Auxiliary DC Control Power System Design for Substations

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Abstract—**The most critical component of a protection, control, and monitoring system is the auxiliary dc control power system. Failure of the dc control power can render fault detection devices unable to detect faults, breakers unable to trip for faults, local and remote indication to become inoperable, etc. The auxiliary dc control power system consists of the battery, battery charger, distribution system, switching and protective devices, and any monitoring equipment. Proper sizing, design, and maintenance of the components that make up the auxiliary dc control system are required. Many references for stationary battery system design address only a specific battery technology, making it difficult to compare different types of batteries for their overall suitability to substation application. Also, most references do not address the particular requirements of the electrical substation environment and duty cycle. This paper provides an overall review of things to consider in designing the auxiliary dc control power system for an electrical substation.**

I. INTRODUCTION

The most critical component of a protection, control and monitoring (PCM) system is the auxiliary dc control power system. Failure of the dc control power can render fault detection devices unable to detect faults, breakers unable to trip for faults, local and remote indication to become inoperable, etc. In many cases, the dc system is not redundant, which makes reliability an extremely important consideration in the overall design. The auxiliary dc control power system consists of the battery, battery charger, distribution system, switching and protective devices, and any monitoring equipment. Proper design, sizing, and maintenance of the components that make up the dc control power system are required.

PCM systems that do not include an auxiliary dc control power system can be used if properly designed. These schemes typically use devices that do not require a station battery source to function. Examples include fuses, self-contained reclosers, CT/VT-powered relays, capacitor trip devices, integral battery trip devices, etc. These same devices might also be used in backup systems for unmanned facilities without remote monitoring and without redundant battery systems. The design of these types of PCM systems is beyond the scope of this document.

Many references for stationary battery system design address only a specific battery technology, making it difficult to compare different types of batteries for their overall suitability to substation application. Also, most references do not address the particular requirements of the electrical substation environment and duty cycle. This paper provides an overall review of things to consider in designing the auxiliary dc control power system for an electrical substation.

II. BATTERY SYSTEMS

A. Battery Sizing Requirements

Under normal operation, the battery charger supplies dc power to recover the battery voltage after a discharge and to maintain the float voltage while supporting any self-discharge losses in the battery system. The charger also supplies the continuous loads on the auxiliary dc system, while the battery supports intermittent medium-rate and momentary high-rate loads, such as trip coils and dc motors. Upon failure of the battery charger or loss of its ac supply, the battery has to support the continuous loads along with the intermittent and momentary loads that may occur before the battery charger is repaired or the ac supply is restored. Battery sizing calculations are based upon assumptions of a worst-case scenario load profile of continuous, intermittent, and momentary loads during outage of the battery charger and/or loss of ac supply.

The total battery charger outage duration is a critical factor that must be based upon realistic operational criteria. For example, upon failure of a battery charger, if the design criteria for sizing the battery uses an eight-hour load profile, then available spare equipment, operating, monitoring, and inspection practices must ensure that maintenance personnel can respond to and resolve the problem in less than eight hours. When evaluating a battery's ability to meet the design criteria, the minimum and maximum acceptable operating voltage of critical equipment determines the "voltage window" for battery sizing and the end of the discharge cycle.

If corrective action cannot be guaranteed within the design criteria time frame, the protection and control system must be designed such that there is some means of protection for complete loss of auxiliary dc control power. In many cases, remote backup cannot provide detection of all faults covered by the local PCM system (transformer low-side faults in a radial distribution substation for example). Unmanned facilities without remote monitoring capability such as SCADA are especially problematic in this regard.

The various battery types have different discharge performance characteristics that often result in different capacity (ampere-hour) ratings to meet the same load profile. Some batteries may require larger ratings than others in order to meet the momentary high-rate tripping duty portion of the load profile. Another factor that can affect battery sizing is the design margin required to compensate for capacity and performance degradation caused by aging and the prescribed capacity testing intervals. The expected low ambient temperature at which the battery will have to perform requires a capacity derating factor for lead acid designs in sizing calculations. References [1], [2], and [3] include a detailed discussion on battery sizing calculations for three common types of batteries used in electrical substations.

There have been several developments in substation equipment technology that can have an impact on battery size requirements. These changes will result in different battery sizes being required than may have been used in the past. This must be considered when building a new substation or when upgrading the PCM systems in existing substations.

One factor that tends to increase the continuous load portion of the load profile for a given size of substation is the use of microprocessor-based protective relays. Electromechanical relays derived their operating power from the power system quantities that they were measuring. The relays themselves typically did not have any continuous load draw, nor did they store any data to assist in troubleshooting faults. Microprocessor relays, on the other hand, have power supplies that continuously draw power. In addition to the relays, there are often additional devices such as communications processors, HMI computers, etc., that replace physical switches, lights, annunciators, and SCADA RTUs. These typically represent a net increase in continuous loads on the battery system.

The intermittent and momentary loads may be reduced or increased with modern circuit breakers. For example, lighter mechanisms may use smaller trip coils to operate. On the other hand, independent pole operators have become prevalent, which means three times as many trip coils as there were with ganged operators.

The stored energy operating mechanisms of modern circuit breakers have also changed. In the past, the stored energy mechanism typically used pneumatic or hydraulic pressure to store enough energy for multiple operations. These mechanisms were charged from the ac station service supply. Spring-on-spring breaker mechanisms have become increasingly common. These mechanisms have a large closing spring that closes the breaker and charges the tripping spring. Thus they can only store enough energy for a single trip-close-trip sequence. If the motor that charges the closing spring is supplied from the dc system, this can add a significant high-performance load to the worst-case load profile used in the design criteria. One way to mitigate the impact of this type of mechanism on battery sizing is to automatically disable automatic reclosing during a battery charger outage. This logic is easy to implement in an integrated PCM system.

Appendix A shows a battery sizing calculation for an example substation application.

B. Battery Maintenance and Reliability

There are four common types of batteries that are used in substations. This may change with time because there is continual development of new battery technologies. Selection of which type to use should be based upon both reliability and economic criteria. The four common designs presently used are:

- Valve Regulated Lead-Acid (VRLA)
  Expected life: 3–8 years
- Vented Lead-Acid (VLA) (Flooded Cells)
  Expected life: 10–15 years
- Vented Nickel-Cadmium (N-C)
  Expected Life: 20–25 years
- Recombinant Nickel-Cadmium (RN-C)
  Expected Life: 20–25 years

Reliability of each alternative can be assessed by evaluating the risk priority number (RPN) for each alternative [4]. The RPN is obtained by multiplying the severity of a failure times the likelihood of occurrence, times the ease of detection. A lower RPN number would indicate a more reliable battery system. In substation applications, the severity of an open circuit failure is extremely high because this prevents tripping circuit breakers to clear system faults. This can be mitigated by the use of dual battery systems. Failure to supply capacity can also be severe when the time to detect and respond to a failure is long. Likelihood of occurrence is largely dependent upon the characteristics of the battery technology used, the environmental conditions and discharge cycling frequency, and the maintenance practices of the organization operating the facility. Ease of detection is also dependent upon monitoring, maintenance, and testing practices of the organization.

Maintenance requirements involve both periodic maintenance and periodic testing. Maintenance activities include such things as visual inspection, checking and restoring electrolyte (water) levels, measuring individual cell specific gravity (for lead acid designs), temperature and voltage readings, cleaning and retorquing terminal connections, etc. Watering intervals vary by design from 1–2 years for VLA and N-C to 10–20 years for RN-C and are not possible for VRLA. Periodic tests involve verifying the capacity of the battery and the performance (ability of the battery to deliver the full duty cycle) including the high current required for tripping duty. These tests require specialized equipment to load the battery and record individual cell performance parameters and can be quite expensive, but they are necessary to ensure the ability of the battery to perform when called upon.

An understanding of the failure modes of each battery type drives maintenance and testing requirements for each alternative. References [5] and [6] provide recommended maintenance and testing practices for each of the lead-acid battery types and [7] covers the Nickel-Cadmium battery types. The following are several examples of how differences in technology can affect sizing, maintenance, and testing intervals. These comments are generalizations and only meant to spark thought when evaluating alternative battery systems.

- VLA and VRLA batteries typically exhibit a rapid deterioration of capacity at a certain point in the lifespan of the battery, with the knee of the curve at about 80% [1]. Thus after the capacity falls to 90% of its nameplate rating, [5] recommends reducing the interval between capacity tests to one year. N-C batteries exhibit a more linear degradation in capacity [2], so it may not be necessary to reduce the interval between tests.
- Shorter testing intervals are recommended for VRLA batteries [7]. This increased testing is necessary to de-

tect accelerated aging and allow replacement prior to a failure in service. This can offset the apparent cost savings due to the reduced maintenance that can be performed on these types of batteries.

- The high current output capability (short circuit or tripping duty) of VLA and VRLA batteries is dependent upon the state of charge and the age of the battery (amount of sulfation on the plates). The short rate performance of N-C batteries is not affected by either of these factors. Thus, generally speaking, the tripping duty performance of lead batteries will be degraded due to aging before they fail a capacity test. N-C batteries will continue to be able to provide tripping duty up until their useful life is over as determined by a capacity test [2] [8] [9]. N-C batteries are also less likely to fail in tripping duty due to poor intercell strap-to-terminal connections because they have nickel-plated steel battery terminals versus lead-plated copper for lead-acid batteries [4].
- The ambient environment that the battery will operate in is also an important factor in the design selection evaluation. If the battery will be located in an air-conditioned space, the various battery technologies will perform similarly according to their specifications. However, in uncontrolled temperature installations, extremes in ambient temperature will affect the service life and capacity of different battery technologies differently [10]. This will affect both sizing (low temperature) and service life (high temperature) considerations when evaluating alternative battery types.

Economic analysis should be used to determine the best alternative battery type to use, given that reliability requirements are met. Because the service life of the various alternatives is different and it can be assumed that most substations will remain in service permanently, the annualized cost method is a reasonable choice to use in evaluating alternatives. This method converts the initial cost into an amortized annual cost at the interest rates appropriate for the organization. The annual cost of maintenance and testing requirements for each battery type can then be added to obtain an overall annual cost that can be compared. The installation cost of each alternative battery should include the labor and overhead for engineering, purchasing, operations (removal and installation), freight, and disposal. Appendix B shows an economic analysis calculation for the application described in Appendix A.

Due to the importance of the auxiliary dc control power supply, dual systems are often installed in substations to improve reliability. In some cases, regional reliability councils may mandate installation of redundant auxiliary dc systems for critical facilities. To be fully redundant, each battery must be sized to meet the load profile duty cycle of the entire substation [11]. However, most of the advantages of dual battery systems can be achieved if the batteries are sized using the continuous load of the most heavily loaded auxiliary dc distribution bus and the tripping load for the entire substation. In this case, during a double contingency when one battery is out of service and a problem occurs with the remaining battery, operations personnel must understand that they do not have the full design criteria time span to repair the battery that remains in service. So in the rest of the discussion in this paper, a dual system is defined as a system with two isolated auxiliary dc control power systems, and a fully redundant system is a dual system where each battery is sized to carry the entire load profile of the substation.

Dual auxiliary dc systems address the following risks:

- Failure to supply tripping current due to the high internal impedance of a cell.
- Failure to supply tripping current due to poor connections in the circuit.
- Short circuit on battery leads or dc bus trips one of the auxiliary dc power systems off line.
- Surge appears on one dc system, which causes failure of multiple primary and backup protection systems.
- Battery charger failure occurs that takes longer to repair than the battery sizing design criteria.
- Battery charger failure occurs and the capacity of its associated battery has deteriorated, due to aging, to the point that it fails before the time allowed for battery charger repair.
- Battery charger failure occurs when the battery is already discharged without sufficient remaining run time allowed for battery charger repair.

When dual batteries are applied, it is desirable to provide some means of tying the two systems together. Cross-ties can be beneficial because they facilitate maintenance and testing. They also provide switching flexibility to respond to a failure [11]. When provision for paralleling the two dc supply buses together is provided, maintenance and operations personnel should always use caution when paralleling two battery banks. Paralleling battery banks, which are at significantly different states of charge and terminal voltage levels can cause transients on the auxiliary dc control power system.

If regular periodic maintenance and testing are reduced, or not performed at all, and redundant battery systems are not applied, N-C batteries may be a better choice for the following reasons:

- No sudden loss of capacity at a certain point in the lifespan of the battery.
- The ability to handle tripping duty throughout the lifespan of the battery.
- The lower likelihood of high-impedance connections internal and external to the battery.
- The increased tolerance of high and low temperatures.
- Low water consumption over the lifespan of the battery (especially RN-C).

Maintenance and testing requirements should also be considered in designing the battery installation. Reference [11] recommends installation of a dedicated test circuit breaker and terminal box to provide a convenient location to connect a discharge load bank.

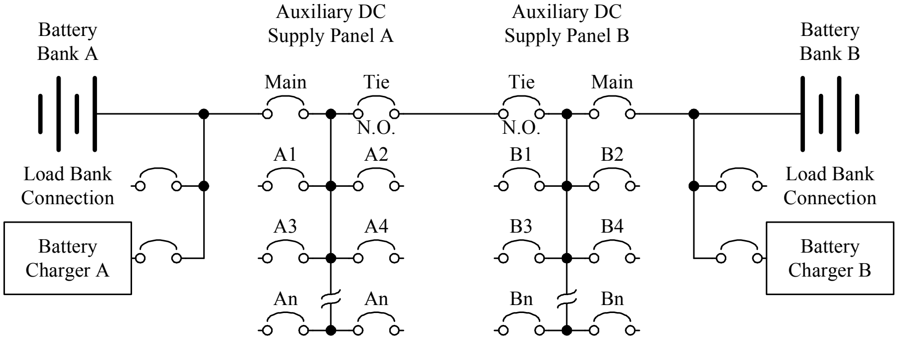


Fig. 1. Example Dual Auxiliary DC Control Power System

If dual batteries are installed, it is recommended to include means to isolate each battery in addition to means for tying the two DC supply buses together. That way one battery can be isolated during a capacity test while the other battery is available to supply the tripping loads during the tests. Fig. 1 shows a typical system layout for a dual battery system. The battery charger is shown connected such that it is not possible to disconnect the battery bank and still feed the auxiliary dc control power system from the battery charger alone. It is not recommended to operate the auxiliary dc supply system on the charger alone with no battery connected during tests or maintenance due to the fact that the charger may happily supply the continuous loads (assuming adequate output filtering and regulation), but current limit when tripping is required. So called "battery eliminator" functions available in battery chargers only include better regulation and filtering to improve the quality of the dc supply when the battery is not in the circuit to absorb transients and ripple.

If a single battery system is used and a portable battery system is available, installation of means to isolate the station battery and means to connect the portable battery may be considered. Alternatively, capacity tests should be conducted with the single battery online to supply the tripping loads during the tests.

C. Battery Chargers and Monitoring

The battery charger must be sized to serve the continuous load and recharge the battery in a reasonable period of time (typically 8 to 24 hours) after a discharge event. Reference [11] provides guidance on performing a charger sizing calculation. The allowable rate of recharge differs between battery types, so the manufacturer of the battery should be consulted to determine the reasonable time period for recharge and the charging efficiency factor prior to performing the battery charger sizing calculations. Specifying a higher rate of recharge will create greater battery heating and greater evolution of hydrogen gas, which may factor into system ventilation requirements and watering interval maintenance.

Sometimes, redundant battery chargers are installed on each independent auxiliary dc control power system. If the two battery chargers are powered by independent station power sources, this can virtually eliminate the occurrence of a failure of the charging system resulting in a long discharge cycle. If the two battery chargers are operated in parallel, they must include voltage-matching functionality. Load sharing control functions can also be specified, but this is generally not required.

If lead acid type batteries are used and the ambient environment of the battery is not controlled to maintain the temperature within a range of 25°C +/–6°C, a battery charger with temperature-compensated float voltage control should be specified. Without compensation during high temperature, hydrogen generation increases, water consumption increases, and overcharging occurs—resulting in increased grid corrosion. During low temperature operation, undercharging can occur if temperature compensation is not used.

Modern battery chargers can include many monitoring features that help oversee the health of the auxiliary dc power system. Features can include high and low output voltage alarms, ac input status, dc current output status, charger circuitry, rectifier diode health, and battery ground detection (in ungrounded battery systems). In addition to the current being supplied by the charger, some guides ([5] [12]) recommend installation of metering to measure the current flowing through the battery. This can provide indication of the state of charge of the battery during a recharge cycle and also an open-circuit battery failure (typical of VRLA). However, this function requires installation of a dc current sensor (precision shunt) in line with the battery string. The function to read the current sensor is not readily available as an option in battery chargers used in substation applications.

VRLA cells are quite sensitive to overcharging due to the accompanying heat generation, which is not well tolerated in this nonflooded design, and thus they require more sophisticated monitoring than the flooded battery designs (VLA or N-C).

Ground detection systems should be applied on ungrounded battery systems. The battery ground detection system typically includes a resistive voltage divider circuit that helps to center the positive and negative terminals of the battery above and below ground. This resistive divider circuit has the secondary benefit of providing a path to bleed off any stray voltages to ground that are capacitively coupled into the auxiliary dc control power system. The ground detection system can be as simple as two light bulbs connected between the positive and negative bus and ground. Each bulb will glow at half brightness. If a battery ground occurs, the bulb connected to the pole with the fault will be reduced in intensity and the other bulb will glow more brightly. Modern microprocessor-based chargers may employ an electronic imbalanced bridge technique that has sensitivity adjustment for sites that require more accurate alarming along with a relay closure or communications for remote annunciation.

Modern relays can also provide monitoring of the auxiliary dc supply system. Many relays include the ability to measure the dc voltage level at their power supply inputs. This can be used for providing high- and low-voltage alarms. They also provide a sample-by-sample view of the voltage levels in the event reports. This can provide an indication of the voltage drop during closing or tripping duty. Fig 2 shows a recording of the auxiliary dc supply voltage profile during an automatic reclose attempt. In this case, the breaker fails to close because the auxiliary dc supply voltage collapses when the close circuit is energized.

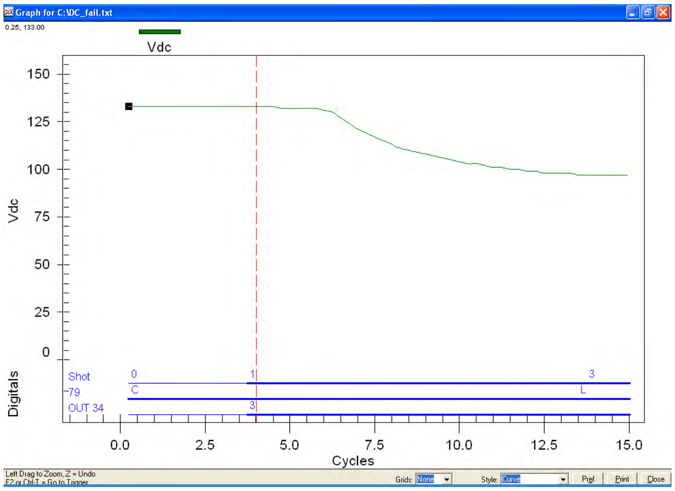


Fig. 2. Record of Fail to Close Caused by DC Voltage Collapse

When using relay functions to monitor the dc bus voltage levels, it is recommended to gather information from multiple relays on multiple dc circuit feeds so that functionality is not lost when a relay is taken out of service.

Some PCM devices include dedicated dc monitoring circuits that can be connected to monitor the dc voltage level at the bus or even at the point of utilization, such as the trip circuit in the yard. This extends monitoring capability so that problems in the branch circuit wiring can also be monitored. The dc monitoring features in these relays also include detection and alarming for dc system grounds [13]. Excessive ac ripple voltage is also monitored, which could indicate a charger problem (such as a failed filtering capacitor) or an open circuit battery failure [14] [15] [16]. Integration systems make it easy to utilize these features to enhance reliability of the system without additional cost.

Dedicated battery monitoring systems are available for critical applications. However, these devices vary greatly in cost and functionality, with more sophisticated models data logging individual cell voltage, temperature, and internal impedance levels and even electrolyte levels. Threshold levels can be set to annunciate alarms via SCADA communications to trigger a maintenance response.

As mentioned previously, many of these monitoring functions can be accomplished using the microprocessor relays and battery charger already in place at little or no added cost. A preferred alternative is to invest in a higher reliability battery technology, which has fewer failure modes and requires less monitoring.

III. PCM SYSTEM DESIGN, DC LOGIC CIRCUITS

The critical protection and control system devices and logic circuitry are typically supplied by the auxiliary dc control power system. This isolates it from the ac power system that these circuits are designed to protect and control so that power system disturbances do not affect the PCM system just when it might be called upon to operate.

A. Protection System Redundancy

Protection systems consist of devices that detect faults on the power system (protective relays) and devices that interrupt fault current (circuit breakers and circuit switchers) [17]. In some cases, both functions are combined. Fuses and self-contained circuit reclosers are examples of this.

The way we design our protection system to deal with failure of either of these two functions can generally be categorized in one of two ways:

- Overlapping relays tripping different interrupters.
- Dual redundant systems.

With overlapping relays tripping different interrupters, we use relays that are capable of “seeing” faults in adjacent or downstream zones of the power system. Thus, if the primary relay or circuit breaker fails, the adjacent or upstream relay will time out and trip to clear the fault. This scheme has typically been used at distribution levels and industrial facilities where the loads are fed radially and the consequences of delayed tripping for a failure are less severe. This architecture treats failure to detect faults and failure to interrupt faults as the same failure.

Dual redundant systems apply two independent relays to eliminate a single point of failure for fault detection. These two systems can be equal, or the backup system can be a lower cost, lower performance system. Then, to cover the failure to interrupt the fault, we apply a circuit breaker with breaker failure backup tripping. Dual redundant schemes have typically been used at transmission levels where the system is networked and the ability of relays to see all faults in adjacent zones is less assured. It is also typically used where the consequence of delayed tripping for a failure is more severe.

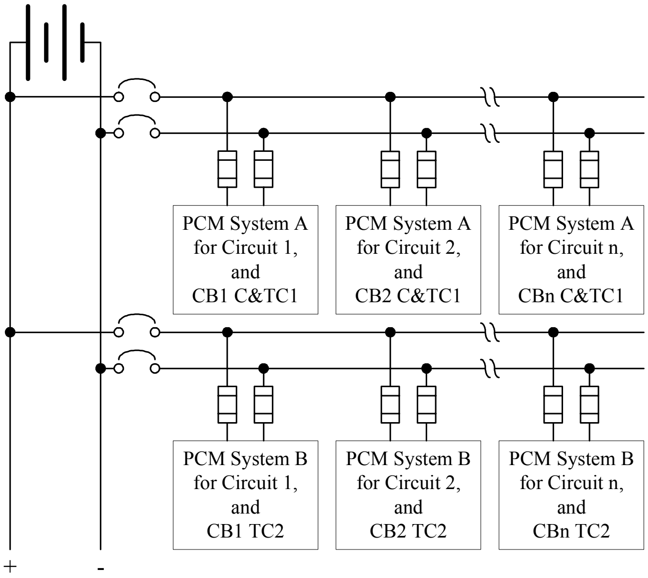
Either type of system may be used in different portions of the same substation. However, with the low cost of modern PCM devices and the elimination of most other equipment by utilizing the ancillary features of these devices, dual redundant PCM systems can be economically applied at all levels of the system. Dual system architecture actually reduces the complexity of many tasks such as coordination and designing for elimination of single points of failure. It also enables the user to design into the system many continuous self-testing features that can reduce the possibility of hidden flaws and eliminate most periodic maintenance and inspection [17].

These concepts are well developed in the industry. The purpose of presenting them here is to place in context the discussion of circuit layout and elimination of single points of failure. In many cases, the details of how we approach the design are dependent upon which architecture is used.

B. Circuit Layout

The arrangement of the dc circuits is important to the overall reliability of the PCM system. Careful analysis of which PCM circuits provide backup or redundancy to other PCM circuits protecting each zone of the power system is required. An effort should be made to ensure that there are no single points of failure where loss of a single branch circuit will cause loss of protection and control for any protective zone. This analysis is easier when dual protection systems are applied. It is more difficult, but no less important, when backup is provided by overlapping relays tripping different devices.

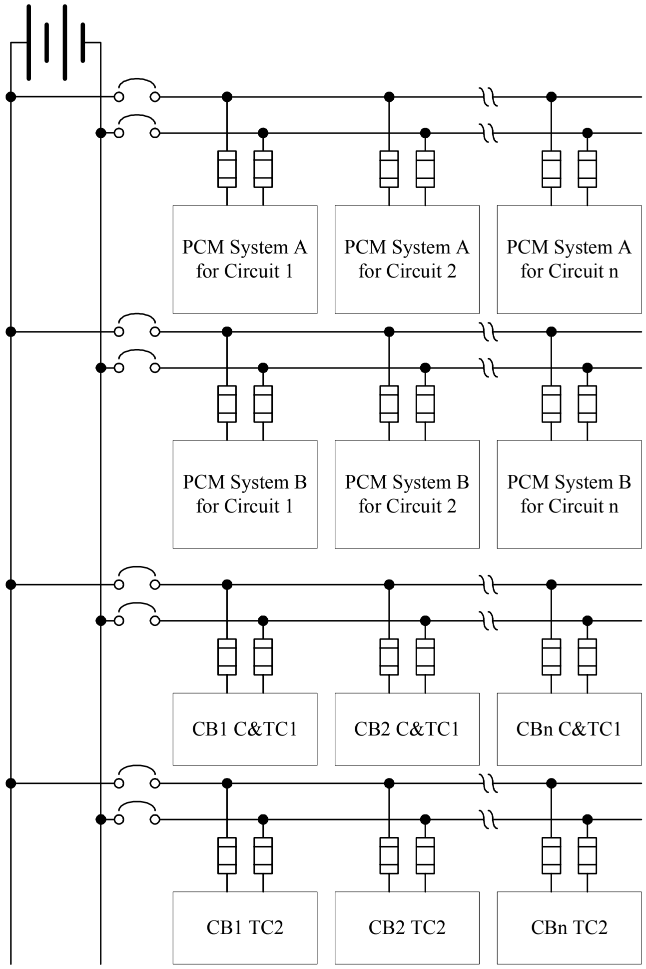
Fig. 3 shows arranging the redundant systems on separate auxiliary dc system feeders. If dual auxiliary dc systems are available, the PCM and breaker systems that are redundant to each other would be connected to the separate supplies instead of merely separate feeders. If the PCM system is not based upon dual PCM devices and instead uses overlapping protective devices tripping separate breakers, we would carefully arrange the overlapping relays and their associated circuit breakers on the separate auxiliary dc system feeders. In the arrangement shown in Fig. 3, the breaker trip circuits are common to the PCM circuits. This arrangement is not applicable for more complex protection schemes where there may be more than one breaker associated with a PCM system protection zone.



PCM = Protection, Control, and Monitoring
Circuit = Protected Power System Zone
CB = Circuit Breaker Associated With Power System Zone
C&TC1 = Close and Trip Circuit 1
TC2 = Trip Circuit 2

Fig. 3. Circuit Arrangement w/ Common Relay and Circuit Breaker Circuits

Fig. 4 shows an arrangement where all of the PCM circuits are isolated from the breaker circuits. This is the recommended arrangement for all applications. It is desirable to limit the exposure of the circuits that supply the microprocessor-based protective relays so that it is less likely that they will loose supply power and not be able to perform their function of monitoring the power system. The circuit breaker circuits must go out into the yard where they have greater exposure to surges, faults, or physical damage that can trip the auxiliary dc supply protection.



PCM = Protection, Control, and Monitoring
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Fig. 4. Circuit Arrangement w/ Isolated Relay and Circuit Breaker Circuits

The contact-sensing inputs on most modern PCM devices are galvanically isolated from each other. This allows you to use the dc supply voltage in the circuit breaker cabinet to wet the inputs instead of the PCM device's supply circuit. Additional isolation and a huge reduction in wiring can be achieved by using remote I/O (RIO) modules and fiber-optic links in the substation design.

Fig. 5 shows an example of using RIO modules to reduce wiring and improve isolation. Only three dc circuit wires are required for each circuit breaker trip circuit between the control building and the substation yard—positive, negative, and trip. The trip wire can be eliminated in simple systems where only the feeder circuit protection trips the circuit breaker. The breaker dc supply circuit powers the RIO module and wets the RIO contact sensing inputs. All status and alarm signals are sent from the RIO to the relay via the fiber-optic link. Close and other control signals to the circuit breaker are sent from the relay to the RIO via the same fiber-optic link. In this example, 8 to 16 wires are replaced by two fiber-optic pairs.

Note that this example uses dual battery systems with the circuit arrangement shown in Fig. 4 where the relay circuits are isolated from the yard equipment circuits. The status and alarm circuits are continuously monitored by the communications monitoring functions and the hardwired circuits are monitored by the trip circuit monitor function. So in addition to reducing wiring and improving isolation, the possibility of any hidden wiring problems is virtually eliminated.

Note also that in Figs. 3 and 4, the closing circuit is common with one of the trip circuits. The supply of the close circuit should be tapped after any protective device in the trip circuit supply to ensure that at least one trip circuit is healthy when the breaker is closed. An example of this is illustrated in Fig. 5 as well.

The most common dc circuit routing arrangements are the radial system or the radial system with switchyard routing. A looped arrangement is also possible but will not be discussed here [18]. Fig. 6 shows an example of a radial system. A common modification to the radial system is shown in Fig. 7. In this arrangement, the trip and close circuits are connected after the breaker's auxiliary power isolation switch. This has the advantage that all sources of voltage in the breaker cabinet can be isolated at that location. It has the disadvantage that the voltage drop in the tripping circuit is increased due to the additional distance that the circuit has to travel.

Reference [18] provides additional details on trip circuit design for electrical substations.

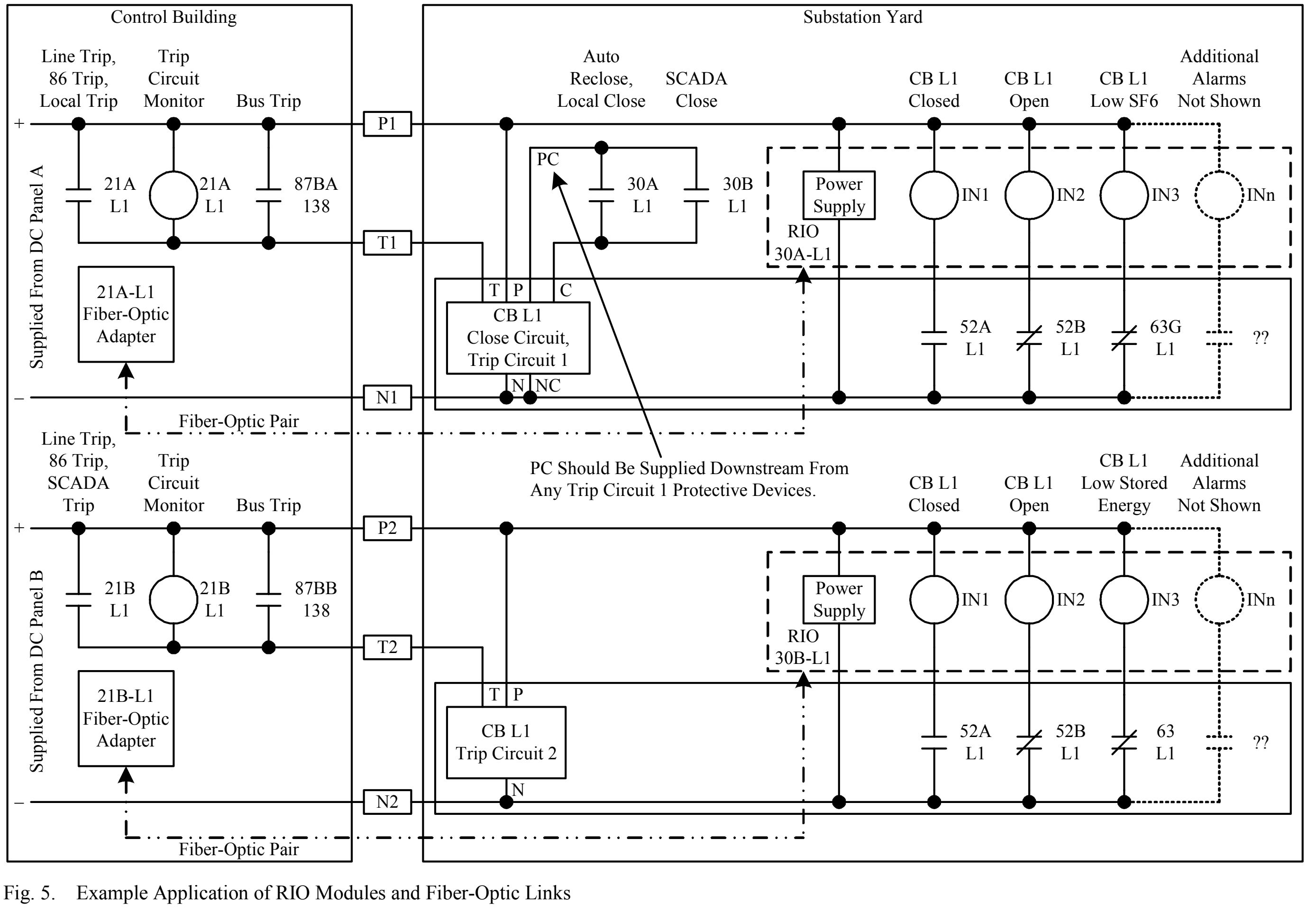

Fig. 5. Example Application of RIO Modules and Fiber-Optic Links

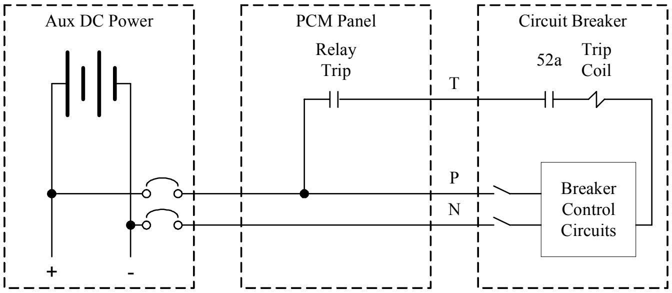

Fig. 6. DC Circuit Routing, Radial System

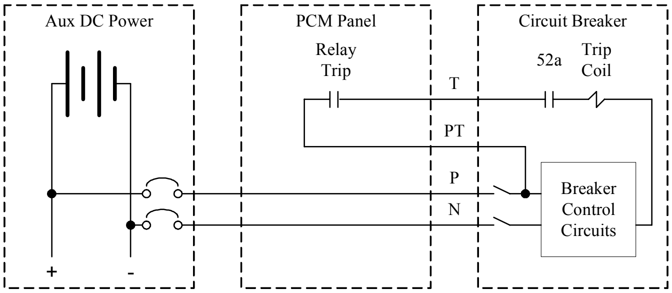

Fig. 7. DC Circuit Routing, Radial System w/ Yard Routing

C. DC System Fault Protection

The auxiliary dc control power system must include protection from faults. Reference [8] provides a fairly comprehensive discussion of dc distribution bus arrangements, such as location of dc switches, circuit breakers, and/or fuses and connections of the battery and charger to the bus.

Overcurrent protective devices will often have a different interrupting rating for dc than they will for ac operation. AC systems have the advantage of zero crossings in the current and voltage waveforms that aid current interruption [8]. It is recommended to only use dc-rated devices in the auxiliary dc control power system. References [8] and [11] contain discussion of short-circuit characteristics of batteries and chargers and rating of protective devices. The available short-circuit current from a battery is dependent upon its construction. There are rules-of-thumb, as well as more precise methods to estimate the short-circuit current that can be used to rate the interrupting capability of overcurrent protective devices [11] [18]. However, the battery manufacturer can be requested to supply this information with their proposal when specifying the battery for purchase. If dual battery banks with a crosstie circuit are used, the batteries should only be paralleled long enough to transfer loads. If they are to be paralleled for longer than that, the increased fault duty should be taken into consideration when sizing the interrupting capacity of circuit protective devices [11].

As with any protective system, the protective devices should be coordinated to provide selective interruption of the faulted circuit. This task can be simplified somewhat by using fuses from the same manufacturer and type in a coordination string [18]. It is important that proper device operating characteristics be used for coordination. For example, instantaneous elements in molded case circuit breakers have a higher trip threshold on dc systems than ac systems because they are essentially peak-detecting devices. Because the published time-current-characteristic (TCC) is typically calibrated for ac RMS currents, the manufacturers of these devices sometimes publish multiplying factors to be used to adjust the curves. These multiplying factors are almost never printed on the TCC curve itself, but rather are found in an application guide or manual. The increased trip threshold impacts coordination and can also cause the device operating current to be greater than the available fault current.

IV. BATTERY ROOM VENTILATION

The area or enclosure where the battery system is located should have an adequate level of air changes to prevent buildup of hydrogen gas to an explosive level. The minimum explosive level is 4% by volume. A design value of 2% should typically be used. The amount of hydrogen evolution during operation varies based upon the battery technology in use and the operating conditions. VLA batteries will evolve very little gas during normal float and equalize operation. Nonrecombinant N-C batteries only evolve hydrogen during the final stage of charging.

Charger malfunction can cause high current to be driven through a fully charged battery, which will cause the worst-case gas evolution rate in both VLA and N-C type batteries. Most chargers have a failure mode of low or no voltage output; however, ferroresonant-type chargers do have a failure mode that can result in high output voltage. When adequate monitoring of the auxiliary dc control power system is in place, high battery voltage associated with a malfunction can be alarmed and addressed before excessive gas accumulation can occur. Microprocessor-controlled SCR chargers often include a high Vdc shutdown feature to eliminate this hazard.

Reference [12] recommends designing VLA battery installations using a maximum of 2% concentration with an evolution rate of 0.127 mL/s per charging ampere per cell at 25°C and standard pressure (760 mm Hg) that will occur during maximum charger output with a fully charged battery [12]. Reference [19] requires that ventilation be provided to prevent hydrogen gas concentration above 1% with the evolution rate based upon maximum charger output into a fully charged battery. If the recommended practice in [12] is followed, or the standard in [19] governs the installation, forced ventilation of the battery area may be required. If forced ventilation is required for the installation, airflow sensors to monitor and alarm for failure of the ventilation fan may also be required.

An example will help illustrate the issue of battery ventilation. An example 60 cell, 360 Ah, VLA battery evolves 0.062 ft^3 of gas per hour when operating at normal float voltage per the manufacturer's specifications. This roughly triples to 0.190 ft^3/hr when operating at equalize voltage. Let's assume that this battery is located in a control building that is 12 ft wide, 24 ft long, and 10 ft high. The total volume of the control building is approximately 2880 ft^3. Therefore, the hydrogen gas concentration will be 0.190/2880 = 0.0066% after one hour on equalize charge. To keep the concentration below 2%, 0.0066/2 = 0.003 air changes per hour will be required. Using the criteria in [12] on our example battery with a 25 A charger that current-limits at 110%, the worst-case hydrogen evolution will be:

$$\frac{0.127\,mL}{s}\cdot\left(27.5\,A-13\,A\right)\cdot 60\,Cells\cdot\frac{3600\,s}{hr}\cdot\frac{0.0353\,ft^3}{1000\,mL}=\frac{14.04\,ft^3}{hr}$$

The hydrogen gas concentration will be 14.04/2880 = 0.5% after one hour on full charger output current. To keep the concentration below 2%, 0.5/2 = 0.25 air changes per hour will be required. In the above calculation, the continuous load (13 amperes) is subtracted from the maximum charger output to obtain the maximum charging current. Natural room ventilation is typically around 2.5 air changes per hour so no forced ventilation would be required. This example is for illustrative purposes. Each battery installation should be evaluated separately.

Forced ventilation over and above that required for safety can cause increased HVAC operating costs. If forced ventilation is installed, it can be automatically controlled during times of abnormal operating conditions, such as a high-voltage charger malfunction.

V. SUMMARY AND CONCLUSIONS

The reliability of the auxiliary dc control power system is extremely critical. Failure of the system can result in failure to detect and clear faults, resulting in catastrophic damage to power system equipment, public property, and the power system itself.

Battery banks for substation applications must be sized to provide reliable auxiliary power for the duration of the maximum outage of the battery charging system or its ac supply. The duration of the load profile must be based upon a realistic assessment of operational criteria, such as available spare equipment, operating, monitoring, and inspection. Battery sizing for substation applications takes into account, not only the continuous load, but also the momentary high current loads required to trip circuit breakers. Extensive use of microprocessor-based PCM devices with power supplies has increased the continuous load portion of the load profile over older substations. This may mean the battery sizes that have been suitable in the past may no longer be adequate for a given substation application.

There are four common types of batteries that are used in substations. Each battery technology has different characteristics. An understanding of the failure modes relative to substation applications is necessary to properly assess reliability, as well as maintenance and testing requirements. The choice of battery should be based upon both economic and reliability criteria. The annualized cost method is a reasonable choice to use in evaluating alternatives.

The auxiliary dc control power system should be monitored to ensure that any problems will be detected and corrected before the dc system fails to operate during a power system event. Smart battery chargers and the dc monitoring features built into modern PCM devices can provide no-cost/low-cost means to monitor the system.

The arrangement of the PCM system auxiliary power circuits is important to the overall reliability of the PCM system. Careful analysis of which PCM circuits provide backup or redundancy to other PCM circuits protecting each zone of the power system is required. An effort should be made to ensure that there are no single points of failure where loss of a single dc branch circuit will cause loss of protection and control for any protective zone.

Fault protection on the auxiliary dc control power system is just as important as on the ac power system. It is recommended to use only dc-rated devices for short-circuit protection. DC current is more difficult to interrupt than ac current due to the fact that there are no zero crossings to aid in extinguishing the arc. The available short-circuit duty of a battery can be obtained from the manufacturer at the time that it is purchased. Alternatively, there are rule-of-thumb calculations that can be used.

The battery installation should be evaluated for adequate ventilation to prevent buildup of hydrogen gas concentration to an explosive level. The rate of hydrogen evolution for most batteries under normal operating conditions is generally well below the level that will require forced ventilation. Monitoring of the dc system can allow corrective action to take place during abnormal operating conditions before an explosive concentration can accumulate. However, there are standards and recommended practices that specify that the ventilation must be based upon worst-case hydrogen gas evolution rates. If these standards govern the installation, then, forced ventilation may be required.

VI. APPENDIX A
EXAMPLE BATTERY SIZING CALCULATION

Fig. A-1 shows a single line diagram of a relatively large transmission and distribution substation that we will use as an example for performing the battery sizing calculations. The following assumptions have been made:

- The substation will have a dual battery system. Both batteries will be sized to meet the continuous load of the most heavily loaded battery and the tripping load for the entire substation. Thus they will be dual but not 100% redundant. An extended outage of the battery charger on one bank while the other bank is out of service is considered a rare double contingency. It is recognized that the time to repair for this double contingency will be less than the design criteria.
- The PCM devices will be carefully allocated such that the System A and System B PCM devices (those that provide redundancy for critical functions or backup detection of faults in a zone of protection) are on opposite battery systems.
- The circuit breakers have pneumatic operating mechanisms that are charged from the ac station power.
- The transmission circuit breakers have dual trip circuits, and the distribution circuit breakers have single trip circuits.
- The transmission portion of the substation uses dual PCM devices, and the distribution portion of the substation uses single PCM devices.
- The dc system is monitored via SCADA and maintenance and operations practices dictate that a charger

malfunction must be corrected within eight hours or the substation must be taken out of service.

- The dc system emergency will start with a trip that opens five transmission breakers and must be capable of tripping for this same worst-case trip at the end of the dc system emergency.

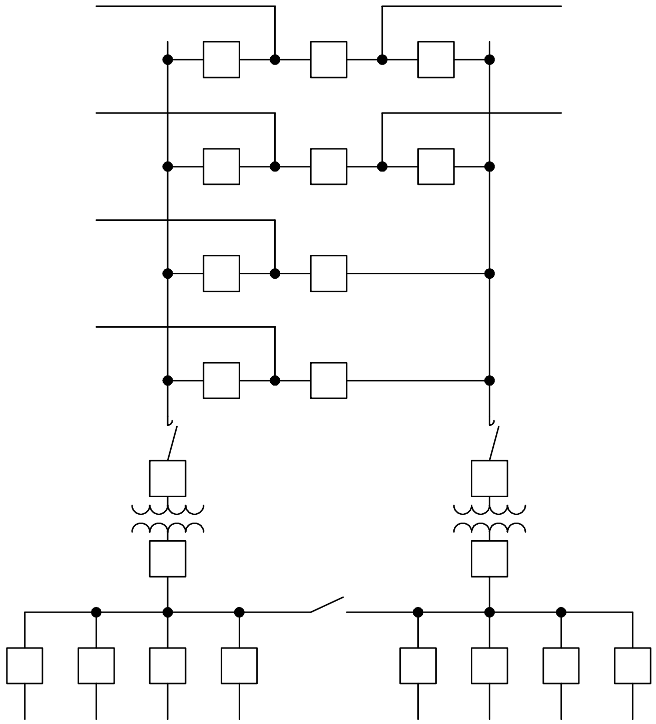

Fig. A-1. Example Large Substation Application

Table A-1 shows a tabulation of the various continuous loads, and Table A-2 shows a tabulation of the momentary loads used to develop the duty cycle shown in Fig. A-2. Table A-3 shows the design parameters for doing the battery sizing calculations. The two battery technologies considered for this application were VLA and N-C.

The IEEE-485 [1] and IEEE-1115 [2] standards prescribe the equations to be used to calculate the required battery capacity for the given load profile using the intrinsic characteristics of the selected cell design and the temperature and voltage window supplied. These calculations can be performed manually; however, several battery manufacturers have developed software programs to automate the sizing process.

The results of the sizing calculations for this example require a VLA (pasted plate) design of 200 Ah capacity and a N-C design of 110 Ah.

TABLE A-1
CONTINUOUS LOAD CALCULATIONS

Device	Load, Amps	System A	System B
Transmission Line Relay	0.22	• 6=1.32 A	• 6=1.32 A
Pilot Transceiver	0.33	• 2=0.66 A	• 0=0.00 A
Tie Line Meter	0.10	• 2=0.20 A	• 0=0.00 A
Transmission Bus Relay	0.22	• 1=0.22 A	• 1=0.22 A
Transformer Relay	0.16	• 2=0.32 A	• 2=0.32 A
Distribution Bus Main Relay	0.16	• 1=0.16 A	• 1=0.16 A
Feeder Relay	0.16	• 4=0.64 A	• 4=0.64 A
Logic Processor/ Communications Processor	0.16	• 3=0.48 A	• 4=0.64 A
HMI Computer	0.26	• 1=0.26 A	• 0=0.00 A
Touch Screen Monitor	0.50	• 1=0.50 A	• 0=0.00 A
Indicating Light	0.01	• 12=0.12 A	• 12=0.12 A
Ethernet Switch	0.50	• 1=0.50 A	• 1=0.50 A
GPS Clock	0.06	• 1=0.06 A	• 0=0.00 A
Total		5.44 A	3.92 A

TABLE A-2
MOMENTARY LOAD CALCULATIONS

Device	Load, Amps	System A	System B
Transmission Circuit Breaker Trip Coil	12	• 5=60 A	• 5=60 A
Total when one battery is out-of-service and battery tie circuit closed	12	• 10=120 A	NA

Note: when the dc bus tie circuit is closed, the battery will be required to support the current in both trip coils of the circuit breaker.

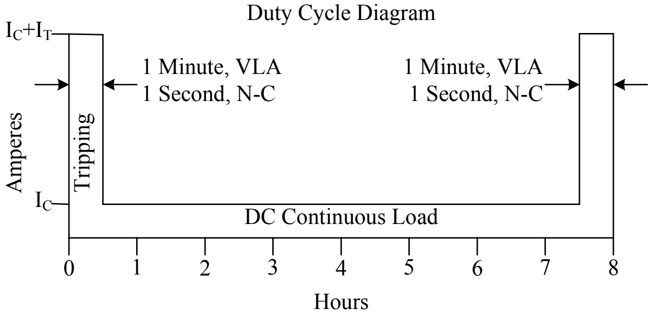

Fig. A-2. Example Battery Duty Cycle for Large Substation

TABLE A-3
BATTERY SIZING CRITERIA

Operational Parameters	**Minimum**	**Nominal**	**Maximum**
Ambient temperature	5°C/41°F	20°C/68°F	30°C/86°F
Voltage	105 Vdc (VLA) 100 Vdc (N-C)	125 Vdc	140 Vdc
Sizing Parameters	**Value**		
Design margin for future growth	110%		
Aging factor	125% (VLA), 100% (N-C)		
Continuous load, IC	5.44 A		
Tripping (momentary) load, IT	70 A (1 min. VLA) (1 s N-C)		

VII. APPENDIX B
EXAMPLE ECONOMIC ANALYSIS CALCULATION

Two alternative battery types are being compared for installation in the example substation described in Appendix A—VLA and N-C. Because the expected service life is different for the two alternatives, and the substation will be in service for many multiples of the service life of the battery, the annual cost method will be used.

The cost analysis will not be a total cost of ownership analysis. It is intended to determine the difference in annual cost of ownership for the two alternatives. Thus only the annual costs that will be different for the two batteries will be included in the analysis. Any annual costs that will be the same regardless of alternative chosen are excluded. To simplify the analysis, the cost of performance tests (capacity and integrity tests) every five years is excluded because it is assumed that when the battery reaches the point that annual performance tests are required, it will be retired and replaced instead.

In the annual cost method, the initial cost of each alternative is converted to its annual cost based upon the expected life span of the alternative and the effective annual interest rate for the organization. The annual cost for each alternative is calculated using the following equation:

$$EUAC = IC\left(A/P, i\%, n\right) + AC$$

Where:

$EUAC$ = Equivalent Uniform Annual Cost
IC = Initial Cost
A/P = Principal to Annual Conversion Factor
$i\%$ = Effective Annual Interest Rate
n = Expected Life in Years
AC = Annual Cost

If the costs of five-year (and eventually annual) performance tests are to be included in the analysis, the equation can be modified to include these costs on an annualized basis.

Table B-1 shows the economic evaluation calculations for the Appendix A application using example costs.

TABLE B-1
EXAMPLE ECONOMIC EVALUATION

Interest rate	8%		
Engineering labor rate/h w/ burden	$75		
Installation labor rate/h w/ burden	$57		
Alternative		**VLA**	**N-C**
Service life @ 20°C	Years	15	25
Initial cost	Hours		
Fully burdened engineering cost to prepare specifications and evaluate alternatives	12	$900.00	$900.00
Fully burdened purchase cost of battery and rack		$13,312.40	$24,707.40
Freight		$665.00	$326.00
Fully burdened installation and commissioning cost	48	$2,736.00	$2,736.00
Disposal cost		$500.00	$500.00
Total initial cost		$17,613.00	$28,669.40
Annualized Initial Cost		**$2,057.72**	**$2,685.75**
Annual maintenance costs			
Per IEEE 450 (VLA) and IEEE 1106 (N-C) recommendations	Hours Each Time	Times Per Year	
Inspection (includes travel to sub)	3.0	12	4
Cost per year		$2,052.00	$684.00
Read per cell voltage	0.5	4	2
Cost per year		$114.00	$57.00
Specific gravity per cell	1.5	1	0
Cost per year		$85.50	
Temperature (10% of cells)	0.1	4	0
Cost per year		$22.80	
Connection resistance	1.0	1	0
Cost per year		$57.50	
Total Annual Maintenance Cost		**$2,331.30**	**$741.00**
Equivalent Uniform Annual Cost		**$4,389.02**	**$3,426.75**

VIII. REFERENCES

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IX. BIOGRAPHIES

Michael J. Thompson received his BS, Magna Cum Laude from Bradley University in 1981 and an MBA from Eastern Illinois University in 1991. He has broad experience in the field of power system operations and protection. Upon graduating, he served nearly 15 years at Central Illinois Public Service (now AMEREN) where he worked in distribution and substation field engineering before taking over responsibility for system protection engineering. Prior to joining Schweitzer Engineering Laboratories, Inc. in 2001, he was involved in the development of a number of numerical protective relays. He is a Senior Member of the IEEE and a main committee member of the IEEE, PES, Power System Relaying Committee. Michael is a registered Professional Engineer in the State of Washington and holds a patent for integrated protection and control system architecture.

David L. Wilson received his BS degree from Washington State University in 1978. He has diverse experience in the fields of energy R&D, aerospace, medical and commercial electronics manufacturing, and electrical power system and component sales. He is co-owner of McLaren, Inc., a manufacturers' representative firm with technical sales responsibilities for (15) manufacturers including Alcad Standby Batteries and Schweitzer Engineering Laboratories, Inc. He has 14 years experience selling and advising on utility battery system applications.

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