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# Test profiles for stationary energy-storage applications

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**Abstract**

Evaluation of battery and other energy-storage technologies for stationary uses is progressing rapidly toward application-specific testing. This testing uses computer-based data acquisition and control equipment, active electronic loads and power supplies, and customized software, to enable sophisticated test regimes which simulate actual use conditions. These simulated-use tests provide more accurate performance and life evaluations than simple constant resistance or current testing regimes. Several organizations are cooperating to develop simulated-use tests for utility-scale storage systems, especially battery energy-storage systems (BESSs). Some of the tests use stepped constant-power charge and discharge regimes to simulate conditions created by electric utility applications such as frequency regulation (FR) and spinning reserve (SR). Other test profiles under development simulate conditions for the energy-storage component of remote-area power supplies (RAPSs) which include renewable and/or fossil-fuelled generators. Various RAPS applications have unique sets of service conditions that require specialized test profiles. Almost all RAPS tests and many tests that represent other stationary applications need, however, to simulate significant time periods that storage devices operate at low-to-medium states-of-charge without full recharge. Consideration of these and similar issues in simulated-use test regimes is necessary to predict effectively the responses of the various types of batteries in specific stationary applications. This paper describes existing and evolving stationary applications for energy-storage technologies and test regimes which are designed to simulate them. The paper also discusses efforts to develop international testing standards. 

*Keywords:* Batteries; Electric utilities; Energy storage; Renewables; Power quality; Testing

## 1. Introduction

The development and use of energy-storage components and systems for stationary applications has reached a stage of maturity which demands accurate and comparable performance and life evaluation methods. Testing of hardware according to stationary application requirements is essential for the successful optimization and widespread use of storage technologies [1]. A critical step in the evaluation of the performance and/or life of the storage component or the system as a whole is the specification of hardware test profiles which are representative of the application use. It is generally recognized that simple constant resistance or current testing does not adequately represent the complex use conditions which are present in most stationary or mobile applications. The dramatic difference in storage system performance in simple laboratory tests compared with actual field use has led to the creation of standard tests based on field conditions for electric vehicles [2], generating stations, telecommunications, and other standby [3] applications. On the other hand, standard tests for evolving stationary applications of storage technologies for general utility, renewable, and other uses have yet to be established.

One reason for the lack of standard tests for stationary systems is the continuing evolution of these applications. Utility uses for energy storage have expanded dramatically to include power quality, peak shaving, frequency regulation (FR), spinning reserve (SR), and transmission and distribution upgrade deferral. Renewable applications, which are a specialized subset of stationary applications, may be categorized as either remote-area power supplies (RAPSs) or grid-connected systems. Test requirements for each of these uses are unique and involve a variety of loads and recharge conditions. The usage patterns are very

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different from simple constant resistance or current testing. Duty cycles may involve high-pulse discharge, variable power charge and discharge profiles, and prolonged periods at partial states-of-charge.

A second reason for the lack of standard tests is that the specific conditions in which batteries serve depend on the geography and social characteristics of the application sites. SR requirements in San Juan, Puerto Rico are different than SR requirements in Anchorage, AK. Remote grid support in Metlakatla, AK, which has hydroelectric and diesel generation, is different from hybrid support for a PV-diesel system on the equator. The differences are the result of both climate and the way people use technology.

A further complication and a third reason for the lack of standard tests is that there are several possible objectives for hardware testing. Development testing in the laboratory typically involves characterization of hardware capabilities and parametric tests to determine limits of performance and life. Alternatively, with demonstration testing in the laboratory or field, hardware is subjected to real or simulated use conditions to prove the feasibility of the technology in that environment. A third possible test objective, in which hardware is tested for certification purposes for specific applications, is to help end users select systems for unattended field use. Each of these test objectives may require different test conditions and equipment, and a variety of standards may be necessary to help implement these tests.

The variety of technologies which may be used for these applications and their disparity in state of development is a fourth reason for widely different testing methods. While conventional batteries are used today in many of these applications, improved and advanced batteries are beginning to enter demonstrations and precommercial systems. In addition, flywheels, superconducting magnetic energy-storage (SMES), and ultracapacitors are being actively developed for many of these applications, and these technologies must be considered as testing methods are developed. With each of these storage technologies, appropriate power-conversion systems (PCSs) and control systems must also be viewed as part of the system because their integration is a crucial factor in the performance of the system. In fact, test profiles may increasingly be used to evaluate the entire energy system, rather than just the storage device.

This paper describes application-specific test profiles which are being developed, used, and proposed for use as a first step toward standardized testing methodologies for stationary energy-storage applications. Prior to implementing any test regime, rated or initial capacity must be verified for prototype or commercial hardware submitted for testing. Then, application-specific testing, consistent with the intended system use, is applied to determine the suitability of the hardware for actual field implementation. The applications for which tests are described are FR and SR, power quality, RAPS, and peak-shaving. Possible data sets and reporting formats will be described in a subsequent paper.

## 2. Rated capacity verification

Prior to initiating an application-specific testing profile, an energy-storage system must be operated under manufacturer- or developer-specified conditions to verify its rated capacity [3]. The minimum hardware arrangement to be tested is the storage device, the PCS, and the system controller. If appropriate, system generation, a.c. and/or d.c. switch gear, and protection equipment should also be included to verify fully proper system performance. The capacity verification process begins with the storage system in a fully charged state, according to the manufacturer's recommended process.

A continuous discharge should be conducted, again according to the manufacturer's recommendations for rate (current or power), duration, termination criteria, and environmental conditions. The measured discharge energy (W h) should be $\pm 10\%$ of the rated value. Once the discharge is completed, the system must be recharged and returned to a full state-of-charge (SoC). This test should be performed three times for statistical reasons. Also, repetitive tests provide data on system stability and variability that are particularly important for developing technologies.

If the measured capacity is greater than 110% of the rated value, then the measured capacity can be used for scaling the application-specific tests, i.e., the device is effectively rerated. Or, the excess capacity can be ignored and the rated value used for later test scaling, with the understanding that the storage system is not being as deeply discharged as would be indicated from the rating. This decision should be clearly stated in any test report of the results.

On the other hand, if the measured capacity is less than 90% of the rated value, then the manufacturer should be consulted and the reason(s) for the discrepancy identified. If a simple adjustment or maintenance procedure can be made and the test repeated such that the system will deliver $\pm 10\%$ of the rated capacity, the system should be considered acceptable for further testing. If these actions do not result in the specification being met, then the system should be returned to the manufacturer for modification. Only those systems which meet or exceed their ratings should be used in application-specific testing.

## 3. Test profile for FR and SR

An application-specific test profile based on the requirements of the Puerto Rico Electric Power Authority (PREPA) 20-MW, 14-MWh BESS was developed in 1993 for scaled, thermal testing of the flooded lead–acid battery used by the system [4]. The PREPA system has been in

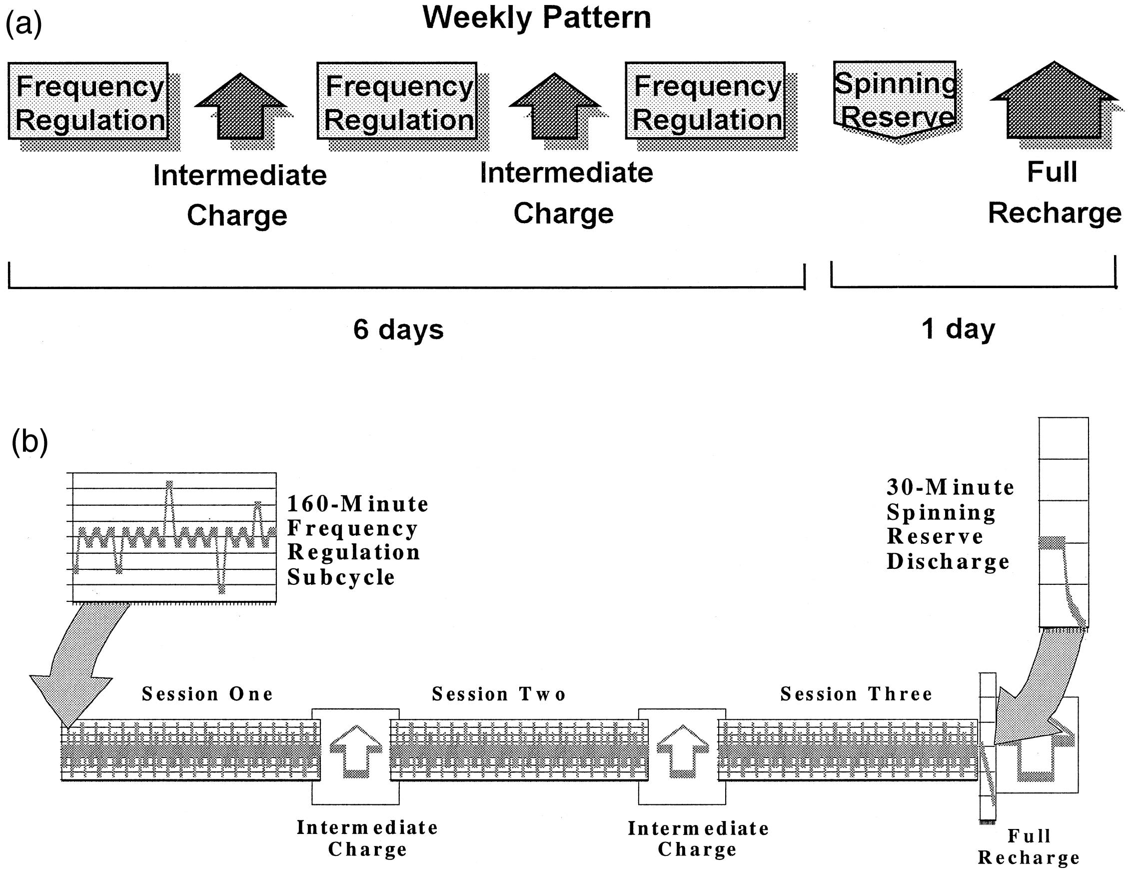


Fig. 1. (a) FR and SR assumed usage pattern. (b) FR and SR test profile.

operation since 1995 [5], primarily for FR and SR uses on the utility grid. The test profile is illustrated in Fig. 1.

The first part of the cycle is composed of several repeated sessions of constant-power pulses which are representative of FR operation. The sessions are separated by intermediate charges. This part of the test operates the storage device in the 70 to 90% SoC range. After three such FR sessions, a SR test is performed. The latter discharges the storage system to about 40% SoC during a 30-min test. During the SR operation, the first half of the test is spent at constant power, and then the power ramps down to zero over the second half of the discharge. The test is conducted based on calculated SoC limits with a back-up voltage cut-off for limiting the depth-of-discharge (DoD). This sequence of operation closely simulates the PREPA plant usage in that, for most of the time, the storage system is used for FR operations. Occasionally, an outage takes place that requires the system to perform a SR discharge. Adequate capacity is maintained in the storage system to meet the demands of the SR operation at any time during FR.

To perform the test properly, the charge and discharge profiles must be scaled to impose the correct power levels on the test hardware such that the PREPA system is being modelled. This is illustrated in Table 1 which also includes test values scaled for a valve-regulated lead–acid (VRLA) battery [6]. The scaling process is based on the rated capacity of the storage system. For example, the PREPA

Table 1
Power levels scaled from the PREPA BESS

| Application | PREPA BESS system power levels (MW) | Scaled VRLA power levels (kW) |
|---|---|---|
| Frequency regulation | 2.0 | 1.12 |
| Frequency regulation | 6.0 | 3.37 |
| Frequency regulation | 10.0 | 5.62 |
| Spinning reserve, constant | 21 (15 min) | 12.64 (15 min) |
| Spinning reserve, ramp | 21–0 (15 min) | 12.64–0 (15 min) |

battery is rated at the 40-min rate for SR duty, and measurements on the Puerto Rico grid indicated that the FR duty cycle could be approximated by discharges at the 7.5-, 2.5- and 1.5-h rates. The energy capacity of the VRLA battery (at the 40-min rate) is 8.5 kWh, and for the above rates, the power values in Table 1 can be obtained. To complete the test successfully, the FR and SR tests must be run without the storage system reaching a termination criteria. In addition to the pass/fail information, the number of FR sessions can be determined, along with the energy accumulated in and out of the system. If the tested system cannot complete the entire FR and SR tests, then the test should be rescaled to select the appropriate power levels and SoC levels for the particular hardware. If the system still cannot complete the test, then it may be considered to have failed.

This test regime is appropriate for evaluating storage systems on a grid-connected utility with multiple generation sources. While the load values can be scaled to address smaller storage systems, test regimes for applications with limited generation options may have different operating characteristics. Therefore, this test profile must be applied selectively.

## 4. Proposed test profile for power quality

Power-quality applications for energy-storage include uninterruptible power supplies (UPS) and other, more versatile energy-storage systems [7]. Testing has been performed on prototype full system hardware such as the PQ2000 system [8] at Pacific Gas and Electric [9] and at an industrial site in Southern Georgia [10]. The test relates to storage systems, in parallel with the load, that can switch into the circuit within a cycle (17 ms) or less, and operate at full or partial power for at least 10 s. These tests simulate field conditions to prove system feasibility and could be used to determine operating and maintenance (O&M) frequency.

The test profile, illustrated in Fig. 2, begins with the storage system fully charged according to manufacturer's guidelines. The system is then subjected to a scaled, constant-power discharge for 10 s. After a recharge and rest period, specified by the manufacturer, the discharge test is repeated for a predefined period or until the system cannot complete the 10-s duration within specified power levels (±10%) or cannot switch on within one cycle. Adherence to utility power voltage, frequency, and phase requirements must also be satisfied. The test regime must be scaled to a practical power level consistent with the rated capacity of 2 MW. Exact scaling depends on the power and energy limits of the storage system which is being tested, and the practical physical size limits of the system. For example, if a system capable of a peak output of 250 kW is to be tested, it would be a one-eighth scale test for 10 s.

Depending on the recharge and rest requirements of the system, the number of multiple discharge operations in a given period (availability) can be quantified. In addition, simple feasibility of system operation can be determined and reported as a pass/fail. Further, system O&M requirements can be identified and reported.

The relative similarity of power-quality applications makes site-specific considerations less crucial for this test profile. A review of the testing regime should be conducted, however, to ensure applicability in each test situation.

## 5. Proposed test profiles for RAPS systems

Certification testing of RAPS system has been proposed [11] by an international group for approving hardware

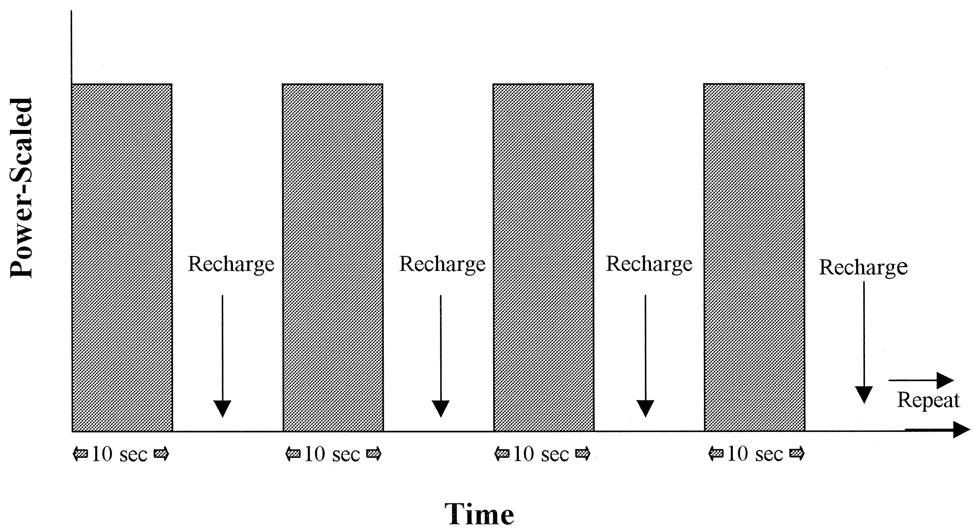


Fig. 2. Power-quality test profile.

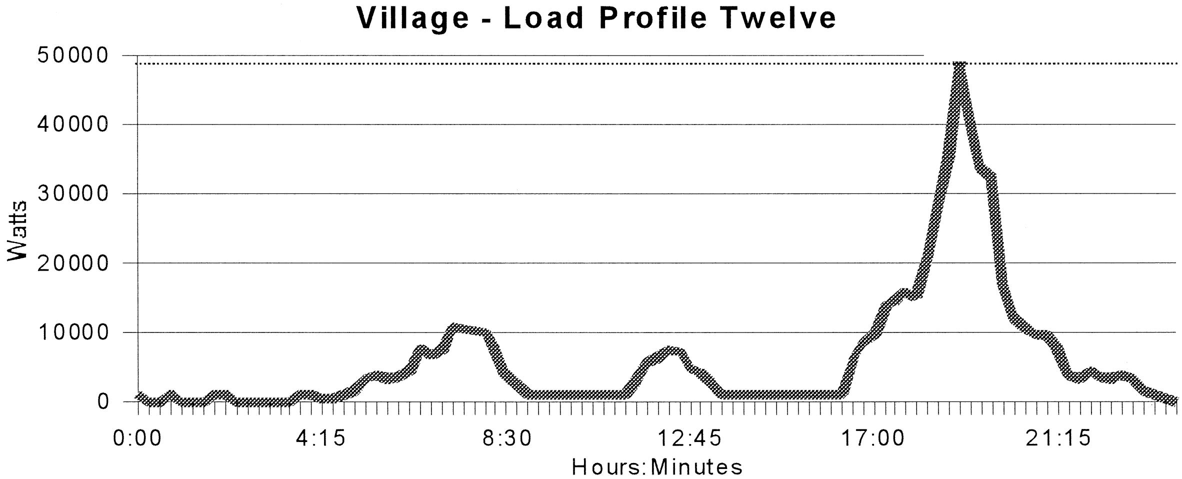


Fig. 3. Example RAPS test profile.

before it is installed in isolated, hard-to-reach locations. This effort is similar to, but broader than, an effort to standardize tests for solar home systems [12]. Field experience with hardware which was not sufficiently robust for the extreme environments typical of such applications led to this initiative. The expectation is that system certification will encourage the use of robust, highly reliable equipment in RAPS applications and promote more aggressive market development.

A series of RAPS test profiles has been proposed based on end-use applications. These are single residence, community and village system loads. The load profiles have been developed using appliances typical of these remote locations and expected usage during the day. Also, the profiles are being validated against actual field data from existing systems. It is anticipated that the most representative load profiles will be combined with generation source(s) (fossil-fuelled generators, photovoltaics, or wind) and a series of generator-load profiles will be developed.

An example load profile is illustrated in Fig. 3 for a village system. Additional simplification is expected as the test regime is further defined and tried on test hardware. A short, repetitive test or series of tests will be developed that can be implemented in the laboratory or in field conditions such that certification decisions can be determined with only a few months of testing.

Certification criteria also must be developed. Stable performance within 10% of manufacturer's ratings for power, energy and lifetime during the predefined test period is a likely part of the criteria. Limitations on O&M during the certification testing are also probable. Because of their remote location, RAPS systems must be able to operate unattended for long periods of time. Once a system is certified, warrantees for performance will still be the responsibility of the manufacturer. The certification process must only be viewed as an indication of probable robust performance and not a guarantee. In addition, if a system cannot meet the certification criteria, no liability will be accepted by the testing organization. The certification test should be approached as a design guide for developers and manufacturers, and once systems meet the test criteria, their field performance is very likely to be good and to encourage a growing market.

## 6. Proposed test profile for peak-shaving

Peak-shaving is increasingly being used to reduce high demand charges and the use of inefficient, polluting peaking generators during the few hours a day when baseload generation is unable to meet demand. One to two hours of storage can cover most significant peak demand periods at industrial sites and increase the efficiency and cost effectiveness for both the end-user and the utility. The Crescent Electric Membership [13] and GNB Technologies are both shaving peak loads with battery systems. Crescent operates a facility in a substation in Statesville, NC, and GNB operates a facility at a Vernon, CA, lead–acid battery recycling plant [14]. A test based on loading at the Vernon facility is proposed as a characterization regime to determine the applicability of a storage system to this mode of operation.

The proposed test profile for peak-shaving is illustrated in Fig. 4. It consists of a stepped constant-power profile which simulates the operation of a storage system during peak shaving; if gradually takes on more of the peak during the first half of the test, and then reduces the output as the peak decreases. The test may be repeated after the manufacturer's recommended recharge/or rest operation. It should be terminated when a predetermined time period or number of charge–discharge cycles has been completed, or when the storage system output falls below

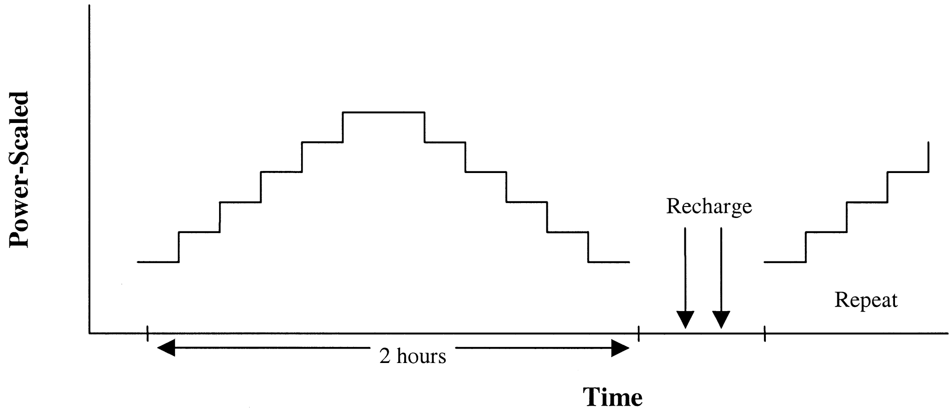


Fig. 4. Peak-shaving test profile.

that required to perform the peak-shaving operation. The storage system may be fully charged or at a partial SoC when starting the test, depending on whether it will be used or held ready for additional applications. The power levels must be scaled to the size of the storage, PCS, and other system capabilities. The range of SoC must be stated when reporting test results.

The magnitude of the test load and the duration of discharge are both scaleable and should be applicable to many peak-shaving sites. A standard test must, however, address explicitly the effects of increased cycling frequency on system performance and life. Also, the characteristic SoC at the beginning of discharge and the ability to perform opportunistic recharge must be considered.

The key objective of this test is to show that the storage system is available for peak shaving on a highly reliable basis. Peak demand charges for a month are typically based on the highest demand from any single, 15-min period. Thus, if the storage system is unavailable for even a short period during a month, all economic benefits can be lost. Therefore, high reliability and low maintenance are critical to this application and must be reported with the test results.

## 7. Conclusions

Test procedures are described for FR and SR, power quality, RAPS, and peak-shaving applications of stationary energy-storage. All tests must be preceded by a capacity verification procedure which is also described. Combining the capacity verification with an application-specific test profile should result in the best method to accurately characterize performance and life for each application. This benefit of testing will be enhanced if the test standards allow for some flexibility in which site-specific characteristics can be considered. When these procedures are implemented consistently by developers, testing laboratories, and prospective users of energy-storage technologies, expectations for system operation and reliability will be more realistic and should promote enhanced acceptance of storage by many user groups.

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