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Development and testing of 100 kW/1 min Li-ion battery systems for energy storage applications

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Abstract

Two 100 kW min^{-1} (1.67 kW h^{-1}) Li-ion battery energy storage systems (BESS) are described. The systems include a high-power Li-ion battery and a 100 kW power conditioning system (PCS). The battery consists of 12 modules of 12 series-connected Saft Li-ion VL30P cells. The stored energy of the battery ranges from 1.67 to 14 kW h^{-1} and has an operating voltage window of 515–405 V (dc). Two complete systems were designed, built and successfully passed factory acceptance testing after which each was deployed in a field demonstration. The first demonstration used the system to supplement distributed microturbine generation and to provide load following capability. The system was run at its rated power level for 3 min, which exceeded the battery design goal by a factor of 3. The second demonstration used another system as a stand-alone uninterrupted power supply (UPS). The system was available (online) for 1146 h and ran for over 2 min.

Keywords: Li-ion; Battery systems; Energy storage applications

A goal of the U.S. Department of Energy's Energy Storage Systems Program is to alleviate short outages and voltage sags to provide a required level of power quality for providers and consumers of electricity in the United States. The goal of this project was to design and construct a 100 kW/1 min (1.67 kW h) Li-ion battery energy storage system (BESS) for use in providing power quality for grid-connected microturbines. The Li-ion BESS was designed to carry a critical load for a short duration to allow time for microturbines to come online. Once the microturbines are started, the load is seamlessly transferred from the BESS to the microturbines. The BESS can supply enough power to start industrial motors if necessary and can provide an immediate source of power until microturbines can be brought online to handle the load. Additionally, the BESS can supply or absorb power during any load shifts and can function as a stand-alone UPS.

Saft America, in cooperation with SatCon Power Systems of Canada and the U.S. Department of Energy's Energy Storage Systems Program at Sandia National Laboratories, designed a prototype system and built two systems suitable for field demonstrations. The system operates in conjunction with a 60 kW microturbine and comprises a high-power Li-ion battery and a 100 kW SatCon power conditioning system (PCS). A one-line drawing of the complete system is shown in Fig. 1.

Fig. 2 shows the modular design of the Saft Li-ion battery. The battery has 11 individual Li-ion modules and 1 battery management module. Each module contains 12 series-connected Saft Li-ion VL30P cells plus module-level control electronics. The stored energy of the battery ranges from 1.67 to 14 kW h and it is designed to provide 100 kW of power for 1 min. The battery's operating voltage window is 515–405 V (dc). The typical operating mode is floating with occasional power pulse. The battery is designed to operate in a non-condensing environment with an estimated operating temperature range between −30 and 50 °C. The PCS hardware for the system is shown in Fig. 3. The rated output power of the PCS is 100 kW/100 kV A. It is designed to operate at 110% overload. The rated frequency and ac output voltage are 60 Hz and 480 V (ac), respectively. In line-link mode, the PCS operates within +10 to −12% of the rated voltage and within ±1% of the rated frequency. The PCS has 95% efficiency when calculated without the transformer and

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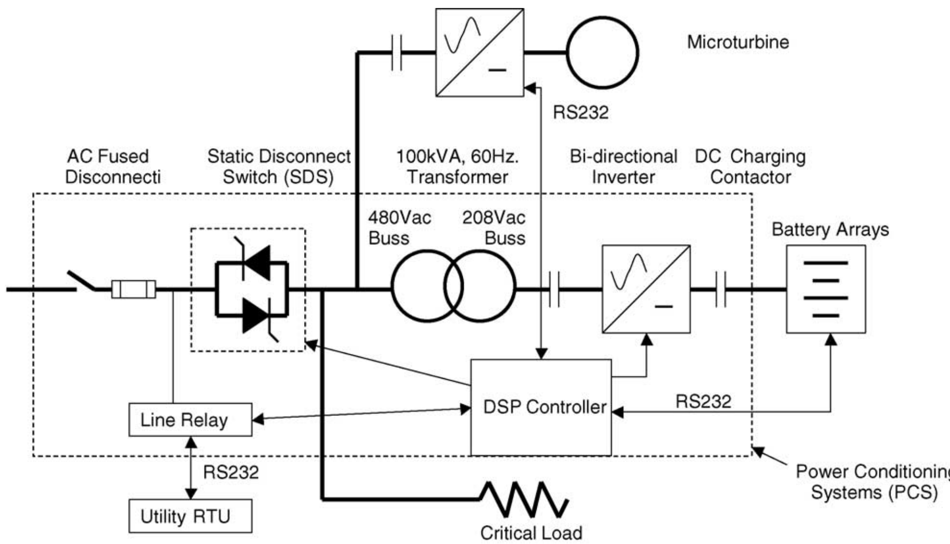

Fig. 1. One-line diagram of BESS.


Fig. 2. Li-ion Battery.

93% efficiency when transformer losses are included in the calculation. The power factor is 0.8 lead–0.8 lag.

Factory acceptance testing of both systems was performed by SatCon Power Systems (the PCS manufacturer) at their facility. The testing comprised the following three stages, each of which is described in more detail below: basic operational testing, functional testing and battery testing. Additional system demonstration testing is being conducted by two utilities.

1.1. Basic operational testing

A basic visual inspection was performed to check for loose parts, foreign material on the circuit boards, etc. The units' components and assembly were then inspected to verify that the units were assembled and labeled according to their specifications. The units' wiring was verified by comparing the as-built wiring to the specification drawings. Each unit was checked to ensure that upon application of 2000 V (ac) between the power circuit and the unit's cabinet, flashover did not occur. For each unit, the power supply was electrically isolated from the unit and checked to ensure that it was supplying power in the proper voltage range. The units' feedback signals (inverter output voltages, line voltage and current, inverter current phases, output current phases, etc.) were calibrated according to the appropriate specifications to ensure that input and output to the units were correct. Software trip level settings and trip response times were verified


Fig. 3. PCS hardware.

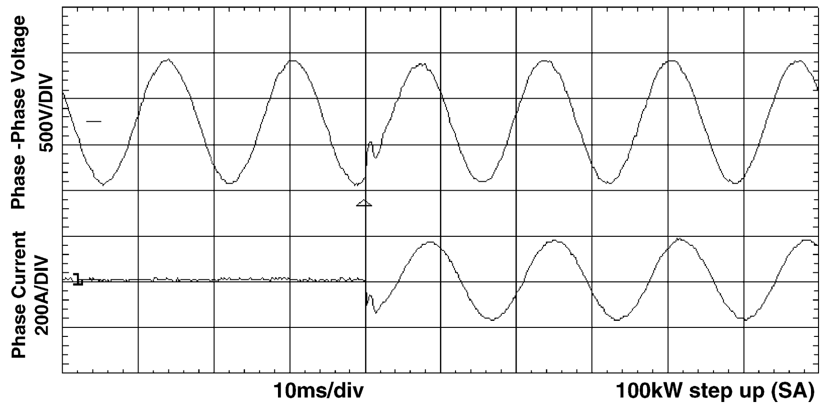

Fig. 4. Waveforms of load under stand-alone mode with 100 kW step up.

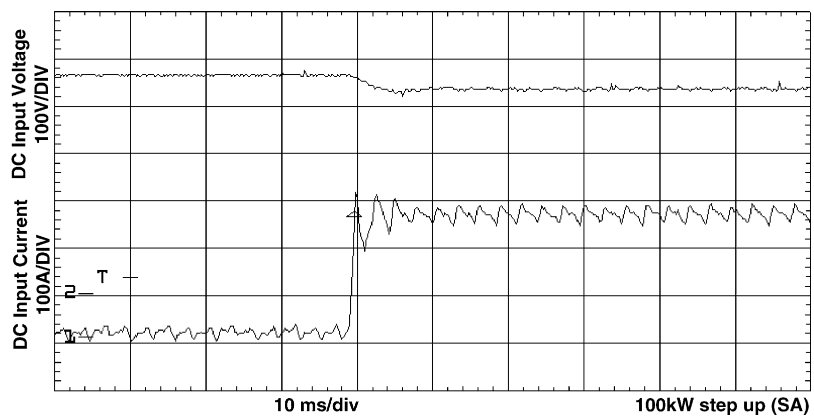

Fig. 5. Waveforms of dc input under stand-alone mode with 100 kW step up.

for conditions that would cause a PCS shutdown and for conditions that would cause the battery system to change from line-link operation to stand-alone operation. Faults and digital signals (grid line status, digital input and digital output) were simulated to ensure the proper fault response or operation.

1.2. Functional testing

The units were tested to ensure that they performed at the rated voltage and current in both stand-alone and line-link mode. Proper operation of the line protection relay was verified during line-link mode functional testing. Proper performance at the rated voltage and current during transfer between line-link and stand-alone operation was also verified during functional testing. The unit was further tested to ensure that it would properly control reactive power and control the charge/discharge of the battery.

During functional testing, dc input voltage was supplied by a 6 pulse rectifier and the PCS output was connected to a three-phase, 480 V grid. The critical load was simulated by connecting the PCS output to a three-phase resistive load with varying power levels (16.5, 33, 50, 66, 82 and 100 kW). Functional testing in stand-alone mode comprised several steps. For each unit, proper startup was verified by setting the load to 16.5 kW and the inverter outputs to 480 V. Each unit was then started with and without the load and proper output voltage was verified. Constant output voltage was verified for each unit by setting the load at 16.5 kW and the outputs at 480 V, starting the unit, varying the dc input voltage from 350 to 546 V (dc) and monitoring the output voltage. The ability of the units to vary the output voltage (from 0 to 480 V) with and without a 100 kW load was verified. The ability of each unit to maintain 480 V output voltage for step loads of 50 and 100 kW was verified (see Figs. 4 and 5 for sample waveforms). As can be seen in the figures, the output voltage is out of sync only momentarily as the transfer is made (the point at which the transfer occurred is indicated by an open arrow in each figure). Protection settings for stand-alone mode were verified for both units during this part of the testing.

Communications between the line protection relay and the battery energy storage system's control computer were verified and the line protection relay settings were set as appropriate. With the PCS shut down, the circuit to the line was closed with and without the 100 kW load. Specific trip levels were induced and the line protection relay tripped signal was verified for both units.

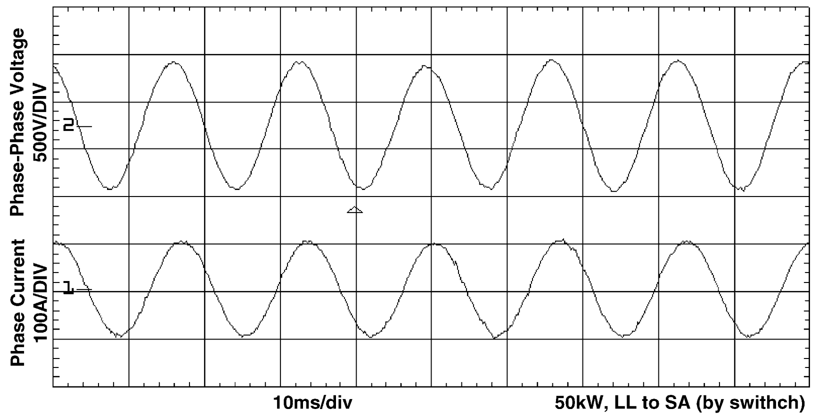

Fig. 6. Stand-alone to line-link automatic transfer with 100 kW load.

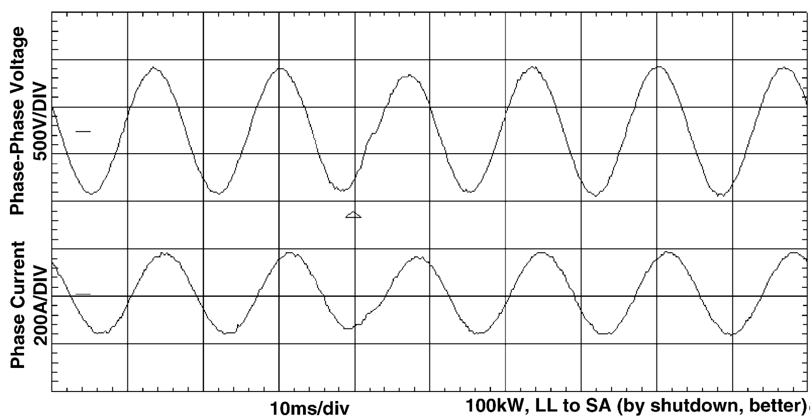

Fig. 7. Line-link to stand-alone transfer by grid shutdown with 100 kW load.

Transfer operations between line-link and stand-alone modes were tested under different loads. Manual transfer commands from line-link to stand-alone mode and vice versa were sent using both the system's control computer and the switch on the front of the units. Both units were also started in line-link mode with no problems. Automatic transfers between operating modes were verified for specified line over/under voltage, over/under frequency and over current conditions. Automatic transfers between modes were also verified for loss of grid power and return of grid power. Sample waveforms are shown in Figs. 6 and 7, the point at which the transfer occurred is indicated by an open arrow in each figure.

The units' ability to control reactive power in stand-alone and line-link modes and to control the charge and discharge of the battery energy storage system's Li-ion battery were verified. Heat testing was performed with the units in line-link discharge mode at 100% of their rated power for 2 h. The maximum temperatures for heat sinks, transformers, inductors, etc. were well within specified limits. For each unit, efficiencies were measured in stand-alone discharge and line-link modes at 50 and 100% of rated PCS power, average results are shown in Table 1. For each unit, the acoustical noise level on each of the unit's sides was measured and both units were within acceptable noise limits of <80 dB.

Table 1
PCS efficiencies

Load (%)	*P* (kW), dc	*P* (kW), ac	Efficiency (%)
Stand-alone mode			
50	52.4	49.1	93.6
100	107.5	100.5	93.5
Line-link mode			
50	53.5	50.0	93.4
100	107.5	100.0	93.0

1.3. Battery testing

Battery testing is the final stage of factory acceptance testing and parallels the functional testing procedure. During battery testing, the system's Li-ion battery was used as the dc source rather than a rectifier. As in the functional testing procedure, the PCS output was connected to a three-phase, 480 V grid. For this series of tests, the critical load was simulated by connecting the PCS output to a three-phase resistive load at three power levels (50, 75 and 100 kW).

Table 2
Battery status after discharge

Load (kW)	Discharge time	Cell V_{max} (V)	Cell V_{min} (V)	SOC (%)	Cell T_{max} (°C)	Stopped by alarm
50	14 min 34 s	3.12	2.48	3	32	Low cell V_{min}
75	10 min 10 s	3.13	2.48	3	51	Low cell V_{min}
100	3 min 40 s	3.38	3.35	71	55	Over temperature (55 °C)

For each unit, the battery's charge and discharge functions were tested. With each unit in line-link mode, the battery was charged to 98% and then discharged at 50 kW by controlling the ac output current. The test was repeated for discharge powers of 75 and 100 kW. Discharge stopped when any alarm came from the battery. Results of this testing were the same for both batteries and are shown in Table 2. Battery status before discharge was as follows: SOC = 98%, cell V_{max} = 3.898 V and cell V_{min}=3.883 V. To charge each battery from 3 to 98% SOC took about 25 min.

Battery discharge for 50 and 100 kW loads was also tested with the units in stand-alone mode. Discharge was stopped if any warning came from the battery. To verify the units' under voltage protection, the batteries were discharged (with the units in line-link mode) until the battery cell voltage was too low and the batteries stopped by themselves. For each unit, it was verified that upon battery shutdown, the battery contactors opened and the PCS was shutdown. Proper fault indications (battery fault and/or dc input under voltage fault) were also verified.

1.4. System testing

Both units were accepted and were sent to utility partners—Southern Company Services (SCS) of Birmingham, Alabama, and American Electric Power (AEP) of Columbus, Ohio—for demonstrations. The demonstration at SCS uses the BESS to supplement distributed generation (via microturbines) and to provide load following capability. The system was installed and commissioning tests were successfully completed. The system was run at its rated power level of 100 kW for 3 min, which exceeded the battery design requirements by a factor of 3. The system was available for ∼1200 h. Fig. 8 shows the preliminary test results. Characterization testing is continuing at the SCS laboratory. When the characterization is complete, SCS will find a customer site suitable for a field demonstration.

A second demonstration at American Electric Power uses the BESS as a UPS. The system was installed at AEP and successfully completed commissioning tests. Following commissioning, the system was available for 1146 h. Results of the preliminary testing are shown in Fig. 9. AEP is further characterizing the battery and based on the test results, they expect to find a customer site for a field demonstration. Please note that in Figs. 8 and 9, the data is provided in the original format given by each of the two utilities and, consequently, the line styles for voltage and load are different in each figure.

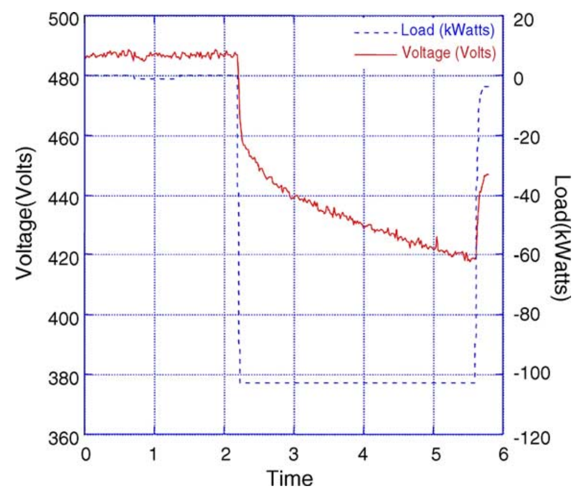

Fig. 8. Testing at SCS (time in minutes).

In conclusion, the design and development of two 100 kW/1 min Li-ion battery energy storage demonstration systems was successfully completed. The systems have been online at two utility test facilities for over 2400 h. After successful completion of the utilities' laboratory testing, both utilities will find customer sites suitable for deploying the systems in the field, where their performance will continue to be monitored.

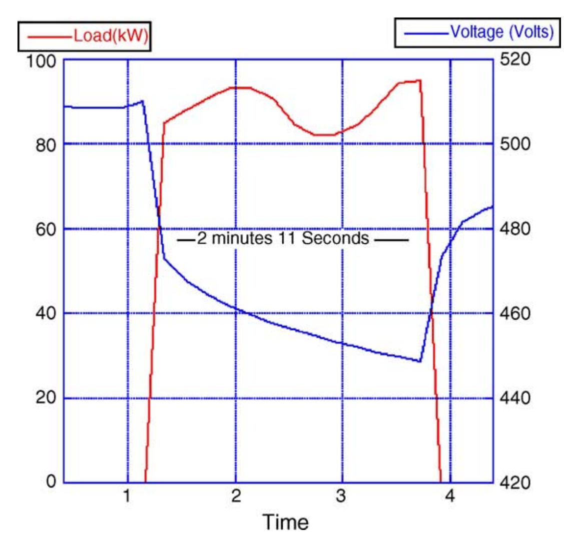

Fig. 9. Testing at AEP (time in minutes).

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