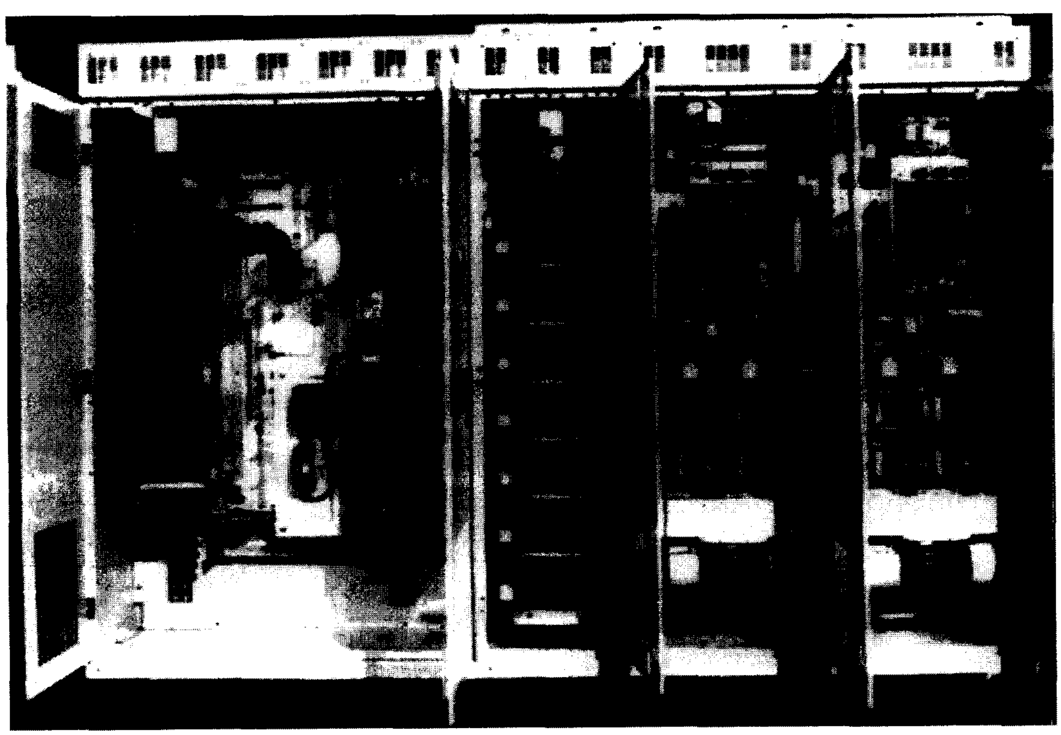

Fig. 4. PCP converter line up.

Fig. 5. VRLA battery strings.

was designed and certified to meet a seismic zone-4 earthquake.

Low maintenance is especially important for utility companies and industrial users having a BESS. Since the Vernon BESS system is unmanned and operates automatically, servicing the system is kept to a minimum with the VRLA battery system and operating costs are lower.

7.1. Battery layout

The battery system shown in Fig. 5 below, consists of two parallel strings. Each string has 378 GNB model 100A99, 2 V, VRLA Absolyte® IIP modules connected in series to provide a nominal 756 V d.c. Each 100A99 module contains three model 100A33 cells connected in parallel. A metal housing for the 2 V cells is used to assemble a single power module. The tray has three basic parts: (i) a container to house the cells; (ii) restraint bars to hold the cells within the container, and (iii) a clear plastic protective cover to insulate the cell connectors.

The system contains 48 stacks of batteries per string. These are arranged into 46 stacks, 8 high and two stacks, 5 high. The total installed weight of the battery assembly is around 305 short tons. At the end of each string, there is a d.c. disconnect switch fused at 4000 A. Each of the battery stacks are monitored for voltage, temperature, and potential ground faults. Pilot cells, as well as string current and hydrogen sensors are also monitored.

8. Theory of operation of Vernon BESS

For most operating conditions, the BESS is equivalent to a voltage source behind the transformer reactance (X_T), as shown in Fig. 6. The PCS generated voltage (V_B) is completely controllable within the current rating of the converter equipment. Consequently, the a.c. current can be supplied at any phase-angle relative to the terminal voltage (V_T). This feature permits the BESS to generate real and reactive power in all four quadrants, as indicated by the capability curve. The BESS power-generating capability is limited by the thermal rating of the converters and the available battery voltage. Overload capability will permit

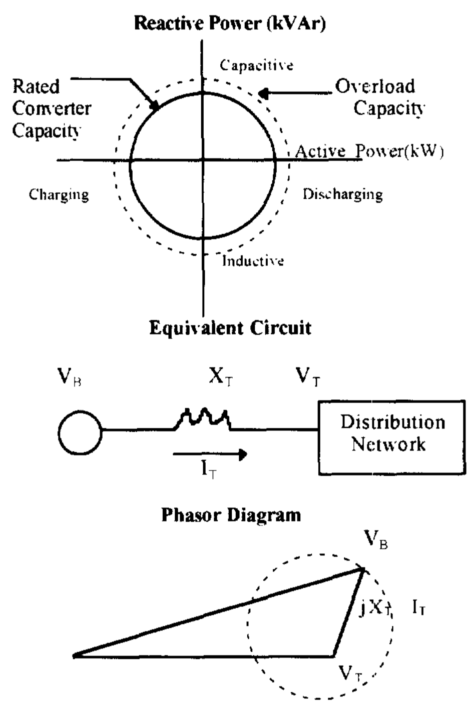

Fig. 6. Active and reactive power capability [2].

operation at higher currents for limited periods of time, as suggested by the dotted capability curve.

9. BESS control system

A simplified block diagram of the control system is shown in Fig. 7. Terminal voltage magnitude and power control loops are included with the PCS. Power and voltage orders are provided by the station control.

9.1. Station control

Control of the PCS to meet the various modes of operation is provided by the station level control, as shown in Fig. 7. The control consists of a microprocessor controller for regulator functions and a PLC for sequencing and protection.

When operating on utility, the voltage order is derived from a closed loop VAr regulator which maintains the PCS at a desired power factor. The power order follows the charging needs of the battery, or the operator can schedule the system to reduce automatically the plant demand charges.

When isolated from the power grid, the voltage order is adjusted to maintain nominal plant voltage (4160 V) and the power order is dynamically adjusted to hold frequency at 60 Hz.

When resynchronizing, voltage is adjusted to match measured utility voltage and plant frequency is adjusted to match measured utility frequency and phase-angle. Synchronizing with the utility is supervised by a standard synchronism check relay.

9.2. Battery monitor control

The battery monitoring control performs five major functions:

1. calculates the state-of-charge of the battery;
2. provides for battery charging and discharging control;
3. monitors the health and status of the battery;
4. records battery operation for future optimization and warranty management, and
5. detects ground faults should one occur.

The battery monitoring function is implemented in a PLC working with the operator interface computer. The computer consists of an industry standard PC running a graphical interface program for data storage and display.

9.3. Relay panel control

The relay panel consists of standard, utility grade, protective relays that are designed to monitor the point of utility connection. The control logic will trip the main plant breaker if the utility feeder is faulty.

The following conditions are detected:

- faulted phase detection
- three-phase power interruption
- one-phase power interruption
- over/under frequency

While the plant is isolated, the relay panel will detect when three-phase utility feeder voltage is restored. If the operator then requests a resynchronization, the relay panel will supervise the breaker closing using a synchronism check relay. All relays are self resetting to allow for unattended automatic operation.

10. Final commissioning test results

Acceptance tests of the Vernon BESS installation were completed on 5 November 1995. Testing of the various pieces of hardware actually started in late September. A brief overview of the results follows.

10.1. VRLA battery strings

Battery capacity developed to 100% on the third 80% depth-of-discharge cycle. This was accomplished by run-

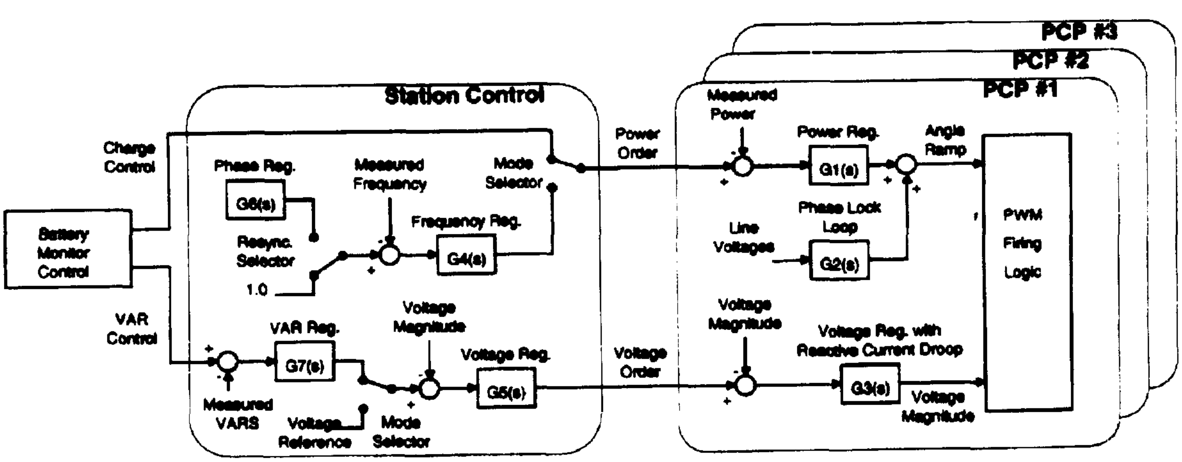

Fig. 7. BESS control system [2].

ning the BESS as a peak-shaving device taking 500 kW per hour off the peak demand of the plant over an 8 h discharge period (4000 Ah). The system was cycled at increased loading (up to 2 MW) for short periods of time (10 min, then 20 min), and then allowed to recharge.

10.2. BESS plant take-over (UPS protection)

The power conditioning system consists of three PCP converter pairs connected in parallel. This hardware performed extremely well under several different power output operations. Following the battery cycling tests, the battery energy storage system was ramped up in blocks of 500 kW to within a few hundred kW of the total plant demand. At that time the plant requirements were running at around 2900 kW. The BESS was supplying 2500 kW and the utility was supplying the other 400 kW. When the power output of the BESS was increased to a point that it reached or exceeded 100% of the plant load requirement (by design, the system will not allow power to back-feed into the utility grid), the main plant substation breaker opened and isolated the BESS from the utility feeder. The system was allowed to operate for 15 min and carried the entire plant load before transitioning back to the utility grid following a synchronism check.

Having demonstrated that the system was fully capable of carrying the entire plant load and worked according to plan, the next critical test was to simulate a power failure and allow the BESS to pickup instantaneously the entire plant load from a standby condition.

The critical loads spread throughout the plant consist of about 25 induction motors plus lighting and controls. Four of the motors, totaling 1600 hp, are connected at the 4160 V bus. The balance of the motors (about 1400 hp) are connected at 480 V a.c. Just prior to running the test, the battery strings were charging at a low rate that corresponded to about 480 kW. While charging, the BESS is also compensating the reactive component of the plant load to maintain unity power factor at the point of utility connection. This is done to maximize the power available for charging the battery. The total reactive compensation while charging, including the filter component, is about 2200 kVAr. The total plant load when the test was conducted was about 3000 kW (excluding the BESS charging kW) and included about 2100 kW of critical loads.

To simulate a power interruption, the plant breaker was manually tripped. The critical plant loads transferred immediately to the BESS following the manual breaker trip. To support these loads, the battery string current increased to about 1300 A and the battery voltage dropped slightly.

Since the BESS regulators maintain the proper voltage magnitude and frequency, the power output naturally follows the needs of the plant loads. From the plant perspective, the breaker trip test was essentially bumpless. All critical loads, including sensitive electronic equipment such as PCs, were unaffected by the transition.

10.3. Motor starting

While the plant was isolated from the utility feeder, a 100 hp motor was started. The test proceeded without difficulty.

10.4. Resynchronizing

Once utility feeder voltage is present, the BESS may be requested to reconnect the isolated plant load with the utility. Resynchronizing requires that the instantaneous voltage across the open plant breaker be reduced to zero. To accomplish this, the isolated plant voltage magnitude, frequency and phase-angle are adjusted to match the utility. The breaker is closed if the voltage is within $\pm 10\%$ and $\pm 6°$ for a 2 s period.

When this test was run, the isolated plant load was about 2300 kW (the plant loading is increased slightly during the test). The battery voltage following 30 min of operation is about 740 V and the string current is about 1550 A. Immediately following the breaker closing the BESS output power is reduced to transfer smoothly the plant load back to the utility feeder.

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