PARALLEL SODIUM BATTERY FOR FIVE NINES AVAILABILITY

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INTRODUCTION

Advanced batteries based on sodium-metal halide chemistry ("Sodium Batteries") have many advantages for critical stationary applications such as datacenter UPS systems and telecom backup power. Sodium batteries are capable of long term operation with frequent cycling in a wide range of ambient conditions. In addition, their compact design allows for a battery bank built from full-voltage modules connected in parallel. This fundamental change in architecture enables near-100% operational availability.

A parallel-connected system of battery modules is capable of supporting a load if one or more modules are removed from service prior to, or even during, a discharge. The remaining battery modules will continue to support the load at a higher discharge rate per battery and reduced system run time. This is in stark contrast to the typical series-connected lead-acid battery bank where a single point of failure may take down the entire system.

GE has tested a parallel-connected system of prototype battery modules to demonstrate module-to-module interactions, robustness to varying UPS module demands, and ability to continue discharge through a battery module outage.

PARALLEL BATTERY SYSTEM CHARACTERISTICS

Present large scale energy storage systems typically use a series-connected battery bank, where the full system current passes through each cell. The building block of a series-connected system is the battery ‘jar’, comprising one to six cells. Each jar provides a portion of the full system voltage. An open circuit anywhere in the system renders the system unable to recharge or power the load. Bypassing or removing jars reduces the system voltage.

A parallel-connected battery system (Fig. 1) is comprised of a number of battery modules, each of which operates at the full system voltage and provides a portion of the current required to support the load. An outage of one or several modules does not prevent the rest of the system from operating: the effect of the ‘missing’ modules is that run time at constant power will be reduced, as the remaining batteries must now discharge at higher current to support the load.

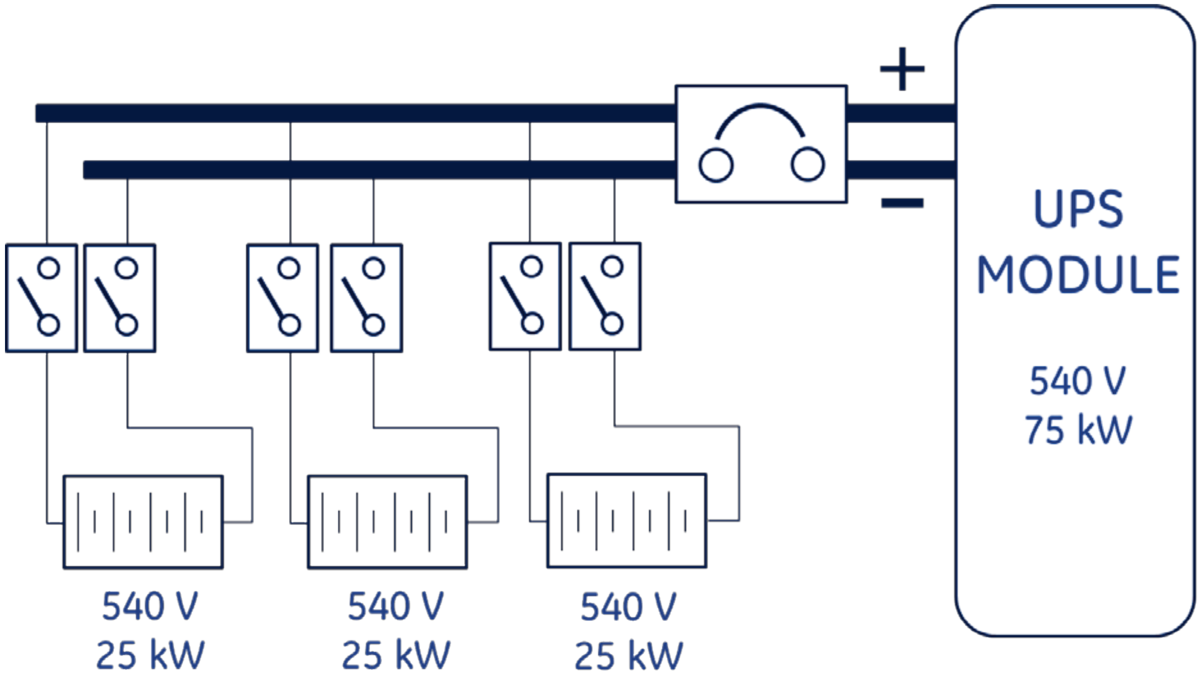

Figure 1: Simplified Parallel Battery Bank System

The main advantage of the parallel system over the series system is operational availability. In the event of a fault, any of the battery modules can be disconnected from the system bus and replaced with a new module without preventing the remaining modules from supporting a load if required.

Another significant advantage is that old and new battery modules may be mixed in a system without difficulty. As in any parallel circuit, the voltage in each branch is the same and the current is divided according to the ratio of resistances among the branches. An older battery with higher resistance than a new battery will simply provide a smaller share of the current during a discharge. Similarly the system power delivery rating and capacity can be extended over time, by adding new modules in parallel with the existing ones.

BATTERY MODULE REQUIREMENTS

Battery modules with different resistances and even capacities can be mixed—however this means that the modules must be robust against certain phenomena having to do with charging and discharging on a parallel bus. For example, one module could exhaust its capacity while the other modules are still capable of supporting the load. In this case the 'weak' battery must be able to disconnect itself to avoid overdischarge.

When a parallel battery system is recharged, each battery module will experience the same charging voltage. Individual batteries will tend to reach top-of-charge at different times, depending on their initial state of charge. This means that when the system is fast-charged at elevated voltage, some fully-charged modules will remain at the elevated voltage while the rest of the modules 'catch up'. Similarly, a fast charge of a certain timed duration could finish with some modules still at less than 100% state of charge. Different battery technologies respond to these phenomena in different ways.

For a given battery chemistry, the voltage of a single cell is the same regardless of the size of the cell; therefore a parallel system will have many more individual cells than an equivalent series system. For example, if 240 cells of 1000 Ah capacity are required in a series-connected system, an equivalent ten-module parallel system must have 10x240=2400 cells of 100Ah capacity each. This means that the battery technology selected for a parallel system must be one that can be optimized for minimum cost at comparatively small cell sizes. Also, the increase in the number of cells for a given installation may prove problematic if the cells are not reliable or require maintenance on a cell-by-cell basis.

These unique characteristics of the parallel system require battery modules with the following features:

- Full system voltage in each parallel-connected module.
- Able to discharge at higher current than nominal, to support load with one or more modules unavailable.
- Modules must be able to disconnect themselves from the system bus in case of overdischarge.
- Modules must be robust against overcharging damage if 'fast charge' modes are used, or else be able to automatically disconnect.
- Compact size that can be installed or removed by on-site personnel.
- Meet power and energy density requirements.
- Meet cost requirements.
- Reliable cells that do not require individual maintenance.

These requirements are very difficult to meet with traditional batteries. The main problem is scale: each lead-acid wet cell 'module' would still require 240 cells in series for a nominal 480-540V UPS system. Each would require the same monitoring and maintenance as current systems. A parallel-connected wet cell string would have to be installed and replaced jar-by-jar, the same as a series-connected string. This makes meeting energy density, cost, and maintainability requirements very difficult.

Performance of a lead-acid parallel system is also hampered by c*oup de fouet* effects, which limit the ability to discharge at higher than normal current—thus if one or more modules is disconnected, the remainder may not be able to support the system load.

VRLA (valve-regulated lead-acid) batteries can be made small enough to package into parallel modules; however, the low power density and voltage per cell limits performance; while large-scale VRLAs may last 7-13 years, the small cells used in modular systems have an expected lifetime of only 3-5 years[1]. These systems are typically used in small-scale applications under 500 kVA.

Tier III and Tier IV UPS systems are typically in the 500-1000 kVA class, and have an expected design life of 15-20 years. A more advanced battery technology is required for use in parallel battery systems at this scale.

SODIUM BATTERY MODULE FOR UPS DATACENTERS

Sodium-metal halide batteries are well-suited for use in a parallel system. The nominal cell design is very compact, and because of its high open-circuit voltage fewer cells are required per module than in a lead-acid battery.

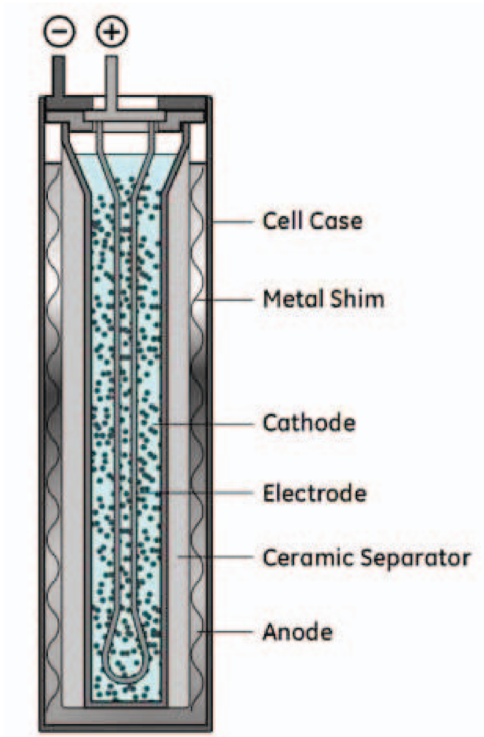

Figure 2: Sodium Cell Schematic

GE's prototype sodium battery modules for a nominal 480-540 Vdc system are comprised of 216 cells in series. These modules, intended for datacenter UPS service, have the following characteristics:

Nominal Float Voltage	567 V
Open-Circuit Voltage	557 V
Constant power delivery, 15-min rate	24-30 kW
Capacity (C/10)	32 Ah
Dimensions (approximate)	900x700x300mm
Weight (approximate)	200kg
Service Life	20 years

Table 1: GE Durathon^{TM} prototype battery specifications

PARALLEL SODIUM BATTERY TESTING

A three-battery parallel system was tested at the General Electric Energy Storage development laboratory in Schenectady, NY. The system comprises three prototype Durathon batteries and a Digatron 600V, 100A cycler.

Figure 3: Three-battery test system at GE Energy Storage

Performance Testing

The system was exercised over several weeks in simulated UPS service using a distribution of battery discharge durations and loads as shown in Table 2. This distribution is based on EPRI statistics of utility outages[3] for the 95th percentile (the worst 5%) of locations in North America.

Battery discharge distributions were estimated based on the outage statistics by assuming that each battery bank is in a "system plus system" redundant installation, such that the battery discharges at half of full rated power in approximately 80% of all grid outages.

Similarly, practical UPS systems use generators for grid outages of over one minute duration; therefore most long-duration grid outages require only a one-minute battery discharge.

Cycle Duration	Half Power Cycles	Full Power Cycles	Total Cycles
30 sec	55.7%	14.0%	69.7%
1 min	18.6%	3.7%	22.3%
5 min	4.0%	1.0%	5.0%
15 min	2.5%	0.6%	3.1%

Table 2: Battery Discharge Distribution for UPS Datacenter Service

The three batteries used in the test represent different phases of development and have slightly different internal arrangements which affect their performance. In addition, each has a different history:

- Battery "A" : ~300 full power, full duration cycles, ~800 total cycles.
- Battery "B" : Damaged in shipping. ~200 full power, full duration cycles, ~500 total cycles.
- Battery "C" : New battery, <50 total cycles.

Figure 4 shows the current in three parallel batteries during a discharge at 36 kW constant power for 15 minutes, followed by a full "slow recharge" at float voltage.

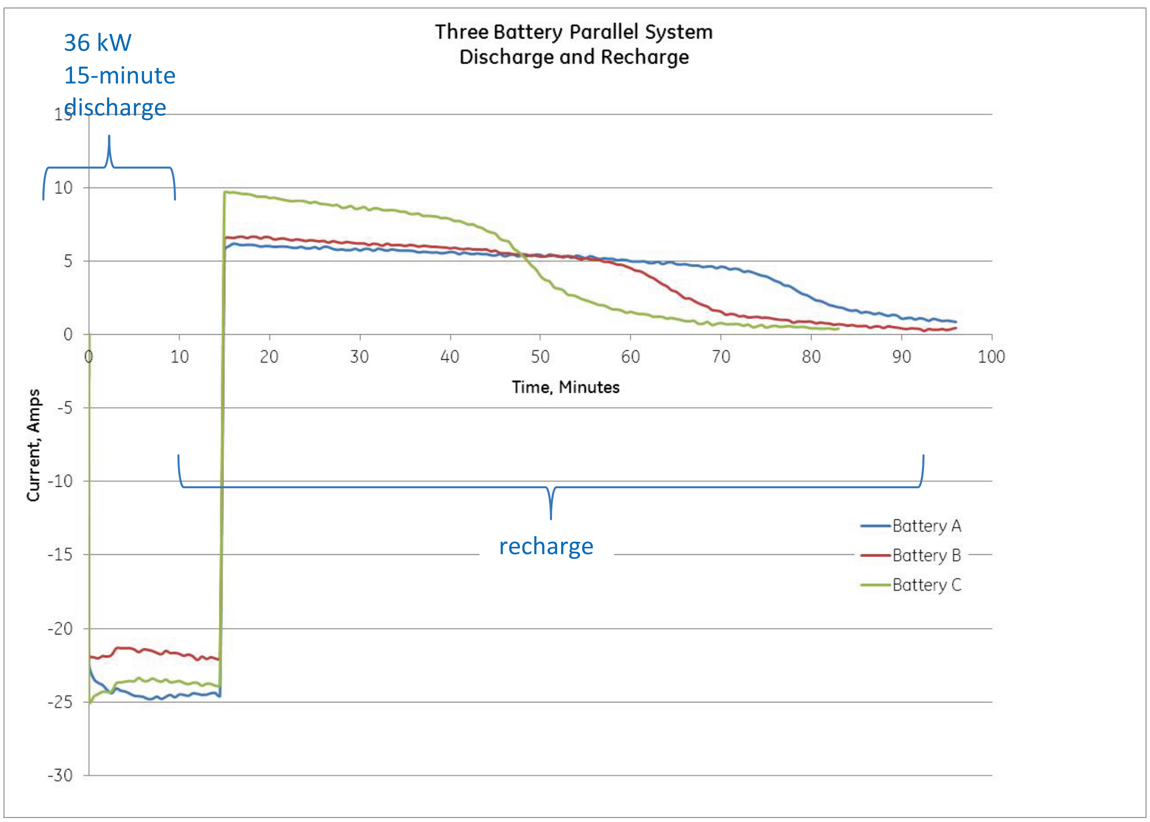

Figure 4: Three-battery parallel system discharge/recharge test

All three batteries are held at the same voltage throughout the cycle: floating at 567V before the discharge, discharging down to approximately 507V, and then being recharged at constant 567V. No two batteries have exactly equal resistances, and resistance in a given battery tends to increase as the battery is discharged. Thus, the three batteries in the parallel system have different currents throughout the discharge.

"Battery C" had the lowest initial resistance, and therefore it provided the largest share of current at the beginning of the discharge: 25 Amps, as opposed to approximately 22 Amps each from the other two batteries. However, the higher current in Battery C caused its resistance to increase at a faster rate than the other batteries. After approximately two minutes, Battery A became the least resistive battery. Note also that the current from Battery A begins to decrease at approximately 6 minutes, as its resistance approaches that of Battery C. Battery B remains the highest resistance, lowest current battery throughout the discharge.

When the batteries are recharged, again the voltage is constant across the parallel system and each battery module draws current proportional to its resistance, with the lowest resistance battery drawing the most current. Resistance increases in each battery until it is fully charged. At this point the effective battery open-circuit voltage matches the system bus float voltage, and current stops flowing into the batteries.

The ~3 Amp difference in current between the three batteries is somewhat high, and would not be expected in a practical installation where all the battery modules are of the same design and condition. This test indicates that battery modules with different performances can work together in a parallel system, a significant advantage for UPS system operators—aged battery modules can be replaced, or an existing system can be expanded with additional modules, without jeopardizing performance.

Battery Module Outage Experiment

Figure 5 shows the three-battery system's response to a single module outage. The test began with a 36 kW discharge using all three batteries. At the 5-minute mark, Battery B was manually disconnected. The other two batteries immediately supplied the additional current and completed the discharge.

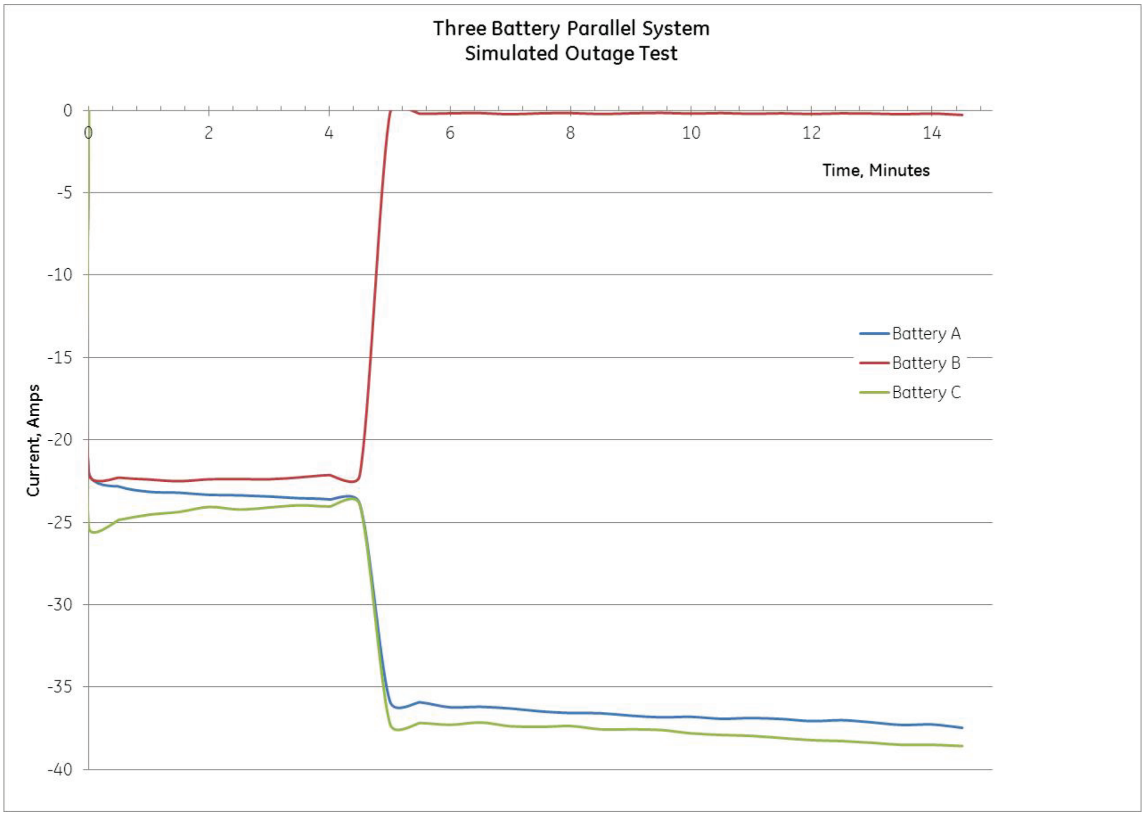

Figure 5: Parallel system with manually induced battery module outage

Other scenarios were performed including outages at various other times in the 15-minute discharge and reconnection of 'faulted' batteries to the system during the discharge. In each case the current distribution changes as necessary to support the constant 36 kW load.

PARALLEL SYSTEM AVAILABILITY STUDY

Battery systems for critical UPS datacenters are typically provided with excess capacity for reasons of redundancy and long-term performance degradation. In a series-connected battery system the additional capacity can increase available runtime, but does not increase availability. For the parallel-connected battery system, every additional module increases overall system reliability and availability.

For example, a UPS sized for 750kVA with 15 minutes of battery backup may be arranged as follows:

$$750\ kVA * \frac{.90\ power\ factor}{.945\ inverter\ efficiency * .80\ degradation\ factor} = 900\ kW\ per\ battery\ bank$$

Assuming a fifteen-minute discharge capability of 25 kW per battery module, this system requires 36 parallel batteries.

This traditional sizing, based on the battery being able to support a full-power 15-minute discharge at end of life, results in an highly redundant system. In a "system plus system" arrangement the batteries may be discharged at only half load. Additional redundancy comes from the degradation oversizing factor. In a half-power discharge at beginning of life, for example, only 15 out of 36 batteries are required to support a 15-minute discharge. Other scenarios are presented in Table 3 based on sodium battery performance, assuming 20% degradation in power delivery capability over the module's lifetime.

The only scenario without redundancy is the full power discharge at end of life; this is the condition the battery bank was designed to handle, and all 36 modules are required to sustain a 15-minute discharge. However, a module outage in this scenario does not *prevent* a discharge—it simply shortens the run time. The final entry on the table represents the extreme condition of a full-power discharge at end of life. Sodium batteries can exceed their 15-minute power delivery rate by approximately 30% for one minute: this means that as few as 26 battery modules could support a one minute discharge even at end of life—more than enough time to start a generator.

Scenario	Power per Battery	Required Modules	Redundant Modules
15-min, Half Power Discharge, Beginning of Life	25 kW	15	21
15-min, Full Power Discharge, Beginning of Life	25 kW	29	7
15-min, Half Power Discharge, End of Life	20 kW	19	17
15-min, Full Power Discharge, End of Life	20 kW	36	0
1-min, Full Power Discharge, End of Life	~28kW	26	10

Table 3: Redundancy scenarios for example 36-battery module, 750kVA system

Therefore a parallel battery system always has *some* ability to support load, even with multiple modules unavailable. If failed modules can be replaced with new ones quickly, the system will always be available to discharge. A previous study[2] calculates 100% theoretical operational availability for a 750kVA parallel battery system, assuming module replacement time of three days or less and battery module MTBF (Mean Time Between Failures) of at least one year.

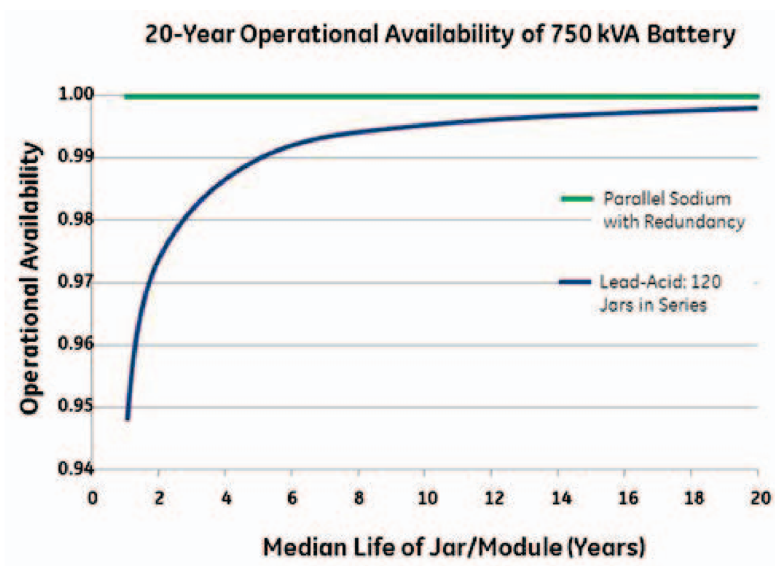

Figure 6: Operational availability of series and parallel systems

Two UPS Modules, One Battery System?

Because of the high availability of a parallel battery system, it may be possible to use a single battery bank in a 'system plus system' style UPS arrangement without degrading overall system availability. Such a system must be arranged to avoid single points of failure: for example, without the battery bank relying on any one switch or section of buswork to supply power to the two redundant UPS modules.

Such a system would always discharge at full rated power, and would therefore require a battery technology with high cyclic life and power capability. Additional battery modules could be added as desired to provide any desired level of redundancy. The obvious advantage of such a system is cost; the number of battery modules required is roughly halved compared to a system plus system installation with one battery bank per UPS module.

SUMMARY

A parallel redundant system is inherently far more reliable and available than an equivalent series system. However, traditional lead-acid technology has made parallel battery systems impractical for datacenter UPS systems. Emerging technologies such as sodium batteries, which can be packaged as field-replaceable high-voltage modules, can make parallel architecture a possibility. Parallel battery systems may also allow novel UPS system architectures to reduce cost while maintaining near-100% operational availability.

The three-battery test system described in this paper demonstrates only some of the advantages of a parallel system. Demonstration systems approaching the 750kVA scale will be tested in the coming months as sodium battery modules for UPS service come closer to commercial availability.

REFERENCES

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3. Sabin, D. *et al*, "Preliminary Results for Eighteen Months of Monitoring from the EPRI Distribution Power Quality Project," Electric Power Research Institute, 2003.