IMPROVEMENTS IN DC POWER SYSTEMS AVAILABILITY AND RELIABILITY

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INTRODUCTION

At times the words availability and reliability are used interchangeably, but they represent two distinct, yet equally important characteristics to consider when designing or deploying a DC power system. To insure that DC power is continuously provided for customer loads, it is imperative that both are maximized. Analyzing a DC power system by its major subcomponents provides a useful method for discussing the impact of availability and reliability.

The classic approach to determining DC power system availability and reliability involves manual testing of battery and power system subsystems. While these testing methods provide valuable insight into the state of the subsystems, they are labor intensive and often prove too expensive for use except on the most critical sites. More recently, DC power systems utilize an advanced controller that provides the benefits realized from traditional manual testing methods, but at a lower ongoing operating cost due to the use of automated testing.

This paper will examine commercially available DC power system based automated testing technologies and provide a cost-benefit analysis of deploying these advanced systems. This new approach makes it possible to achieve greater system availability and reliability with a minimal capital investment, thus reducing the life cycle cost of DC power systems.

AVAILABILITY VERSUS RELIABILITY

Reliability is generally defined as "the possibility that a device will perform its intended function when required to do so if operated within its specified design limits."[1] As such, reliability is a statement of the probability that the system in question will perform to its required standards when called upon. Often this parameter is stated in terms of MTBF (mean time between failure). The greater the MTBF, the longer the time between failures, and the greater the probability that the system will perform its design function. A subtle corollary to MTBF is the reality that the system in question will fail at some point. Stated empirically, the Reliability function, R(t), trends to zero over time.

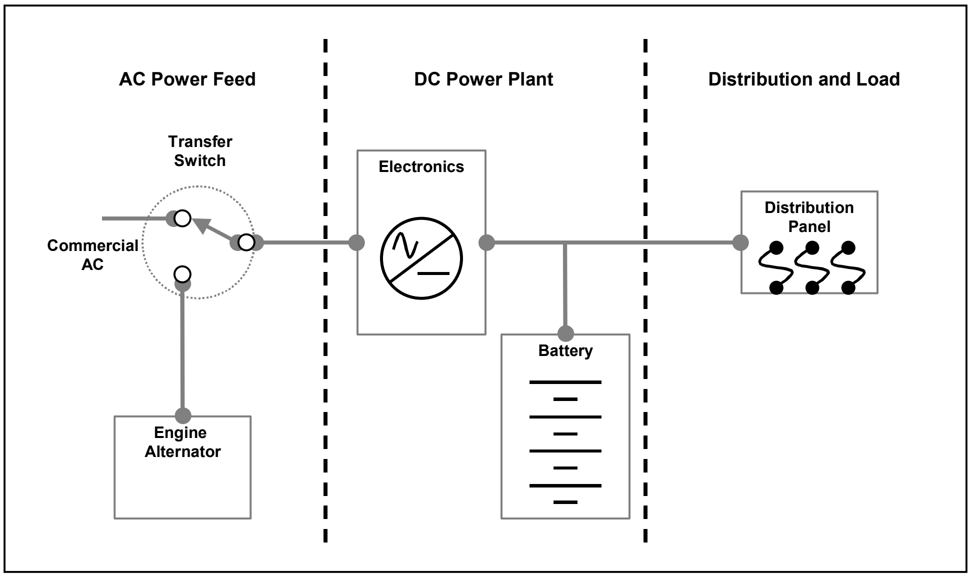
Availability can be thought of as "the probability that a device is successful at time t."[2] The measurement of availability is not concerned with the history or the future of the system in questions, although the conditions a system have been subjected to can certainly affect its present availability. Availability answers the questions, "What is the probability that my power system will perform as required at 2:00 in the morning?" Unlike R(t), the Availability function A(t) does not trend to zero, but rather a number greater than zero. The ultimate value of A(t) is a function of several factors including:

- Original equipment selection
- Operating conditions
- Maintenance practices
- Time to repair

AVAILABILITY AND RELIABILITY IN DC POWER SYSTEMS

A great deal of work has been done analyzing the factors that contribute to what is usually referred to as the reliability of the DC power system. Figure 1 shows a typical power system utilized in telecom applications. The power system can be segmented based on function into three areas for analysis: the AC Power Feed section, the DC Plant section, and the Distribution and Load section.

Figure 1 – Typical Telecom Power System



Reviewing published data on failures allows us to highlight the areas of the systems that are more susceptible. Table 1 summarizes the data published in *Network Reliability: A Report to the Nation*, which investigated the causes of network failures. As can be seen from the data, the failures are split evenly with one-third occurring in the AC Power Feed section, one-third occurring in the DC Plant section and one-third occurring in the Distribution and Load section.

Table 1 – Failure by Area and Equipment Type[3]

AC Power Feed		DC Plant		Distribution and Load	
Commercial power	70	Battery	63	DC Breakers	63
Engine / Alternator	23	Rectifier	32	DC Fuses	60
AC Fuse / Breaker	20	DC / DC Converter	21		
AC Transfer Switch	10	Alarms	9		
Sub total	123		125		123
Total					**371**
Percentage by Area	**33.2%**		**33.6%**		**33.2%**

To gain a better understanding of these failures and how they are interrelated, it is helpful to construct a Fault Tree Analysis (FTA) diagram. In a FTA diagram the various failure conditions are flowcharted. When multiple conditions exist that can create a failure they are connected via a logic gate. Logic gates can be one of two types, AND or OR. An AND gate requires that all of the conditions coming into the gate to be true for the output of the gate to be true. An OR gate requires that only one of the conditions coming into the gate be true for the output of the gate to be true. The FTA allows the power engineer to see the interaction of various failure modes and develop more robust strategies to protect against them.

Figure 2 – Fault Tree Analysis of a DC Power System

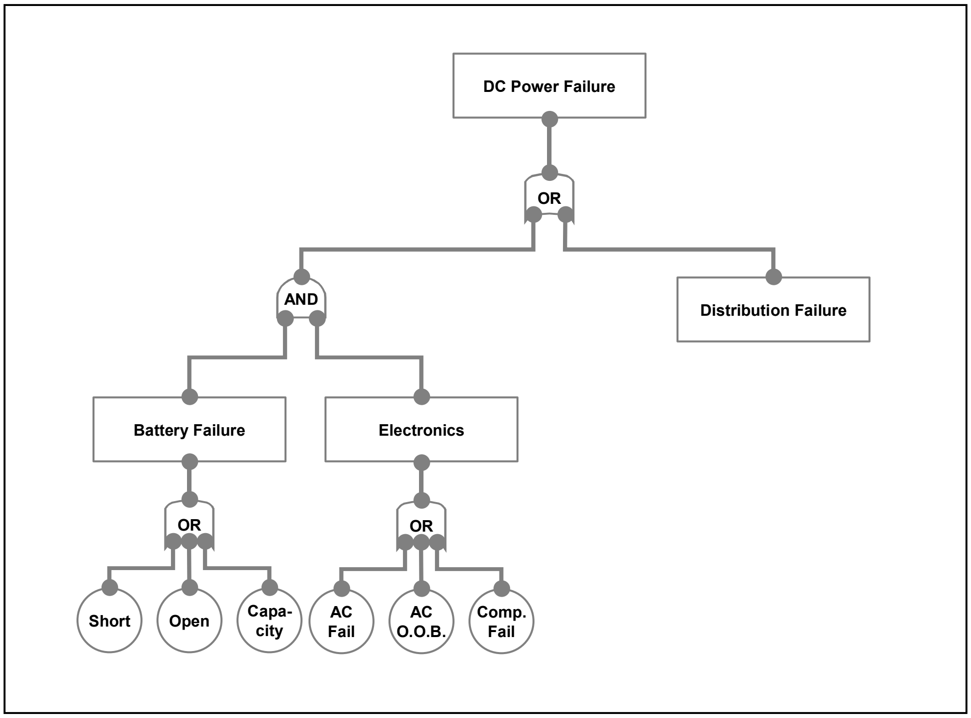


Figure 2 reveals that the loss of both the Battery **AND** Electronics **OR** a Distribution failure will result in a DC Power Failure. Failures listed in Table 2 under Distribution and Load include both malfunctions of breakers and fuses and disconnection of power to the load when the breakers and fuses act as designed to protect personnel and property. Strategies exist to increase the availability of the distribution, such as A and B feeds, but the balance of this paper will focus on the DC Power Plant.

To aid in the analysis of the DC Plant below is a state chart that shows the condition of both the battery and electronics at any instance of time. Since there are two subsystems, each capable of being in one of two conditions, there are four states that the DC Plant can be in. A “1” in the state table indicates that the subsystem is available and a “0” indicates that it is unavailable. At this point, it is useful to return to the definition of available, to be considered available the subsystem must be able to successfully fulfill its design requirements at the time it is called upon to do so. Since the battery and electronics are connected through an OR gate in the FTA diagram, both must be unavailable for DC Power to be unavailable.

Table 2 – DC Power State Chart

State	**I**	**II**	**III**	**IV**
Battery	1	1	0	0
Electronics	1	0	1	0
DC Power	**1**	**1**	**1**	**0**

Table 2 indicates that DC Power is unavailable only in State IV, but State II and State III are also of concern. In State II when the electronics are unavailable the battery is called upon to provide the power to maintain the system and excessive cycling of the battery can adversely affect its life. In State III the battery is unavailable to provide the required backup if there is a failure in the electronics side. Often the state of the battery is not known until it is called upon to provide backup power.

ANALYSIS OF DC POWER PLANT

Evaluating each state that the DC Power Plant can experience provides the means to develop new strategies that increase the overall effectiveness of the backup power strategy.

State I

In State I both the battery and electronics are available to provide power. This can be thought of as the optimum state for the DC Power System because it is the state in which the power system acts as designed and provide continuous power to the equipment.

State II

In State II the battery is available, but the electronics are not. From the FTA diagram we see that three causes have been identified, any of which result in the electronics becoming unavailable and some may contribute to a reduction in reliability as well. These conditions are:

- Loss of AC Power
- AC Power Out-of-Bounds
- Component Failure

The first condition that causes the electronics to be unavailable is a loss of AC power. This is a straightforward cause and effect relationship. The second condition is the condition when AC power is present but it is out-of-bounds for the electronics. An example of this is a sag in the input voltage that drops it below the minimum voltage required by the rectifier. An approach to mitigate this is to design rectifiers that operate over a wider input range. Certain rectifiers will even decrease their output when the voltage drops significantly. The benefit of systems with extended operating ranges is that they typically can provide power even if at a reduced amount, delaying when the battery goes on discharge or slowing the rate of discharge. This allows the system to ride through conditions such as brownouts.

The third condition that can cause the electronics to become unavailable is the failure of a component within the electronics. These types of failures are typically the ones identified in MTBF analysis. Failure of components can occur due to age and overstressing. Failures due to overstressing can result from poorly regulated input power or from extreme temperatures. The design of the rectifier can reduce the susceptibility to these occurrences. To address AC power quality robust input filtering is designed into products that protect the rectifier from extreme variations in AC power. An approach to minimize damage that results from extreme temperatures is to monitor the internal temperature of the rectifier and to gradually reduce its power output if the internal temperature exceeds safe design standards rather than shutting down the rectifier. This serves to regulate the internal rectifier temperature while continuing to provide power.

State III

In State III the electronics are available but the battery is unavailable. There are three conditions in State III on the FTA diagram that will result in the battery being unavailable. These conditions are:

- Short Circuit
- Open Circuit
- Loss of Capacity

The first condition, short circuit, occurs when there is an internal short within a battery cell. When this occurs the voltage of the cell goes to zero and it does not contribute power to the string resulting in the remaining cells having to carry the load. A short circuit is detected by monitoring individual cell voltages.

The second condition is that of an open circuit. This occurs when the continuity of one or more cells is lost. When there is an open circuit the battery is unable to conduct current to maintain the load.

The third condition, loss of capacity, can be the most difficult to determine. When a battery loses capacity it is not able to supply the power required for the desired amount of time. Multiple methods have been developed to determine battery capacity. The principle methods are float current, internal ohmic measurement, and load test.

New technologies now make it possible to incorporate battery testing into the electronics. The integrated load test utilizes the system load to test the battery capacity. When a load test is initiated the controller reduces the output of the rectifiers so that the battery picks up a predetermined amount of the load. This approach provides the benefits of traditional load tests without many of the drawbacks. Table 3 summarizes the types of load tests along with their advantages and disadvantages.

Table 3 – Battery Testing Technologies

Technology	Procedure	Advantages	Disadvantages
Float Current	Float current is monitored	• Inexpensive, simple test • Continuous monitoring	• System level measurement • Ability to identify a bad cell decreases as cell count increases
Internal Ohmic	New cells are measured to establish a baseline, periodic readings are taken and compared to baselines	• Non-invasive • Simple, on-line test	• Infers individual cells' health • "Does not precisely predict overall battery capacity"[4]
Traditional Load Test	Battery string is removed and discharged using a load bank	• Provides accurate measurement of battery capacity	• Labor intensive and expensive • Battery is not available during test • Backup capacity temporarily diminished by test • Temporary battery needed
Integrated Load Test	Battery string is discharged using the system load	• Inexpensive • On-demand testing • Provides accurate measurement of battery capacity	• Backup capacity temporarily diminished by test

State IV

In State IV both the battery and the electronics are unavailable. When this occurs the DC Power System fails and the load is no longer supported.

SYSTEM LEVEL APPROACH TO AVAILABILITY AND RELIABILITY

The advances in component technology and processing power now makes it possible to design electronics and batteries that work as a coordinated DC Power Plant and address many of the potential failure modes that exist. Advanced DC Power Systems now include the capability to protect themselves from widely varying input voltages, temperature extremes, monitor the status of surrounding equipment, and determine the state of the battery. To illustrate the new capabilities of DC Power Plants a system was configured and tested, first in a manner consistent with today's practices and then utilizing the advanced feature set now available.

Test System

The system under test represents a typical telecom power system and includes a –48V DC power plant, a string of VRLA batteries and a load bank to simulate a site load. Table 4 provides the details of the equipment tested.

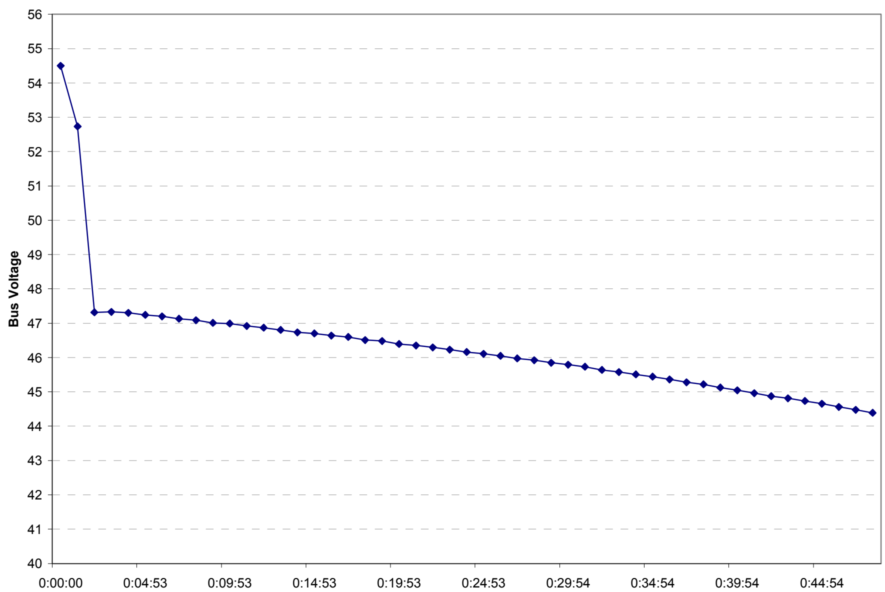
Table 4 – Test System Components

Test Equipment	Manufacturer / Model	Comments
Battery	C&D Technologies' HD 700 VRLA Battery	• Manufacture date 12/97 • A "dry out" failure was simulated by compromising the jar to cover seal in one cell
DC Plant	C&D Technologies' Sageon Power System	• 700 amp system configured with 250 amps of rectifiers • Advanced controller • Battery Monitor
Load Bank	Avtron K-571	

Traditional Discharge Test

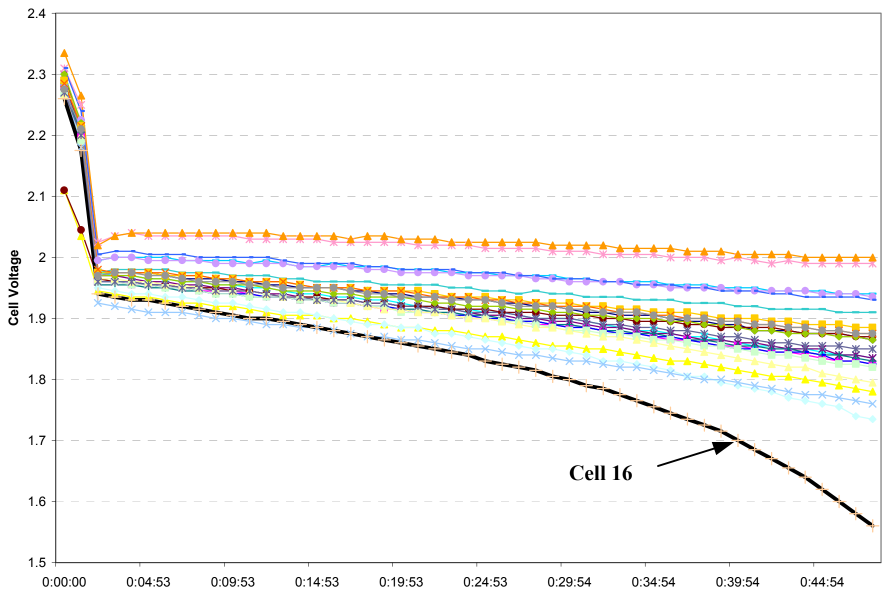
The test system was subjected to a traditional discharge test where 20 percent of the batteries rated capacity was removed. Figure 3 shows the bus voltage. The result of this test is a typical discharge curve which indicates that the string does not have the original rated capacity, but does not identify any underlying problems with individual cells. While most discharge tests would include individual cell readings, many sites are not routinely inspected. Operators rely on reading the bus voltage to determine if the battery is functioning acceptably.

Figure 3 – Traditional Discharge Test Bus Voltage



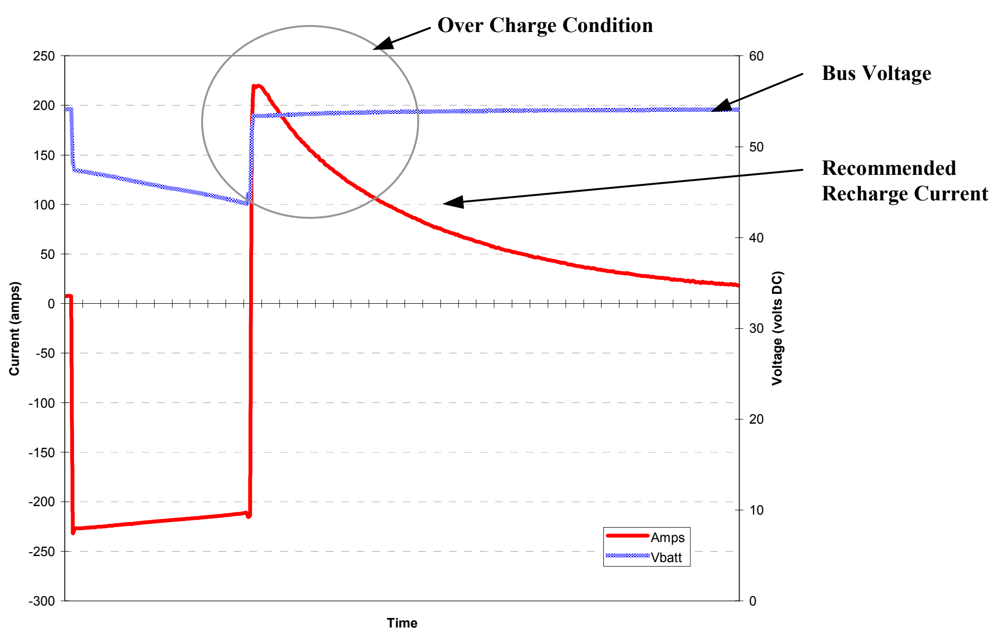
Looking more closely at the individual cells reviews some underlying information. The power system was equipped with a battery monitor so individual cell readings could be recorded. Reviewing the individual cell data reveals that cell 16 has significantly reduced capacity.

Figure 4 – Traditional Discharge Test Individual Cell Readings



After AC power is restored, the electronics begin to recharge the battery. With a traditional control scenario the only limit to the power available to the battery is the maximum capacity of the electronics. For the battery under test, the recommended recharge current, based on an eight-hour recharge time, would be 106 amps. As can be seen in Figure 5, the battery draws over 220 amps initially and remains in the over current state for almost 40 minutes. Over charging on a recharge can cause localized over-heating of battery components, thermal stresses on connectors, and have a negative impact on battery life.

Figure 5 – Unlimited Battery Recharge Current

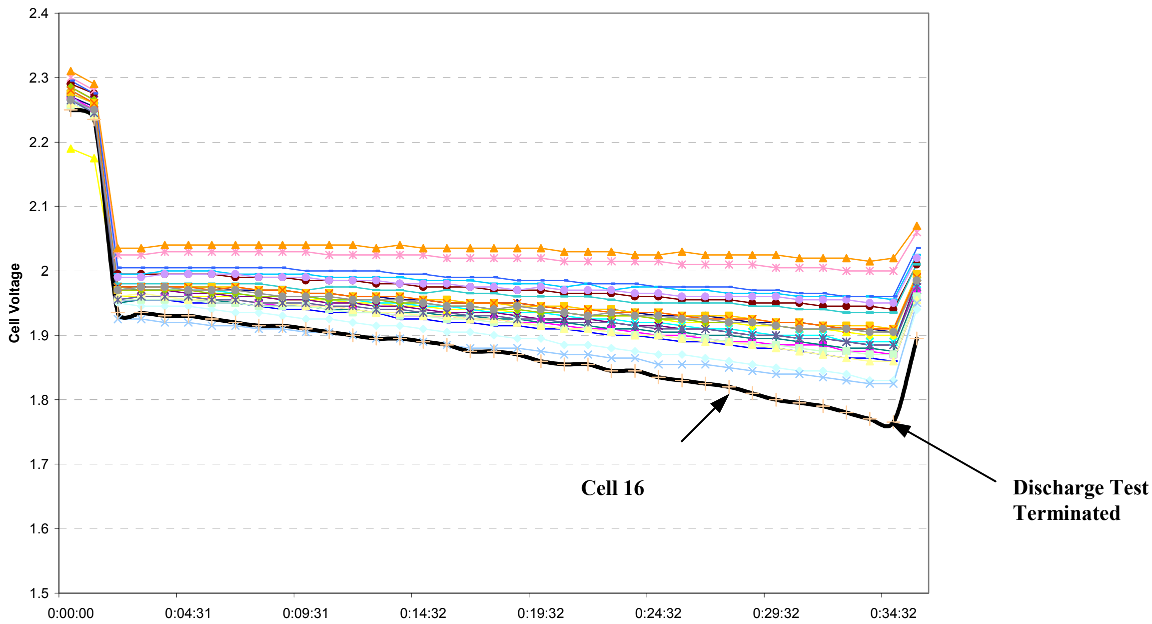


The test was then rerun utilizing the functions of the advanced controller. The controller was configured to perform a discharge test and to remove 20 percent of the battery capacity. The controller is capable of terminating the test when the desired capacity has been removed, or if other conditions exist including:

- Individual cell voltage below low configurable low limit
- Individual cell voltage outside of configurable deviation limit
- Bus voltage below configurable low limit
- Any system alarm (i.e. loss of AC)

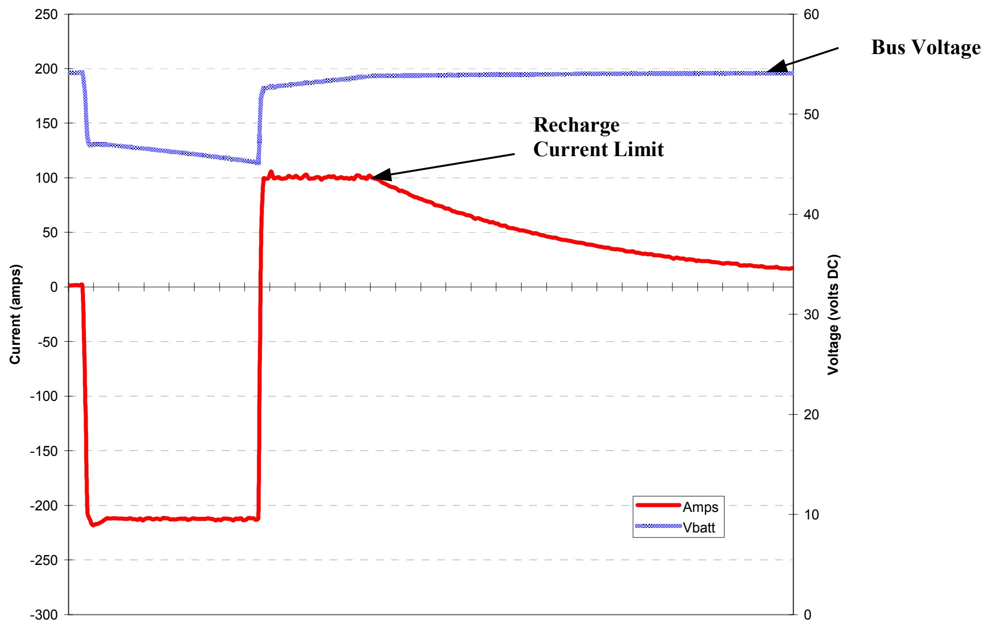
Figure 6 shows the result of an integrated discharge test where the individual cell low voltage limit was set at 1.75 volts. In this test cell 16 reaches the 1.75 volt limit and the controller terminates the tests and returns the rectifiers to normal output.

Figure 6 – Integrated Discharge Test



When the test terminated the battery string went to the recharge condition. The controller was configured to limit the recharge current to 100 amps. As shown in Figure 7 the current was limited by the controller, avoiding damage to the string caused by over current conditions and significantly reducing the risk of thermal runaway.

Figure 7 – Current Limited Battery Recharge



COST – BENEFIT ANALYSIS

By incorporating advanced capabilities into the DC Power Plant, users can realize a significant reduction in the total cost of ownership. The primary driver of this is the ability of customers to extend the life of batteries and electronics while maintaining a high availability. Many customers set a useful life limit on batteries based on manufacturer specifications, warranty, and experience. Once this useful life is reached, customers automatically change out the batteries. The ability to perform cost effective testing on all batteries in the network provides the tool to proactively service cells as needed, while leaving the remainder of cells in place.

Table 5 summarizes the costs a system with a seven year useful life and no battery testing, a system with a ten year life with traditional load testing, and a system with a ten year life an integral load testing. The key variables in this analysis relate to load testing. Without load testing, many customers consider the reliable system life of a VRLA battery to be 7 years. If load testing is being performed, then whether it is manual or automatic impacts the Maintenance and Operation costs. The analysis shows that the system with integrated load testing can reduce the annualized cost of ownership by over 30 percent.

Table 5 – Annualized Cost for Various System Strategies

	7 Year Life No Testing	**10 Year Life Traditional Testing[(b)]**	**10 Year Useful Life Integrated Testing[(c)]**
Installation and Setup[(a)]	$2,080	$2,080	$2,080
Maintenance and Operations[(d)]	$455	$15,650	$1,950
Removal and Disposal	$1,300	$1,300	$1,300
Battery	$12,000	$12,000	$12,000
Power Plant	$12,600	$12,600	$12,600
Total Cost	**$28,435**	**$43,630**	**$29,930**
Useful Life	7 years	10 years	10 years
Annual Cost	**$4,062**	**$4,363**	**$2,993**

(a) All labor cost calculated at $65 per hour
(b) 10 year life based on 10 load tests at $1500 per test, typical market rate
(c) 10 year life based on 10 load tests at $130 per test, 2 hours per test at $65 per hour
(d) Cost based on 1 hour per normal maintenance plus the cost of load testing

SUMMARY

In Table 6 major failure modes from State II and III are summarized along with preventative actions and system level responses. Advances in DC Plant capabilities make it possible to cost effectively monitor and test DC power subsystems. By employing a system level design approach, power engineers and network architects can achieve levels of reliability and availability, once only justifiable at the most critical sites, throughout the network.

Table 6 – Failure Modes and System Responses

	Prevention	**System Response**
State II		
AC Fail	AC subsystem design and maintenance	AC input and generator monitoring
AC Out-of Bounds	Design and maintenance	Increase operating range
Component Failure		
• Component Quality	Product design and manufacturing	Internal diagnostics
• Environmental	Facility design and maintenance	Adaptive power output
State III		
Short	Product quality and maintenance	Voltage monitoring
Open	Product quality and maintenance	Integrated load testing
Capacity		
• Age	None	Integrated load testing
• Usage	Increased availability of electronics	Integrated load testing
• Recharge Current	DC Plant design	Recharge current limit

Key Points

- A systematic analysis of the DC Power System can help reveal less obvious failure modes. An increased understanding allows the power engineer to design a system that will improve availability in an economical manner.

- Advances in electronics now provide increased capabilities that improve the availability of the DC Power Plant. These new capabilities should be included in the overall design of new installations in order to take full advantage of their potential.

- Integrated battery testing is now available. This capability dramatically lowers the cost of determining the state of any battery deployed in the network. The ability to accurately know the state of the battery now makes it practical to increase the useful life of batteries and realize significant cost savings.

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