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Performance and Health Test Procedure for Grid Energy Storage Systems

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Performance and Health Test Procedure for Grid Energy Storage Systems

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***Abstract*— A test procedure to evaluate the performance and health of field installations of grid-connected battery energy storage systems (BESS) is described. Performance and health metrics captured in the procedures are: round-trip efficiency, standby losses, response time/accuracy, and useable energy/ state of charge at different discharge/charge rates over the system's lifetime. The procedures are divided into reference performance tests, which require the system to be put in a test mode and are to be conducted in intervals, and real-time monitoring tests, which collect data during normal operation without interruption. The procedures can be applied on a wide array of BESS with little modification and can thus support BESS operators in the management of BESS field installations with minimal interruption and expenditure. Simulated results based on a detailed system simulation of a prototype system are provided as guideline.**

Index Terms-- ***energy storage, energy efficiency, batteries, condition monitoring, system testing.***

I. Introduction

The large capital investment in grid-connected energy storage systems (ESS) motivates standard procedures measuring their performance. In addition to this initial performance characterization of an ESS, battery storage systems (BESS) require the tracking of the system's health in terms of capacity loss and resistance growth of the battery cells.

Protocols for the measurement of performance via duty cycles of specific applications, such as frequency regulation and peak shaving, are available for the initial measurements of the performance of ESS [1]. The protocols are designed to guide prospective system operators in the qualification process for the specific applications. IEEE recommended practices define technical parameters and requirements for various types of rechargeable energy storage systems, including electrochemical systems such as BESS, with the goal of defining a general approach to describing and comparing such systems [2]. Both approaches are described for general ESS and do not consider BESS-specific metrics in performance characterization or provide protocols for the tracking of the system's health. Test procedures specifically for batteries capture a wide array of battery performance and health metrics [3]. These tests capture the necessary battery metrics, but are so far designed for automotive batteries in laboratory settings and thus do not include the influence of the complete BESS installation and are not suitable for tests in field installations. To our knowledge, no standard test procedure currently exists specifically for field performance and health monitoring. Such a test procedure should be easily conducted in the field with a minimum of equipment and time but able to capture BESS-specific metrics.

Round-trip efficiency and useable energy are exemplary performance and health metrics. To measure such system parameters in a controlled procedure, reference performance tests (RPT) are defined to be conducted at intervals. To also measure parameters during normal systems operation, real-time monitoring tests (RTM), which collect data during normal use, are defined to capture the necessary data during operation.

The contributions of this paper are as follows: 1) definition of BESS-specific performance and health tracking parameters and their calculation (Section 2), 2) a description of the necessary system instrumentation and control (Section 3), 3) a protocol for the RPT (Section 4.A), 4) RTM measurements and calculations to track the system's metrics in operation mode (Section 4.B) and 5) Simulated results for a 192 kWh system as a guideline for expected results (Section 5) [4]. Section 6 presents the conclusions.

II. Performance and Health Metrics

For tracking performance and health of systems through the lifetime of field installation, parameters must be defined that quantify the system's performance from an operator's point of view. Measurement should begin before normal operation. Table I describes the parameters.

III. System Measurements & Control

A. Measurements

Fig. 1 provides a schematic of an ESS installation, with measurements needed for performance and health metrics.

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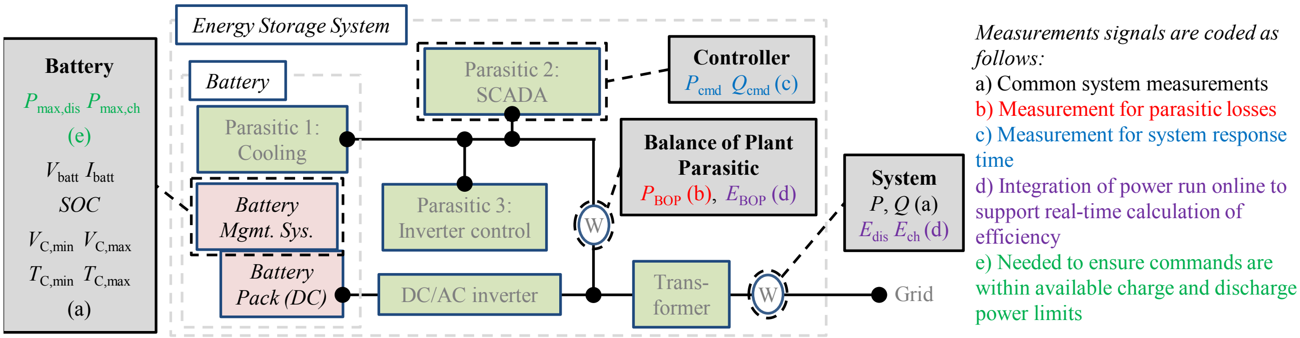

Figure 1. ESS schematic with required system measurements and controls.

TABLE I. PERFORMANCE AND HEALTH PARAMETERS.

	Metric	Unit	Description
Useable Energy & State of Charge	$E_{N,RPT}$	Wh	Energy – discharge energy measured during cycling at nominal power
	$E_{5h,RPT}$	Wh	Energy – discharge energy measured during cycling at C/5 power
	$SOC_{max,N,RPT}$ $SOC_{min,N,RPT}$	%	State-of-charge range capable of delivering nominal power
	$SOC_{max,5h,RPT}$ $SOC_{min,5h,RPT}$	%	State-of-charge range capable of delivering power at C/5 power
Round-trip Efficiency	$RTE_{N,RPT}$	%	Round trip efficiency - measured during cycling at nominal power
	$RTE_{5h,RPT}$	%	Round trip efficiency - measured during cycling at C/5 power
	RTE_{RTM}	%	Round trip efficiency – estimated based on normal operating data
Resp. Time & Accuracy	$t_{step,RPT}$	s	Step response time
	$Acc_{P,RPT}$ $Acc_{Q,RPT}$ $Acc_{S\ RPT}$ $Acc_{P,\ RTM}$ $Acc_{Q\ RTM}$	%	Response accuracy, calculated as root-mean-square error between actual response and command
Standby Losses	$dSOC_{BOP,RPT}$	%/d	Percentage of SOC (or energy) lost per day due to balance of plant (BOP) parasitics
	$dSOC_{selfDis,RPT}$	%/d	Percentage of SOC (or energy) lost per day due to battery self-discharge

To measure system response time and accuracy, it is necessary to record system commands for active power P_{cmd} and reactive power Q_{cmd}, in addition to their response, P and Q.

All parasitic losses on the ESS should be measured to quantify standby losses. If it is not possible to measure all parasitics at one convenient point as drawn in Figure 1, they should be instrumented individually and their losses added to estimate the total parasitic load, P_{BOP}.

Real-time round trip efficiency calculations require large numbers of high frequency (> 1 Hz) samples to resolve fast transitions in power. To avoid storing large amounts of sample data, the system monitor should integrate power in real time, E_{dis}, E_{Ch} and E_{BOP}, to be used in efficiency calculations. The integrated values can be stored at low resolution, e.g. once per minute, and still enable accurate efficiency calculation.

The weakest cell in a series string will limit the entire string's discharge/charge capacity. Tracking min./max. cell voltages and temperatures, $V_{c,min}$, $V_{c,max}$, $T_{c,min}$ and $T_{c,max}$, provides insight into impending cell failures that may require maintenance actions.

B. *Temperature Control*

Temperature strongly influences battery performance. Temperature variability from test-to-test will thus contribute to measurement uncertainty for the RPTs. Recommended temperature is 25 ± 2.5 °C. The thermal control should be used to maintain the battery at this desired test temperature. If the ESS installation has no active thermal control, tests should be run at consistent ambient temperature. Spring and fall seasons are preferable to summer and winter.

All temperatures that might influence performance or health metrics should be logged with the metrics. These include ambient; container; and maximum, minimum and average cell temperature, as available.

C. *System Control Modes*

In normal operation, the ESS may be controlled in a number of different modes with different objectives, e.g. target SOC, load smoothing or frequency regulation. For the purposes of this test, the ESS need be commanded in one of three modes: *Standby Mode*, wherein the system is at rest with battery contactors closed; *SOC Mode*, commanding the system to charge or discharge to a target SOC (%); *P/Q Mode*, commanding a combination of real and reactive power to the grid (W, VAr).

The battery self-discharge test further requires that the battery (DC) be disabled from the ESS system by opening contactors and that battery management system (BMS) be turned off to eliminate DC-side losses during an initial rest period. These two additional battery control modes are: *Contactors Open/Closed* and *BMS On/Off*.

D. *Required System Information*

Before tests are run, information listed in Table 2 should be collected for each ESS installation. This includes current, voltage and temperature operating limits. Test scripts should use a common set of code that enforces these cell and pack current/voltage/temperature operating limits (IVT-limits) to protect the battery. If any limit is exceeded, the test shall immediately be halted and the system placed in a safe mode. Test scripts shall also maintain power commands within limits reported by the BMS.

TABLE II. REQUIRED SYSTEM INFORMATION.

Description	Variable name (units)	Example Values
System nominal ratings		
System rated energy capacity	E_N (Wh)	100 kWh
System rated active power	P_N (W)	100 kW
System rated reactive power	Q_N (VAR)	20 kVAr
System rated apparent power	S_N (VA)	102 kVa
Configuration		
AC-side parasitic components	$P_{AC,parasitics}$	400 W
DC-side parasitic components	$P_{DC,parasitics}$	150 W
Operating limits		
Max. battery pack current	$I_{max,lim}$ (A)	250 A
Min. battery pack current	$I_{min,lim}$ (A)	–250 A
Max. battery pack voltage	$V_{max,lim}$ (V)	574 V
Min. battery pack voltage	$V_{min,lim}$ (V)	420 V
Max. battery cell voltage	$V_{c,min,lim}$ (V)	4.1 V
Min. battery cell voltage	$V_{c,max,lim}$ (V)	3.0 V
Max. battery cell temperature	$T_{c,max,lim}$ (°C)	50 °C
Min. battery cell temperature	$T_{c,min,lim}$ (°C)	–10 °C
Open-circuit voltage (V_{OC}) vs SOC look-up table, referred to below as SOC=f(V_{OC}) or V_{OC}=f(SOC) [a,b]		
Battery open-circuit voltage table [a]	$V_{oc,table}$ (V)	[420 484 …558 574]
Battery State of Charge table [a]	SOC_{table} (%)	[0 10 … 90 100]

a The open-circuit voltage vs SOC data is used in the calculation of Standby Losses due to battery self-discharge. The intent is to obtain more accurate measurement of self-discharge by calculating the SOC-loss rate from voltage loss rate rather than using the manufacturer's estimated SOC which may accumulate error over time. If this data is unavailable, the manufacturer's SOC-estimate may be used.

b Note that, in order to maintain a battery's performance and lifetime, manufacturers sometimes define a "useable" SOC window whose limits fall within a narrower window than the battery's full capability. The open-circuit voltage data vs SOC data should be consistent with manufacturer's SOC definition.

IV. TEST PROTOCOL

A. Reference Performance Tests

The RPT consists of four independent parts, 1-4. Total duration for the complete RPT is about 203 hours or 70 hours if RPT D (self-discharge) is not measured.

1) Useable energy and efficiency at nominal power

This first part of the test (RPT 1/4) measures useable battery capacity at the system's nominal power rating. Four full discharge/charge repetitions are run. The last three repetitions are used to calculate round-trip efficiency. End of charge and discharge SOC-points are logged when the system no longer can sustain the full nominal power rating. The procedure is as follows: 1) P/Q Mode: Discharge the battery at nominal power ($P_{cmd} = P_N$, $Q_{cmd} = 0$) until system available discharge power falls below nominal power ($P_{dis,limit} < P_N$) or until an IVT limit is reached; log the final SOC of this step as $SOC_{min,step1,repX}$. 2) P/Q Mode: Continue discharging following the system available discharge power limit ($P_{cmd} = P_{dis,limit}$, $Q_{cmd} = 0$) to 0% SOC or until an IVT limit is reached. 3) Standby Mode: Rest for 1 hour. 4) P/Q Mode: Charge the battery at nominal power ($P_{cmd} = –P_N$, $Q_{cmd} = 0$) until system available charge power falls below nominal power ($|P_{ch,limit}| < P_N$) or until a IVT limit is reached; log the final SOC of this step as $SOC_{max,step4,repX}$. 5) P/Q Mode: Continue charging following the system available charge power limit ($P_{cmd} = P_{ch,limit}$, $Q_{cmd} = 0$) to 100% SOC or until an IVT limit is reached. 6) Standby Mode: Rest 1 hour; log the final SOC of this step as $SOC_{end,step6,repX}$.

Repeat steps 1 to 6 for $X = 1 … 4$. Additionally, data logging is required during steps 1-6 and repetitions 1-4:

- Sum energy discharged ($P > 0$) during step X, repetition Y and log as $E_{dis,stepX,repY}$.
- Sum energy charged ($P < 0$) during step X, repetition Y and log as $E_{ch,stepX,repY}$.

Total energy available at nominal power will be calculated as the smallest of those measured over the final three repetitions of step 1:

$$E_{N,RPT} = \min(E_{dis,step1,rep2}, \ldots, E_{dis,step1,rep4}). \quad (1)$$

The minimum/maximum SOC at which the system can still be discharged/charged at full nominal power will be the greatest of those logged over the final three repetitions of step 1 respectively 4:

$$\begin{aligned} SOC_{min,N,RPT} &= \max(SOC_{min,step1,rep2}, \ldots, SOC_{min,step1,rep4}) \\ SOC_{max,N,RPT} &= \min(SOC_{max,step4,rep2}, \ldots, SOC_{max,step4,rep4}). \end{aligned} \quad (2)$$

The round-trip efficiency at nominal power will be calculated as the total energy discharged, divided by the total energy charged. Each of these totals is first calculated by summing the individual discharge/charge energies logged during steps $X = 1 … 6$, during the final three repetitions, $Y = 2 … 4$:

$$\begin{aligned} E_{dis,total} &= E_{dis,stepX,repY} \\ E_{ch,total} &= E_{ch,stepX,repY} \end{aligned} \quad (3)$$

$$RTE_{N,RPT} = E_{dis,total} / E_{ch,total}. \quad (4)$$

Accurate calculation of round-trip efficiency requires that the three discharge/charge repetitions start and end at the same SOC. This metric shall be declared invalid if $SOC_{end,step6,rep1}$ differs from $SOC_{end,step6,rep4}$ by more than 1%.

2) Useable energy and efficiency at C/5 power

This test (RPT 2/4) measures the useable battery capacity at the system's C/5 power rating. The test is identical to the RPT at nominal power, except that charge and discharge cycling is performed at the C/5 power rather than nominal power. The C/5 power is the nominal power that it would take to discharge ESS nominal energy over 5 hours. This test and following calculations shall be run in the same manner as the previous test (RPT 1/4), with the substitution of index $_{5h}$ for $_N$.

3) Response Time & Accuracy

This test (RPT 3/4) measures the system's ability to quickly and accurately respond to commanded values of real power, P_{cmd}, and reactive power, Q_{cmd}. Accuracy is calculated as a percentage of nominal power ratings. Step response time is evaluated by comparing actual achieved power to commanded power vs time. The test uses three power profile sequences:

- Active and reactive power step response test: 1) Command 10 seconds steps of ± 100%, respectively ± 25% in real power, with reactive power at zero. 2) Command 10 seconds steps of ± 100%, respectively ± 25% in reactive power, with real power at zero. Resulting profiles for $P_{\mathrm{rel,cmd}}$ and $Q_{\mathrm{rel,cmd}}$ are shown in Fig. 2.

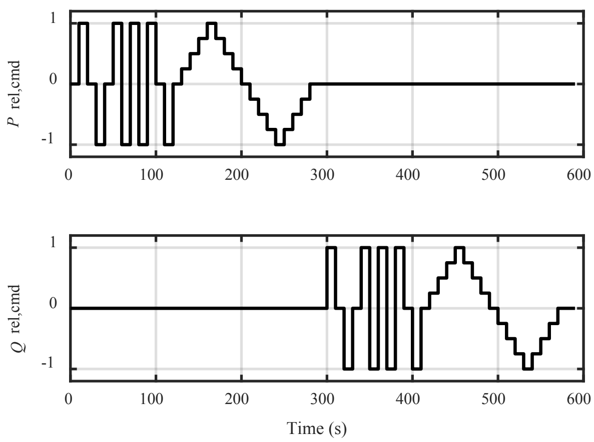

Figure 2. Active and reactive power step response test profile.

- Apparent power rating test at full active power: Command reactive power steps to reach full apparent power rating while system is at full nominal real power. Resulting profiles for $P_{\mathrm{rel,cmd}}$ and $Q_{\mathrm{rel,cmd}}$ are shown in Fig. 3.

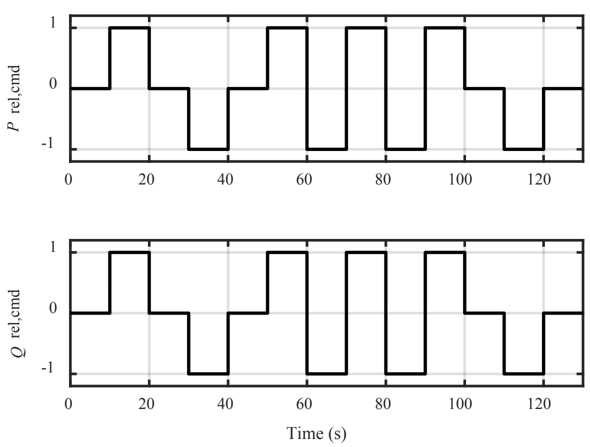

Figure 3. Apparent power rating at full reactive or active power test profile.

- Apparent power rating test at full reactive power: Command real power to reach full apparent power rating while system is at full nominal reactive power; Resulting profiles for $P_{\mathrm{rel,cmd}}$ and $Q_{\mathrm{rel,cmd}}$ are also shown in Fig. 3.

Prior to running the test, Q and P, to be used in steps 7 and 9 have to be determined:

- Reactive power needed to reach full apparent power rating while system is at full nominal real power:

$$Q_{\text{full S Rating at full P}} = (S_N{}^2 - P_N{}^2)^{1/2}. \quad (5)$$

- Real power needed to reach full apparent power rating while system is at full nominal reactive power:

$$P_{\text{full S Rating at full Q}} = (S_N{}^2 - Q_N{}^2)^{1/2}. \quad (6)$$

Test procedure is defined as following: 1) SOC Mode: Command battery to charge or discharge to 50% SOC. Continue until target SOC is achieved with < 1% error. 2) Standby Mode: Rest for 1 hour. 3) Ensure that the data collection system is configured to collect ≥1 Hz data. 4) Standby Mode: Rest for 20 seconds. 5) P/Q Mode: Run active and reactive power step response test profile by setting:

$$P_{\mathrm{cmd}}(t) = P_{\mathrm{rel,cmd}}(t) \cdot P_N$$
$$Q_{\mathrm{cmd}}(t) = Q_{\mathrm{rel,cmd}}(t) \cdot Q_N. \quad (7)$$

6) Standby Mode: Rest for 20 seconds. 7) P/Q Mode: Run apparent power rating test at full active power by setting:

$$P_{\mathrm{cmd}}(t) = P_{\mathrm{rel,cmd}}(t) \cdot P_N$$
$$Q_{\mathrm{cmd}}(t) = Q_{\mathrm{rel,cmd}} \cdot Q_{\text{full S Rating at full P}}. \quad (8)$$

8) Standby Mode: Rest for 20 seconds. 9) P/Q Mode: Run apparent power rating test at full reactive power by setting:

$$P_{\mathrm{cmd}}(t) = P_{\mathrm{rel,cmd}}(t) \cdot P_{\text{full S Rating at full Q}}$$
$$Q_{\mathrm{cmd}}(t) = Q_{\mathrm{rel,cmd}}(t) \cdot Q_{N}. \quad (9)$$

10) Standby Mode: Rest for 20 seconds.

Then, perform following calculations to find time history of P and Q error vs commanded values. Use data from step 5 to calculate the RMS accuracy in meeting real and reactive power commands:

$$Err_P = (P - P_{\mathrm{cmd}}) / P_N \cdot 100\%$$
$$Err_Q = (Q - Q_{\mathrm{cmd}}) / Q_N \cdot 100\% \quad (10)$$

$$Acc_{P,\mathrm{RPT}} = 100\% - (\mathrm{mean}(Err_P{}^2))^{1/2}$$
$$Acc_{Q,\mathrm{RPT}} = 100\% - (\mathrm{mean}(Err_Q{}^2))^{1/2} \quad (11)$$

Use data from steps 7 and 9 to calculate the RMS accuracy in meeting apparent power commands:

$$Err_S = ((P^2 + Q^2)^{1/2} - (P_{\mathrm{cmd}}{}^2 + Q_{\mathrm{cmd}}{}^2)^{1/2}) / S_N \cdot 100\% \quad (12)$$

$$Acc_{S,\mathrm{RPT}} = 100\% - (\mathrm{mean}(Err_S{}^2))^{1/2}. \quad (13)$$

Use data from step 5 to evaluate response time. Plot response vs time (P, Q vs t), command vs time (P_{cmd}, Q_{cmd} vs t), and error vs time (Err_P vs t). For each individual step change i in commanded value (P_{cmd}, Q_{cmd}), find the time it takes for the response error (Err_P, Err_Q) to settle below 5%. Record the values from successive step changes as $t_{\mathrm{step},P,1}$, $t_{\mathrm{step},P,2}$, ... $t_{\mathrm{step},P,i}$, ... $t_{\mathrm{step},P,N}$, respectively $t_{\mathrm{step},Q,1}$ ... $t_{\mathrm{step},Q,i}$, ... $t_{\mathrm{step},Q,N}$. Find the worst step response times:

$$t_{\mathrm{step},P,\max} = \max_{i=1:N} (t_{\mathrm{step},P,i})$$
$$t_{\mathrm{step},Q,\max} = \max_{i=1:N} (t_{\mathrm{step},Q,i}) \quad (14)$$

$$t_{\mathrm{step,RPT}} = \max(t_{\mathrm{step},P,\max}, t_{\mathrm{step},Q,\max}). \quad (15)$$

4) *Standby Losses Due to Battery Self Discharge*

This test (RPT 4/4) measures battery self-discharge due to battery internal electrochemical side reactions and battery DC-side parasitics. An AC-meter measurement is used to quantify standby losses caused by parasitics on the AC-side. Test procedure is as follows: 1) SOC Mode: Command battery to charge or discharge to 50% SOC; continue until target SOC is achieved with < 1% error. 2) Open contactors: Open battery contactors to prevent power flow to/from battery. 3) BMS off: Turn off BMS and any other loads on DC side of battery. 4) Rest for 12 hours. 5) BMS on: Turn on BMS and any other loads internal to the battery DC side; record starting voltage at beginning of step 5, $V_{OC,start}$, BMS-reported SOC at beginning of step 5 $SOC_{start,BMS,}$ standby starting time at end of step 5, $t_{start,}$ and maximum cell voltage difference in the pack $\Delta V_{c,start}$. 6) Standby Mode: Rest for 5 days. 7) BMS off: Turn off BMS to clear BMS previous SOC estimate and rest for 10 seconds. 8) BMS on: Turn on BMS. Record ending voltage at beginning of step 8, $V_{OC,end}$, BMS-reported SOC at beginning of step 8, $SOC_{end,BMS,}$ standby ending time, $t_{end,}$ and cell voltage difference in the pack $\Delta V_{c,end.}$. Note the cell number and location of the cell with voltage $V_{c,min}$. Convert starting and ending voltage readings to SOC estimates using lookup table:

$$SOC_{start,VOC} = f(V_{OC,start})$$
$$SOC_{end,VOC} = f(V_{OC,end}) \quad (16)$$

Calculate the loss rate per day as:

$$dSOC_{selfDis,RPT} = (SOC_{end,VOC} - SOC_{start,VOC}) / (t_{end} - t_{start}) \quad (17)$$

Calculate rate again, using the BMS-reported values of SOC:

$$dSOC_{selfDis,RPT,BMS} = (SOC_{end,BMS} - SOC_{start,BMS}) / (t_{end} - t_{start}) \quad (18)$$

If the values differ by more than 2%, the metric shall be declared invalid and sources of error should be investigated.

B. Real Time Monitoring

This section describes data monitoring calculations to be performed based on measurements taken during normal operation of the system. Unlike to the RPT, no interruption of normal operation is necessary. To facilitate the RTM calculations, the data collection system should be configured to totalize real power charge and discharge from the energy storage system: E_{BOP}, E_{ch}, E_{dis} and

$$Err_{sumSq,P} = Err_{sumSq,P} + (P - P_{cmd})^2$$
$$Err_{sumSq,Q} = Err_{sumSq,Q} + (Q - Q_{cmd})^2 \quad (19)$$

The number of above calculations is counted in $N_{ErrSumSq}$. The variables are saved from the higher resolution data to reduce size, e.g. once a minute. At the performance tracking interval, e.g. monthly, these metrics are updated. All above measured and calculated data shall be logged over the time interval and be used for the calculations. With the starting and ending SOC, SOC_{start} and SOC_{end}, a correction for the efficiency is used:

$$RTE_{RTM} = (\mathrm{sum}(E_{dis}) + (E_N \cdot (SOC_{start} - SOC_{end}))) / \mathrm{sum}(E_{ch}) \quad (20)$$

If the SOC correction is more than 2% of sum(E_{dis}), then the correction influences the measurement excessively and the metric is declared invalid. Response accuracy is calculated as:

$$A_{P,RTM} = 100\% \cdot (1 - \{[\mathrm{sum}(Err_{sumSq,P}) / \mathrm{sum}(N_{ErrSumSq})]^{1/2} / P_N\})$$
$$A_{Q,RTM} = 100\% \cdot (1 - \{[\mathrm{sum}(Err_{sumSq,Q}) / \mathrm{sum}(N_{ErrSumSq})]^{1/2} / Q_N\}) \quad (21)$$

With the duration of the tracking interval, $t_{intervall}$, in units of days, the equivalent SOC lost through balance of plant parasitic losses per day is:

$$dSOC_{BOP,RTM} = \mathrm{sum}(E_{BOP}) / t_{intervall} / E_N. \quad (22)$$

V. Simulated Results for Reference

Guidelines values based on a 192 kWh prototype system [4], are simulated. For calculation of RTE_{RTM}, a two months simulation was performed for the grid application *frequency regulation* in Germany. $t_{step,RPT}$ was measured in Hardware-in-Loop tests at NREL and was used for calculation of the accuracies *Acc* by assuming ideal control after $t_{step,RPT}$.

TABLE III. Model-based Guideline Values

Metric	Units	Metric	Units
$E_{N,RPT}$	164 kWh	$t_{step,RPT}$	17e-3 s (~ 1/f)
$E_{5h,RPT}$	177 kWh	$Acc_{P,RPT}$	~ 98%
$SOC_{max,N,RPT}$	99.6 %	$Acc_{Q,RPT}$	~ 98%
$SOC_{min,N,RPT}$	7.9 %	$Acc_{S\ RPT}$	~ 98%
$SOC_{max,5h,RPT}$	99.5 %	$Acc_{P,\ RTM}$	> 99 %
$SOC_{min,5h,RPT}$	3.4 %	$Acc_{Q\ RTM}$	> 99 %
$RTE_{N,RPT}$	80.3 %	$dSOC_{BOP,RPT}$	15.8 %/d
$RTE_{5h,RPT}$	81.4 %	$dSOC_{selfDis,RPT}$	0.01 %/d
RTE_{RTM}	70 %		

VI. Conclusions and Future Work

The described test procedure provides reference performance tests to track BESS health over their lifetime in field installation and monitoring of BESS performance during normal operation. Simulated results are provided as guideline.

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