PRINCETON POWER SYSTEMS
Clean Power Made Simple™

EFFECTIVE ENERGY STORAGE

October

2016

INTRODUCTION

Battery-based energy storage has long been used as a means of backing up equipment. Critical equipment is often tied to an “uninterruptible power supply” (UPS) to assure continuity of operation. In recent years, there has been a rapid acceleration in the deployment of clean, renewable – but inconsistent – sources of electricity such as solar and wind. In addition, our aging electric distribution grid suffers, in part, because of a mismatch between when electricity is produced and when it is needed. Advances in the underlying technologies and the drop in battery prices driven, in part, by electric vehicles have opened a wealth of applications for battery-based Energy Storage Systems.

“Energy Storage” appears often in the popular press. It refers to broad family of applications as simple as providing backup power during a grid outage to integrating a number of energy sources to power an off-grid facility. In between are applications such as peak shaving, demand response, and frequency regulation.

Princeton Power Systems’ Energy Management Operating System, ***EMOS™***, facilitates the integration of sources of energy with the storage of energy and provides the hardware, control firmware, and high-level software to address the full spectrum of energy storage application. The application knowledge is embedded in ***PPS’*** Energy Storage IQ firmware (***ESIQ™***). ***EMOS™*** together with ***ESIQ™*** have enabled a broad range of energy storage installations. ***PPS***’ flagship project is the ***microgrid*** that powers Alcatraz Island. Alcatraz is one of dozens of successful projects.

> ***Via the integration of energy generation, storage, power electronics, and application knowledge, EMOS™ and ESIQ™ convert complicated projects into the installation of standard products.***

This White Paper describes a sampling of energy storage applications and discusses what is required to address those applications. An appendix highlighting some of Princeton Power Systems’ energy storage projects.

APPLICATIONS OF ENERGY STORAGE SYSTEMS

PEAK SHAVING:

An ***Energy Storage System*** (***ESS***) can be used in a wide variety of applications. Perhaps the simplest to understand is ***Peak Shaving***. There has been much publicity about how our electricity distribution grid is overloaded and in need of upgrading. In reality, the grid is strained for only a small part of each day, typically mid-afternoon. The problem is amplified during events such as heat waves during which air

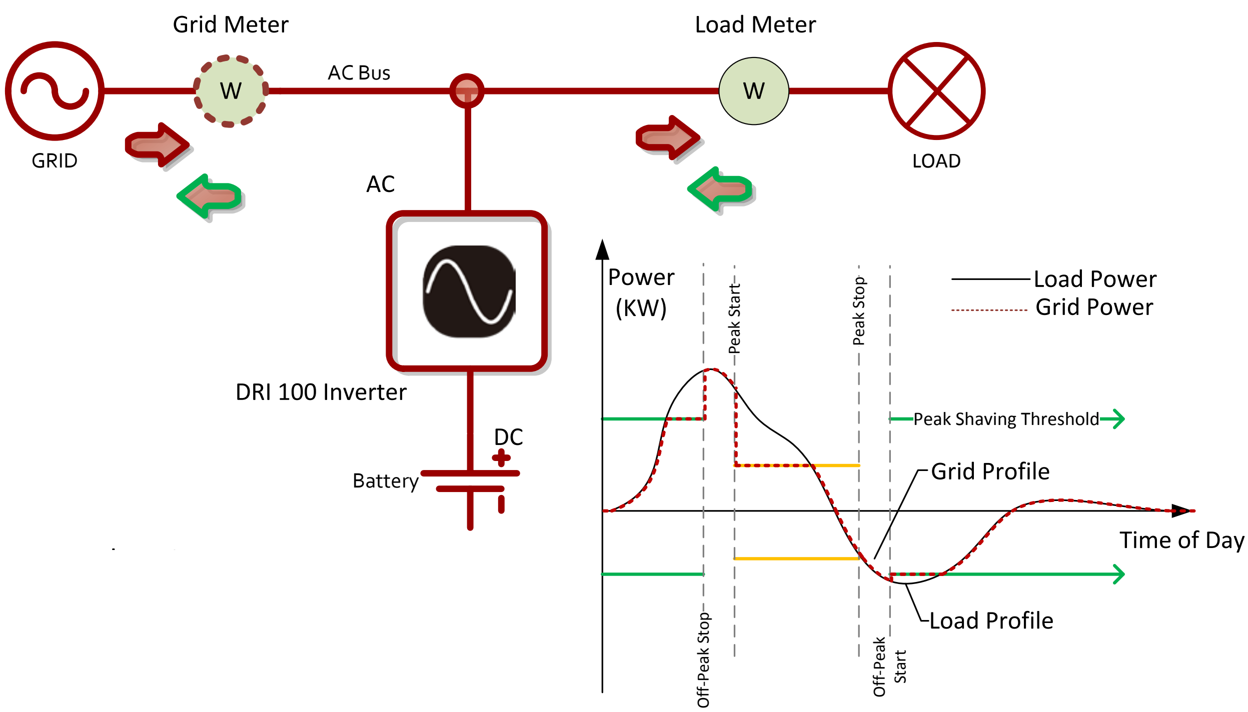

Figure 1: ***Simplified circuit diagram of a Peak Shaving application***

conditioners consume much more electricity while the grid also operates less efficiently. To discourage electricity usage during these peak times, a "demand charge" is often added to the electric bill, which is essentially a fine based on the peak power used. This charge is usually based on the maximum energy used over a 15 minute interval during the month. In some regions, such as Southern California, the demand charge can be larger than the cost of the actual energy used. To avoid this charge, users can install an ***ESS*** which is charged during times of low usage (e.g. overnight) and discharged during periods of peak demand to minimize the amount of peak electricity drawn from the grid. Utilities even allow some commercial customers to negotiate a lower rate for electricity (kWh) in exchange for a steeper demand charge (kW), reducing bills even further. Use of a ***Peak Shaving ESS*** allows a customer to lower their electricity costs with a great degree of confidence, generating a substantial return on investment. At the same time, utilities benefit by postponing the need to upgrade the distribution grid.

FREQUENCY REGULATION:

Another important application for Energy Storage Systems is ***Frequency Regulation***. Most of our electricity is provided by rotating generators driven by coal, natural gas, nuclear power, or hydroelectric power. Electricity is supplied in North America at a frequency of 60Hz, and any mismatch between demand and generation can cause the frequency to drift. If demand exceeds generation, the missing energy is provided by the kinetic energy of the rotating generators causing the generators to slow (frequency droop). Conversely, if demand is less than generation, rotating generators will speed up. For efficiency, generators are designed to work over a narrow range of frequencies (60±0.5 Hz in the U.S.). While they can adjust their speed to accommodate for these frequency changes, the adjustments take time; more than 15-minutes for most traditional power plants. The modern grid incorporates energy sources like wind and solar, which are unpredictable, as well as loads that may come on or off rapidly. Small amounts of electricity are needed on much shorter timescales, sometimes less than 1s, which is ideally suited to a battery-based ***ESS***. A location with a suitable ***ESS*** can generate significant revenue from its electric utility simply by being available and selling capacity to the grid operator.

MICROGRIDS:

A more sophisticated application is an off-grid energy generation and distribution system or ***Microgrid***. In a ***Microgrid***, one or more energy sources (solar panels, wind turbines, mechanical generators) are integrated with an ***ESS*** to power a facility. A ***Microgrid*** is generally totally disconnected from the central utility network. The ***ESS*** in a ***Microgrid*** plays multiple roles. When combined with energy sources, like solar and wind, whose output fluctuates (it gets dark at night or clouds block the sun), the ***ESS*** acts as a

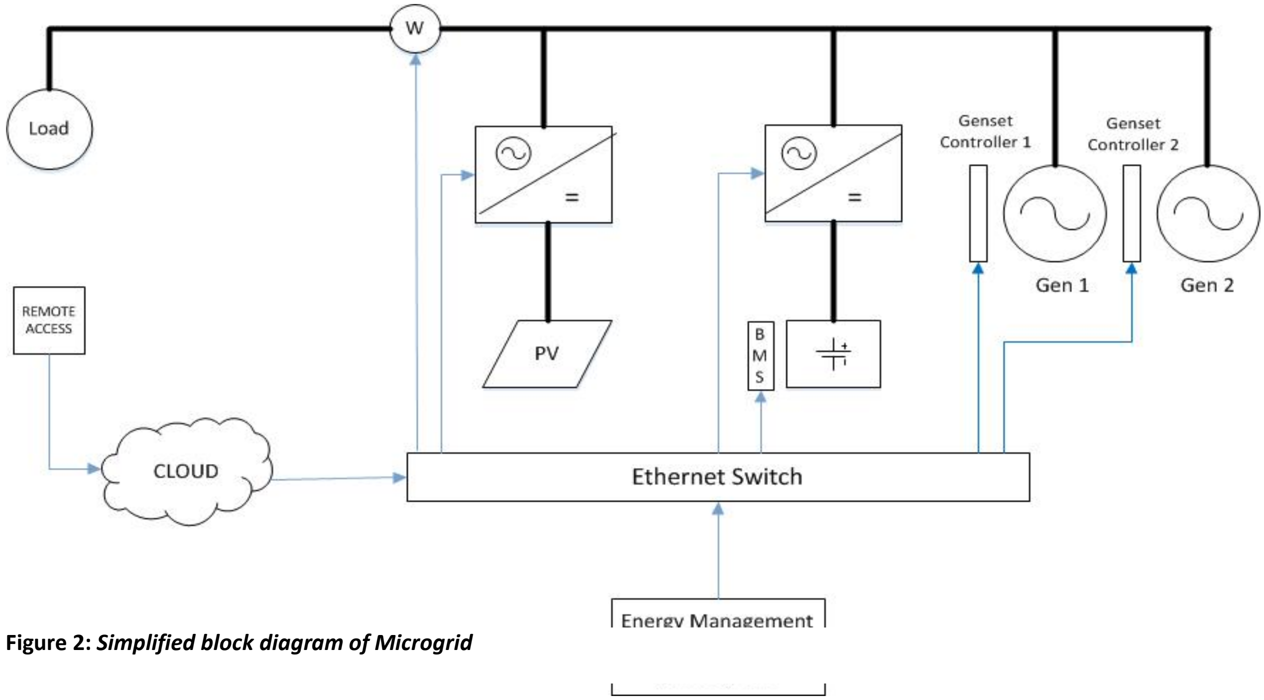

Figure 2: ***Simplified block diagram of Microgrid***

ballast tank storing energy as it is produced and making it available when needed. When combined with a mechanical generator, it makes the generator more fuel efficient and reduces the need for operating time and maintenance. A 100 kW generator, for example, burns the fuel needed to turn the generator no matter how much power is needed. When much less than full power is required, diesel generators run very inefficiently and some even suffer from "wet-stacking" leading to frequent breakdowns.

COMBINING APPLICATIONS:

The most complicated use of an ***ESS*** is in a system that performs multiple functions when the central grid is available but automatically creates a ***Microgrid*** when it is not. When the central grid is available, the power electronics controlling the solar panels or wind turbines act independently of those of the ***ESS***. They are "grid-tied" in the sense that the central grid establishes the voltage, frequency, and phase while the inverters/converters simply synchronize with and add current to the grid. The batteries/electronics in the ***ESS*** carry out whatever functions for which they are programmed such as peak shaving or frequency regulation. The inverters or converters are required to be "anti-islanding"; i.e. to disconnect when the central grid is unable to accept energy so as not to create an "island" of electricity that can damage equipment and be dangerous to repair personnel.

When the central grid is not available, the establishment of a ***Microgrid*** requires that the electronics be able to switch seamlessly from grid-tied mote to off-grid-mode. A voltage-mode inverter/converter, capable of creating its own voltage, frequency, and phase is required to establish the ***Microgrid*** so that the rest of the electronics can synchronize to it. It might be desirable, for example, for the solar panels to power the facility with excess energy stored in the batteries. A mechanical generator would be the energy source of last resort. Most of the installed base of mechanical generators is incapable of synchronization (i.e., they can only run in off-grid mode) so the inverters/converters need to be able to synchronize to and control the generator.

Following Super-Storm Sandy, much of New Jersey suffered prolonged grid outages. Diesel-based backup generators were unable to refuel as gas stations were inoperable. Most of New Jersey's installed base of solar panels (more than 1GW) was unusable. Solar/battery/generator-based ***Microgrids*** would have been able to provide indefinite backup for critical loads.

WHAT TO LOOK FOR IN POWER ELECTRONICS

It is a common misconception that by simply adding a computer to control off-the-shelf solar and battery inverters, it is possible to address the above applications. In fact, it is critical that:

- The electronics must be capable of both current-mode and voltage-mode functionality, and rapidly switching between the two, in order to operate on-grid, off-grid, or with a "weak grid" like a diesel generator.

- The electronics must always maintain U.L. compliance to guarantee safe operation and compatibility with the grid, and to facilitate project permitting.
- The battery electronics must be able to accept a wide range of voltages. Batteries are expensive and, in an ***ESS***, they are repeatedly taken into deep-discharge. This can lead to voltage droop which must be accommodated by the electronics.
- The electronics must provide "virtual generator control." To share power generation on a network, generators follow a protocol commonly referred to as "droop" control. Generators can consist of diesel generators, photovoltaic generators, energy storage systems so long as they can interact in a manner that allows load to be shared. Rotating generators naturally have droop (i.e. the diesel motor slows down when a heavy load is applied), but standard inverters do not "slow down" when they are loaded, making it difficult for them to pair with mechanical generators.
- Solar inverters must be capable of adjusting the power output based on the needs of the ***Microgrid***. A solar inverter includes a maximum power point tracking (MPPT) algorithm that automatically biases the solar panels so as to always maximize the power output. ***Microgrid*** inverters must automatically "turn down the sun" by biasing the panels away from the maximum power point so as to reduce the power output. While this curtailment should be minimized in order to use as much solar energy as possible, it is necessary to maintain the reliability of the ***Microgrid***.
- The electronics must be capable of seamless integration with a network of other electronics. In ***Microgrid*** mode, only one of the inverters can act as the master (voltage-mode) with the other inverters synchronize to it. The electronics must be able to hand-off the master function between the battery electronics, solar electronics, or diesel generator(s) without interrupting **the electricity supply.**

PPS power Electronics featuring *EMOS™* and *ESIQ™* are capable of supporting the full range of *ESS* applications.

The following table summarizes ***ESIQ™*** features. These are essential to allow the power electronics in ***ESS***s to be used for both stand-alone energy storage and/or ***Microgrids***.

Functional Module	Description
Frequency Regulator	Regulates the AC frequency on the Grid.
Inverter Policy Manager	Manages Global Inverter Policies.
Peak Shaver	Allows import/export of Peak Shaver Parameters.
PV Smoother	Reduces the variability of photovoltaic output power.
PV Peak Shifter	Reduces PV power fluctuations due to peaks & valleys
Remote Dispatch/Demand Response	Remotely sets real and reactive power levels.
Scheduler	Allows parameters to be set at specific time intervals.
Volt/VAR Controller	Stabilizes grid voltage by controlling reactive power.
Generator Control Process	Gen-Set Start/Stop and Synchronization controls.

CHOOSING THE BEST BATTERIES FOR THE APPLICATION

Li-ion batteries have achieved broad acceptance in stationary storage applications. Li-ion batteries are well-developed, are readily available, and used in a broad spectrum of commercial applications such as consumer electronics and electric vehicles. In recent years, there has been a dramatic drop in cost which enhances the attractiveness of newer applications such as stationary storage.

"Li-ion" refers to a family of lithium-based chemistries and cell geometries. Strictly speaking, a "cell" is a single anode/cathode (plus/minus) pair. Multiple cells working together to make up a "battery." The various flavors of Li-ion batteries feature different:

- Power/energy ratios (how fast they can be charged or discharged without degradation)
- Cycle life (how many times they can be discharged then recharged)
- Safety (the risk of a fire that cannot easily be extinguished)

18650 cells, for example, are somewhat larger than conventional AA cells and are commonly used in consumer electronics and some electric vehicles, and can typically be fully-cycled 400-500 times before degrading to 80% of their original useable energy capacity.

An important feature of Li-ion batteries is that the cycle life is based on the energy used. Roughly speaking, if only 50% of the available charge is used in a cycle, the battery will last for twice as many cycles. This is important in choosing the best type of Li-ion battery for a given application.

Premium electric vehicles are commonly rated to provide a range of 250 miles. The average vehicle is driven 12,000 miles per year or less than 35 miles per day. EVs are usually charged every day so most often only a fraction of the available energy is used. The expectation is that the battery pack in an EV be able to last for 8 years or 96,000 miles. At 250 miles per full discharge, this requires batteries rated for 400 cycles.

In addition, the power requirements of an EV are highly variable. To accelerate from zero to 60 mph in a few seconds may require more than 300 horsepower (225 kW). An EV using an 85 kWhr battery pack with a range of 250 miles traveling at a steady 60 mph is operating at 20 kW or less than 30 horsepower. With their 400-500 cycle life, 18650 lithium-ion cells can satisfy these performance requirements.

The requirements for stationary storage are very different. The power requirement, or battery discharge rate, tends to be consistent rather than varying by a factor of 10 as is the case with EVs. Unlike EV batteries, stationary batteries are typically fully discharged and recharged every day. For a system to last 10 years, it must then be capable of 4,000 cycles.

It is common for a battery manufacturer to quote a "nameplate" energy capacity, e.g. 100 kWhr DC, but to specify that the battery not be charged above 90% of that capacity or discharged below 10%. Rapid discharging may decrease the available energy as will low or high ambient temperatures. It is important that the manufacturer specifies the available energy and quantifies the trade-offs with power and temperature. A stationary storage system supplier should be expected to supply the battery cycle life data.

Princeton Power *Energy Storage Systems* are rated for 4,500 charge/discharge cycles and are specified by the energy that is actually available.

SYSTEM INTEGRATION

The installation of an ***ESS,*** whether in the simplest peak-shaving application or in the wide variety of more complicated applications, is hampered by the degree of engineering required. Each installation tends to be a custom project.

Princeton Power's unique ***ESIQ™*** platform enables the delivery of efficient, cost effective solutions for commercial, industrial and utility energy storage. The ***ESIQ™*** platform ties together batteries, inverters, cooling systems and enclosures, along with control software, to enable seamless integration of energy storage system components prior to arriving at customer sites.


GTIB-30

Simply put, ESIQ™ turns projects into products.

Princeton's advanced inverters operate in both on-grid and off-grid modes and switch seamlessly between them. They are ready to be used in peak shaving or full microgrid applications, and are compatible with multiple battery types.

Leveraging ***ESIQ™***, Princeton Power delivers a fully-working ***ESS***. When a more complicated ***Microgrid*** operation is required, a proprietary Energy Management Operating System (***EMOS™***) controller is used that enables the design and configuration of a ***Microgrid*** with the ease of drawing an electrical "one-line." The ***EMOS™*** controller is pre-configured at the factory to control various ***Microgrid*** generators, PV inverters, ***ESS***, and other components when it arrives. ***EMOS™*** operates the ***Microgrid*** in real-time and ensures reliable operation of all components, optimization of the controls, and enables remote monitoring. As a component of the ***ESIQ™*** platform, the controller is pre-integrated with Princeton Power's inverters and battery systems.

A SAMPLING OF PRINCETON POWER SYSTEMS' ENERGY MANAGEMENT PROJECTS

ALCATRAZ ISLAND was the first modern solar-plus-battery commercial microgrid in North America, installed and operating since 2010.

Along with partners NYCEDC, Hitachi and others, PPS developed NY's first advanced battery system and microgrid at the **BROOKLYN ARMY TERMINAL**.

SCRIPPS RANCH EMERGENCY RESPONSE CENTER now serves as an "islanded" command center for emergency authorities in events such as wildfires. When an emergency occurs, the recreation center automatically disengages from the city's power grid and starts supplying stored-up energy for crews and victims who come to the center for help.

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