



IEEE Guide for Using IEEE Std 1547™ for Interconnection of Energy Storage Distributed Energy Resources with Electric Power Systems

IEEE SA Standards Board

Developed by the IEEE Standards Coordinating Committee 21
on Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage

IEEE Std 1547.9™-2022

STANDARDS

IEEE Guide for Using IEEE Std 1547™ for Interconnection of Energy Storage Distributed Energy Resources with Electric Power Systems

Developed by the

**IEEE Standards Coordinating Committee 21 on Fuel Cells, Photovoltaics,
Dispersed Generation, and Energy Storage**

Approved 16 June 2022

IEEE SA Standards Board

Abstract: Application of IEEE Std 1547-2018 to the interconnection of energy storage distributed energy resources (ES DER) to electric power systems (EPSs) is described in this guide. Along with examples of such interconnection, guidance on prudent and technically sound approaches to these interconnections is also given. The guide's scope includes ES DER that are capable of exporting active power to an EPS. The guide also considers energy storage-related topics that are not currently addressed or fully covered in IEEE Std 1547-2018 and sets a basis for future development of industry best practices for ES DER-specific interconnection requirements that could be considered in future revisions of IEEE Std 1547.

Keywords: active power export, bidirectional, black start participation, charging, discharging, distributed energy resources, electric power systems, energy storage, energy storage distributed energy resources, ES DER response prioritization, exemptions, fast frequency response, frequency droop response, IEEE 1547™, IEEE 1547.9™, inertial response, interconnection requirements and specifications, interoperability, islanding, monitoring, operational capacity, operational model, operational state of charge, reactive power capability, ride-through, safety, secondary networks, state of charge, testing, use cases, vehicle-to-grid

The Institute of Electrical and Electronics Engineers, Inc.
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PDF: ISBN 978-1-5044-8858-7 STD25527
Print: ISBN 978-1-5044-8859-4 STDPD25527

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Introduction

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Publication	Relationship to IEEE Std 1547.9
IEEE Std 1547	IEEE Std 1547 is the base standard for the family. Although this base standard does apply to energy storage (ES), certain ES-specific issues benefit from additional clarification, and a few topics of importance to ES were not specifically addressed in the base standard. The purpose of IEEE Std 1547.9 is to bolster and clarify the ES-specific content of IEEE Std 1547 and to provide guidance on certain ES issues that are not addressed in the base standard.
IEEE Std 1547.1™	IEEE Std 1547.1 is the next standard in the family and describes the tests to be conducted for compliance with the requirements of IEEE Std 1547. IEEE Std 1547.9 provides a limited amount of guidance on certain ES-specific aspects of the tests defined in IEEE Std 1547.1.
IEEE Std 1547.2™ [B17]	IEEE Std 1547.2 is a guide for applying IEEE Std 1547 and IEEE Std 1547.1 and includes guidance that applies to all distributed energy resources (DER), including ES. It is thus more general than IEEE Std 1547.9, which is intended to complement IEEE Std 1547.2 by focusing strictly on topics specific to ES.
IEEE Std 1547.3™	IEEE Std 1547.3 is a guide that discusses cyber security requirements for DERs. IEEE Std 1547.9 does not identify any security issues specific to energy storage DER (ES DER); therefore, parties interested in cyber security should review the guidance in IEEE Std 1547.3.
IEEE Std 1547.4™ [B18]	IEEE Std 1547.4 is a guide for the design, operation, and integration of what IEEE Std 1547 calls <i>intentionally islanded systems (IISs)</i> . IEEE Std 1547.9 does not directly reference this guide and instead refers only to the IIS subclauses of IEEE Std 1547.
IEEE Std 1547.6™ [B19]	IEEE Std 1547.6 is a recommended practice dealing with interconnection of DERs with low-voltage grid and spot secondary networks. Clause 9 of IEEE Std 1547.9 references IEEE Std 1547.6.
IEEE Std 1547.7™ [B20]	IEEE Std 1547.7 is a guide to conducting Area EPS impact studies prior to DER interconnections. IEEE Std 1547.9 does not refer to IEEE Std 1547.7.

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1. Overview

1.1 Scope

This guide provides information on, and examples of, how to apply IEEE Std 1547-2018 for the interconnection of energy storage distributed energy resources (ES DER). The guide's scope includes ES DER that are interfaced to an electric power system (EPS) via a power electronic interface (commonly referred to as a converter, inverter, or bidirectional inverter), capable of bidirectional active and reactive power flow, and capable of exporting active power to the EPS. The document also provides guidance for non-exporting ES DER that could have power system impacts, e.g., modulating load proportionally to system frequency, such as some uninterruptible power supply (UPS) systems and electric vehicle (EV) chargers.

1.2 Purpose

The purpose of this guide is to provide guidance on prudent and technically sound approaches to interconnection of ES DER to power systems. This guide also considers ES-related topics not currently addressed or fully covered in IEEE Std 1547-2018:

- Guidance for interconnection of EV charging stations with the ability for exporting (i.e., bidirectional active or reactive power exchange) to the connected power system (i.e., vehicle-to-grid [V2G]).
- Guidance on when ES is or is not within the scope of IEEE Std 1547-2018. For example, this guide expands on the exceptions for systems that are non-exporting, e.g., UPS that receive energy from the grid, but use it only for premise loads while off-grid.
- Guidance on charging and generation constraints to minimize negative impacts in the distribution system.

This guide also sets a basis for future development of industry best practices for ES DER-specific interconnection requirements that could be considered in future revisions of IEEE Std 1547.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{1, 2}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

1.4 Conventions in this guide

To facilitate cross-referencing, the numbering and titles of many subclauses in this guide parallel those in the guide's base document, IEEE Std 1547-2018. When a subclause number and title in this guide duplicate a subclause number and title in the base document, that fact is indicated by appending [1547] to the subclause title. Such subclause headings are written in blue text. Note that the text in the guide does not duplicate the base document; it is new guidance. Also, cross references in this guide to clauses and subclauses in the base document are followed by the same indicator and are also written in blue text, e.g., "the requirements in 8.2 [1547]." When a direct quote or extract from the base document is shown in this guide, the extract is placed on a blue-colored background as done in the introduction to Annex D.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std 1547™-2018, IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces.^{3, 4}

IEEE Std 1547.1™-2020, IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Energy Resources with Electric Power Systems and Associated Interfaces.

IEEE Std 1547.3™, IEEE Guide for Monitoring, Information Exchange, and Control of Distributed Resources Interconnected with Electric Power Systems.

¹ The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

² The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is used only in statements of fact.

³ The IEEE standards or products referred to in Clause 2 are trademarks owned by The Institute of Electrical and Electronics Engineers, Incorporated.

⁴ IEEE publications are available from The Institute of Electrical and Electronics Engineers (<https://standards.ieee.org>).

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.⁵

capable of exporting active power: A phrase meaning any energy storage distributed energy resource (ES DER) capable of serving load in parallel with the area electric power system (Area EPS).

NOTE—The following are examples of systems that ARE NOT capable of exporting active power: (1) an uninterruptible power supply (UPS) that never exports active power to the Local EPS and (2) a unidirectional electric vehicle (EV) battery charger that only imports and never exports active power. See Annex B. The following are examples of ES DERs that ARE capable of exporting active power: (1) a photovoltaic energy storage system (PV + ESS) in which the system is controlled to maintain zero export at the point of common coupling and (2) a vehicle-to-grid (V2G) EV charger that exports to the grid based on market pricing signals. See Annex B.

charging: An energy storage distributed energy resource (ES DER) importing active power from the electric power system (EPS).

discharging: An energy storage distributed energy resource (ES DER) exporting active power to the electric power system (EPS).

energy storage distributed energy resource (ES DER): A DER capable of receiving electric energy from an electric power system (EPS) and storing it for later injection of electricity back into the EPS, regardless of size or storage medium.⁶ *Syn:* **energy storage system (ESS); electric storage resource.**

operational capacity: The estimated energy that an energy storage system can provide on discharge, subject to operational constraints. *See also:* **operational state of charge; state of charge.**

NOTE—Examples of factors influencing operational capacity include rated energy, state of health, discharge rate, temperature, and usable state-of-charge range.

operational state of charge: The usable energy stored in an energy storage system as a proportion of the operational capacity, expressed as a percentage. *See also:* **operational capacity; state of charge.**

state of charge (SoC): The amount of energy stored in an energy storage system in proportion to the limit on the amount of energy that can be stored, typically expressed as a percentage.^{6, 7}

3.2 Acronyms and abbreviations

AGC	automatic generation control
AHJ	authority having jurisdiction
BPS	bulk power system
DCI	dynamically controlled inverter
DER	distributed energy resources
DNP	Distributed Network Protocol
EPS	electric power system
ES	energy storage

⁵ *IEEE Standards Dictionary Online* is available at <https://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

⁶ Adapted from FERC Order 841 [B10].

⁷ There is a considerable difference between the FERC definition of state of charge and the definition of state of charge typically used by energy storage manufacturers. This topic is discussed further in Clause 4.

ESS	energy storage system
EUT	equipment under test
EV	electric vehicle
EVSE	electric vehicle supply equipment
FFR	fast frequency response
IFC	International Fire Code
ISO	independent system operator
NP	network protector
PCC	point of common coupling
PoC	point of DER connection
pu	per unit
PV	photovoltaic
ROCOF	rate of change of frequency
RPA	reference point of applicability
RTO	regional transmission organization
SoC	state of charge
TRD	total rated-current distortion
UPS	uninterruptible power supply
V2G	vehicle-to-grid

4. General interconnection technical specifications and performance requirements [1547]

4.1 Introduction [1547]

IEEE Std 1547-2018 describes the requirements for interconnection of distributed energy resources (DER) which includes ES DER. The definition of DER from the standard states “DER includes both generators and energy storage technologies capable of exporting active power to an [electric power system (EPS)]. Given that ES DER are “capable of” exporting active power to an EPS, they therefore are within the scope of IEEE Std 1547-2018 and importantly, whether they are charging or discharging active power or injecting or absorbing reactive power, their interconnection characteristics are still governed by the standard.

The standard does not describe in detail the multitude of connection locations and operating modes related to storage. For example, energy storage being capable of bidirectional flow of both active and reactive power poses distinct challenges (and opportunities) as compared to solar, wind, or rotating generators with unidirectional active power flow.

Other considerations, such as safety switches, point of interconnection, and reference point of applicability can all vary by project and by the requirements of customers, authorities having jurisdiction (AHJs), and utilities.

Clause 4 of this guide is intended to guide the reader about what these different circumstances are, what makes each one unique, and what additional consideration may be given.

4.2 Reference points of applicability (RPA) [1547]

Subclause 4.2 [1547] applies to ES DER without further guidance.

4.3 Applicable voltages [1547]

Subclause 4.3 [1547] applies to ES DER without further guidance.

4.4 Measurement accuracy [1547]

4.4.1 Background

Energy storage poses some unique challenges regarding measurement accuracy, partially because energy storage introduces parameters not encountered in non-storage DER. For example, an important aspect of storage addresses “how much energy is stored?” This is not an issue for solar photovoltaic (PV), or rotating machines where the issue is about how much power is being produced, not how much energy is available for production, or even how much capacity is available for charging.

These questions arise for battery energy storage, flywheels, capacitors, compressed air, thermal storage, and all forms of storage so the units may be in kWh, Ah, kJ, or others; and IEEE Std 1547-2018 does not define the measurement accuracy for these quantities. However, IEEE Std 1547-2018 requires reporting of the operational state of charge of an energy storage type DER. Operational state of charge is an estimated quantity related to the degree to which an energy storage medium is charged relative to its operational capacity. As operational state of charge is expressed as a percentage of operational capacity, it can be difficult to interpret on its own. To avoid confusion, it is recommended that operational capacity, while not required by IEEE Std 1547-2018, be provided wherever operational state of charge is reported. A detailed discussion of the meaning and common usage of the term *state of charge* is included in 4.4.2. The recommendations in this subclause are in addition to the requirements specified in 4.4 [1547]. See Table 1.

Table 1—Energy storage minimum calculation resolution recommendations for manufacturers

Parameter	Steady-state measurements		
	Minimum calculation resolution	Measurement window	Range
Operational state of charge ^a	1% increments	1 s	1% to 100%
Operational capacity ^b	Increments of 0.5% of rated energy	1 s	≥ 0.0 kWh

^a Operational state of charge is expressed as a percentage of operational capacity. No measurement accuracy requirement is specified as there may not exist an underlying ground truth from which it can be calculated. Although increments less than the minimum resolution of 1% may not be meaningful, 0.1% increments may yield smoother control for systems that use operational state of charge as a state variable.

^b Operational capacity should be reported in Wh, kWh, or MWh regardless of storage type and can change as a result of operational conditions such as rate, temperature, future charge and discharge schedules, or if subsystems are undergoing maintenance. No measurement accuracy requirement is specified as there may not exist an underlying ground truth from which it can be calculated. Instead, a resolution of 0.5% of rated energy is recommended for interoperability and smoothness of control systems that use it as a state variable.

It should be noted that operational state of charge and operational capacity are the minimum recommended set of additional values that may be provided for purposes of interoperability. Additional measurements and calculations can be used to improve operational performance, extend operational life, and for a broad range of other uses. An extended set of operational model parameters is provided in 4.4.3 to enable more accurate state forecasting and better performance with feedback control.

4.4.2 State of charge

The term *state of charge* was originally developed to apply to battery cells but has been adopted for use for other types of energy storage. Electrochemically, a battery cell's state of charge is a function of the concentration of the limiting active ionic materials associated with the chemical reactions at the electrodes (see Plett [B42]). This is because these concentrations are directly related to the number of electrons that have been exchanged through the electrodes, electrolyte, and separator ("charge"). This physical association breaks down when applied to battery strings as in the thought experiment shown in Figure 1 (see Rosewater et al. [B43]). Example (a) represents two series-connected cells at different states of charge, while example (b) represents several parallel strings at the same state of charge, but with one string out of service. Similarly, non-electrochemical energy storage technologies do not store "charge" so much as they convert electrical energy into a form of durable potential energy (e.g., kinetic, gravitational, magnetic, thermal) for later use.

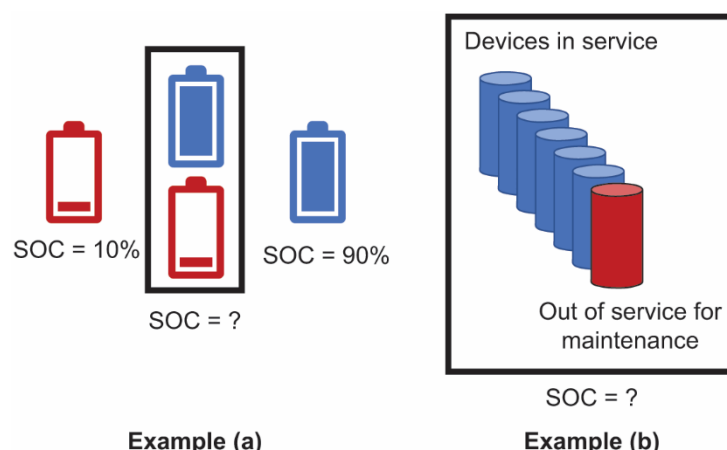


Figure 1—Thought experiment demonstrating how the electrochemical definition of the state of charge of a battery loses physical meaning when applied to strings

Despite this, state of charge is a useful variable for decision making by operators and control systems. Power system operators and other energy storage users often conceptualize state of charge as the percentage of remaining energy in a system. Currently, the Federal Energy Regulatory Commission (FERC) defines state of charge as: "The amount of energy stored in proportion to the limit on the amount of energy that can be stored, typically expressed as a percentage" (see FERC Order 841 [B10]). While intuitive and consistent with the state of charge reported by battery management systems, this definition can lead to confusion and inaccurate assumptions because of operational constraints that may be imposed.

The base standard uses the term *operational state of charge*, which combines state of charge with other relevant operational parameters. Understanding how this value is calculated is important for using it effectively. Figure 2 shows how operational state of charge is calculated, along with other quantities and operational model parameters, regardless of technology. There are four primary elements of this process: the energy storage medium, the physical model, the operational model, and the operational system. The output of this process is the operational state of charge and operational capacity (see Clause 3 for definitions) that are consistent with the intuitive definition of state of charge (i.e., the percentage of the energy capacity available) as well as the numerous assumptions and caveats used to calculate these quantities.

- a) **Energy storage medium:** This is whatever physical materials or containers are used to store energy for later conversion to useful energy. Examples include an electrochemical cell, a flywheel, a pressure vessel, a raised weight, or a volume of material used to store thermal energy. The state of energy in this medium is a physical quantity, such as the concentration of lithium ions in the anode of a battery cell, and it is subject to maximum and minimum limits based on material properties, including aging. A range of physical measurements can be taken to estimate the state of energy, such as the voltage of a battery or the rotation speed of a flywheel.

- b) **Physical model:** Within a device management system (e.g., battery management system) there is a model of the physical dynamics of the energy storage medium. This model interprets measurements of quantities such as voltage, speed, or pressure, compares these measurements to material limits, and provides an estimate of raw state of charge. Physical models can be extremely simple (e.g., a flywheel's speed provides a measure of its stored kinetic energy) or extremely complex (e.g., a battery cell's potential energy is proportional to the average chemical concentration over each electrode). In contrast to the operational state of charge, the raw state of charge reported by a device management system does not necessarily reflect the energy available for charge or discharge to the Area EPS. Instead, this quantity should be interpreted as an estimate of the state of potential energy compared to the maximum and minimum material limits of the energy storage medium. Physical models can also be used for state prediction or control.
- c) **Operational model:** As the raw state of charge reported by the device management system may not be useful on its own for making operational decisions, the operational model incorporates non-physical constraints to provide an operational state of charge to the user. Often a subprocess of a system/fleet controller, the operational model accounts for, among other factors, the total number of devices in service and any contractual obligations. If several devices in a system are out of service (e.g., 3 out of 30 racks in a battery system), then the operational energy reported by the fleet controller will reflect only the remaining devices. Similarly, if some proportion of a device's energy is reserved for providing backup power to a local load, then the operational energy will be limited. The operational model also can incorporate operational limits and aggregation of multi-use or "stacked" storage applications under various contractual obligations to provide the operator with estimates of total operational state of charge and aggregate capacity. Operational state of charge is therefore greatly abstracted from the state of potential energy in any one physical medium. The operational model can also report the model parameters it is using in its calculations, including the current energy capacity, efficiency, and power limits.
- d) **Operational system:** The function of any stationary energy storage device or fleet is to move energy through time, storing it when it is available or perhaps plentiful to supply it when it is absent or scarce. The operational system is an abstracted energy storage system that performs this function for the EPS that it is connected to, supplying energy services agnostic of whatever medium or models underlie its functionality. The layers of abstraction allow grid operators and other users to make use of the system's capabilities without needing to know every detail of the energy storage devices that are aggregated within it. Ideally, the operational system works according to our simplified expectation of how energy storage should work, like a gas tank for energy. This simplified understanding is good enough for many grid services, but the loss of detail can still lead to suboptimal operation or inaccurate estimates of performance.

An example can be used to explain the flow diagram in Figure 2. In a battery ES DER, the energy storage medium is a parallel and series combination of battery cells. Maximum and minimum operational states are defined using the open-circuit voltage representing the saturation or depletion of active material in the highest charged cell and lowest charged cell, respectively. The battery management system takes physical measurements of voltage, current, and temperature from the cells and interprets them using a physical model to estimate raw state of charge. As there may be many strings of battery cells within a single system, the raw state of charge estimates from each string are combined and aggregated using an operational model. The operational model also incorporates operational limits and contractual obligations to provide the user with estimates of operational state of charge and capacity. Both the physical model and operational model can also be used for state forecasting, performance prediction, and/or control design. While physical models are typically more accurate, they do not reflect operational factors. Operational models are more complete and can be used for controlling large and diverse fleets of ES DERs.

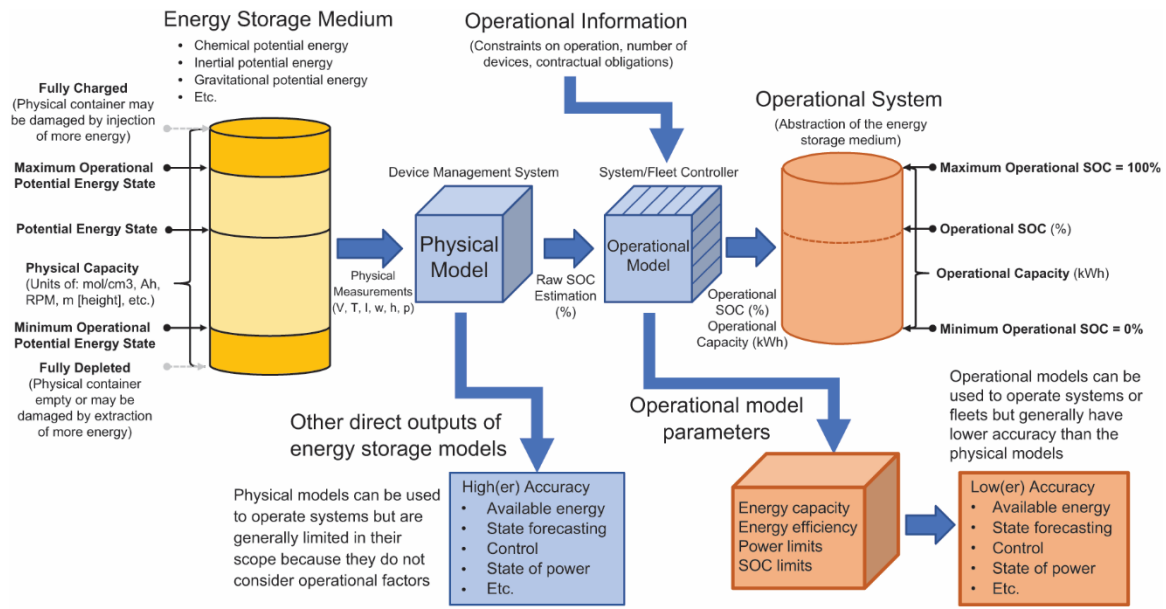


Figure 2—Illustration of the process used to calculate operational state of charge

4.4.3 Operational model parameters

While operational state of charge and capacity are important quantities, they cannot be used on their own to forecast states or to perform automated control. To accomplish these tasks, ES DERs may provide users with the parameters of a simplified operational system model. The list of operational model parameters is given in Table 2. These model parameters can be updated in real time based on the current operational state of charge, the number of systems/devices in service, the distribution of device-level states of charge along with any other factors that affect performance such as temperature or state of health (SOH). If the operational system has short-term ratings for charge or discharge power, then the associated parameters in Table 2 should be included.

Table 2—Operational model parameters

Model parameter	Common symbol ^b	Units	Minimum resolution	Uncertainty (optional) ^c
Operational state of charge	ζ	%	1% ^d	Report 95% confidence interval
Operational capacity	C_{OP}	Wh, kWh, or MWh	Increments of 0.5% of rated energy	Report 95% confidence interval
Operational round-trip efficiency	η	%	0.1%	Report 95% confidence interval
Operational maximum discharge power	$P_{\max-dis}$	W, kW, or MW	Increments of 0.5% of rated power	n/a
Operational maximum charge power	$P_{\max-cha}$	W, kW, or MW	Increments of 0.5% of rated power	n/a
Operational maximum state of charge (100% by definition)		%	n/a	n/a
Operational minimum state of charge (0% by definition)		%	n/a	n/a
Operational discharge derating slope	m_{dis}	W, kW, or MW/%	Increments of 0.5% of rated power/%	n/a
Operational discharge derating intercept power	b_{dis}	W, kW, or MW	Increments of 0.5% of rated power	Report 95% confidence interval
Operational discharge derating intercept state of charge	ζ_{dis}	%	1%	n/a
Operational charge derating slope	m_{cha}	W, kW, or MW/%	Increments of 0.5% of rated power/%	n/a
Operational charge derating intercept power	b_{cha}	W, kW, or MW	Increments of 0.5% of rated power	Report 95% confidence interval
Operational charge derating intercept state of charge	ζ_{cha}	%	1%	n/a
Discharge Ramp Rate	dr_{dis}	W, kW, or MW per second	Increments of 0.5% of rated power per second	n/a
Charge Ramp Rate	dr_{cha}	W, kW, or MW per second	Increments of 0.5% of rated power per second	n/a
Operational short-term max discharge power ^a	$P_{temp-dis}$	W, kW, or MW	Increments of 0.5% of rated power	n/a
Operational short-term max discharge power duration ^a	$t_{temp-dis}$	seconds	1 second	Report 95% confidence interval
Operational short-term discharge derating slope ^a	$m_{temp-dis}$	W, kW, or MW/%	Increments of 0.5% of rated power/%	n/a
Operational short-term discharge derating intercept state of charge ^a	$\zeta_{temp-dis}$	%	1%	n/a
Operational short-term max charge power ^a	$P_{temp-cha}$	W, kW, or MW	Increments of 0.5% of rated power	n/a
Operational short-term max charge power duration ^a	$t_{temp-cha}$	seconds	1 second	Report 95% confidence interval

Table 2—Operational model parameters (continued)

Model parameter	Common symbol ^b	Units	Minimum resolution	Uncertainty (optional) ^c
Operational short-term charge derating slope ^a	$m_{\text{temp-cha}}$	W, kW, or MW/%	Increments of 0.5% of rated power/%	n/a
Operational short-term charge derating intercept state of charge ^a	$\varsigma_{\text{temp-cha}}$	%	1%	n/a

^a Short-term parameters may be included in the operational model if and only if the operational system has short-term performance limits that exceed steady-state performance limits. Short-term parameters capture the duration and magnitude that a system can exceed its normal (steady state) limits on charge or discharge power. These are often a result of thermal limits on heat-generating components, rather than energy capacity limits on the storage medium.

^b Common symbols are used here for reference in equations to follow and are not intended to be normative.

^c Reporting model uncertainty can be useful in risk-averse or robust control applications.

^d Resolution of state of charge can impact dispatch control performance. In applications where state of charge changes quickly in response to dispatch signals, use of 0.1% increments may yield smoother control.

The differential equation relating charge and discharge power to expected changes in state of charge is shown in Equation (1). Note that if operational capacity is ever zero (e.g., because of maintenance or thermal conditions) then the operational state of charge should be set to 0% to prevent this calculation from causing numerical problems.

$$\frac{\partial \varsigma}{\partial t} = \frac{\eta P_{\text{cha}} - P_{\text{dis}}}{C_{OP}} \quad (1)$$

where

P_{cha} is the charge power
 P_{dis} is the discharge power
 t is time

This equation states that the change in state of charge is proportional to the discharge power divided by the energy capacity, and proportional to the charge power times the energy efficiency, divided by the energy capacity. This is referred to as an energy reservoir model (ERM) as its capacity is in units of energy (see Rosewater et al. [B43]). Further, the system operation is limited by the following constraints.

Normal operating constraints ($\varsigma_{\min}$ is 0% and $\varsigma_{\max}$ is 100%):

$$P_{\text{dis}} \leq m_{\text{dis}} (\varsigma - \varsigma_{\min}) + b_{\text{dis}} \quad (2)$$

$$P_{\text{dis}} \leq P_{\text{max-dis}} \quad (3)$$

$$P_{\text{cha}} \leq m_{\text{cha}} (\varsigma - \varsigma_{\max}) + b_{\text{cha}} \quad (4)$$

$$P_{\text{cha}} \leq P_{\text{max-cha}} \quad (5)$$

$$\frac{\partial P_{\text{dis}}}{\partial t} \leq dr_{\text{dis}} \quad (6)$$

$$\frac{\partial P_{\text{cha}}}{\partial t} \leq dr_{\text{cha}} \quad (7)$$

Temporary (short-term) operating constraints:

$$t \leq t_{\text{temp-dis}} \quad (8)$$

$$P_{\text{dis}} \leq m_{\text{temp-dis}} (\zeta - \zeta_{\text{dis}}) + P_{\text{max-dis}} \quad (9)$$

$$P_{\text{dis}} \leq P_{\text{temp-dis}} \quad (10)$$

or

$$t \leq t_{\text{temp-cha}} \quad (11)$$

$$P_{\text{cha}} \leq m_{\text{temp-dis}} (\zeta - \zeta_{\text{cha}}) + P_{\text{max-cha}} \quad (12)$$

$$P_{\text{cha}} \leq P_{\text{temp-cha}} \quad (13)$$

where

ζ is the operational state of charge

The operating regions that these constraints defined are shown in Figure 3. At high operational state of charge, a system or fleet of devices will often have to limit its charge power, just as at low operational state of charge, it may need to limit its discharge power. Even if individual devices do not need to curtail their max power near state of charge limits then an aggregation of homogeneous systems with slightly different individual states of charge will encounter their state of charge limits at different times, leading to a curtailment of the total power available.

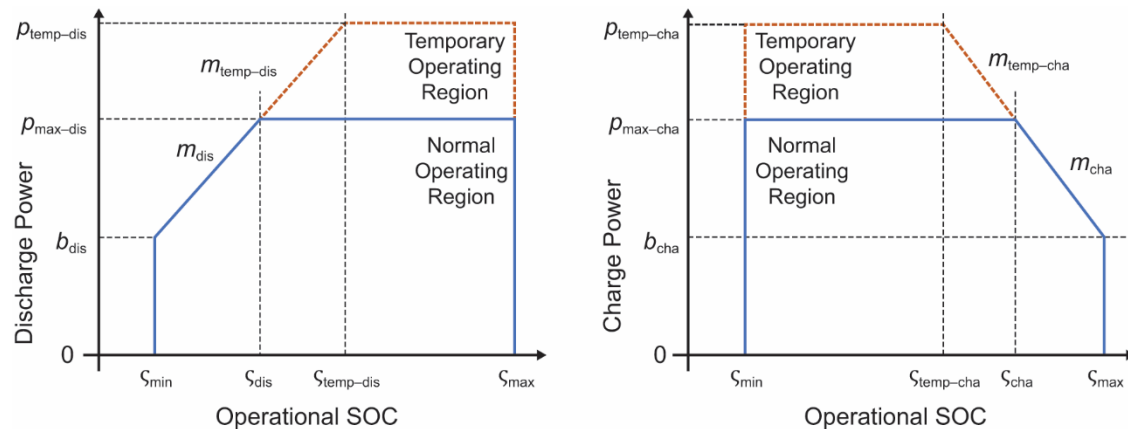


Figure 3—Discharge power (left) and charge power (right) operating regions defined by the operational model constraints

See Annex C for examples of how to use the operational model parameters to calculate minimum and maximum times required to charge and discharge, to perform state forecasting, and to predict available power/energy.

4.4.4 Energy storage market participation model parameters

FERC Order 841 [B10] required each regional transmission organization’s (RTO)/independent system operator’s (ISO) market participation model for electric storage resources to account for 13 different physical and operational characteristics, as defined in the final rule. The parameters specified were (1) State of Charge, (2) Maximum State of Charge, (3) Minimum State of Charge, (4) Maximum Charge Limit, (5) Maximum Discharge Limit, (6) Minimum Charge Time, (7) Maximum Charge Time, (8) Minimum Run Time, (9) Maximum Run Time, (10) Minimum Discharge Limit, (11) Minimum Charge Limit, (12) Discharge Ramp Rate, and (13) Charge Ramp Rate. Notably, batteries and flywheels do not generally have discharge/charge minimums, parameters 6 through 11, that are included to account for pumped hydro and compressed air–type storage systems (EPRI “Independent system operator” [B7]). Notably, this list has significant overlap with the operational model presented above.

When participating in FERC 841 compliant markets, an ES DER operator should work with the RTO/ISO to determine the appropriate parameter values that will communicate when a parameter does not apply. The parameter values in Table 3 are one example for a battery or flywheel type ES DER where these additional parameters are not applicable.

Table 3—Example FERC 841 parameters values for “not applicable”

Parameter name	Value to communicate “not applicable”
Minimum Charge Time	0
Maximum Charge Time	–1
Minimum Run Time	–1
Maximum Run Time	–1
Minimum Discharge Limit	0
Minimum Charge Limit	0

4.5 Cease to energize performance requirement [1547]

Subclause 4.5 [1547] specifies that import of active power and reactive power exchange in the *cease to energize* state is permitted only for continuation of supply to DER housekeeping and auxiliary loads. However, the definition of *cease to energize* includes a non-normative note (NOTE 4) that states “Energy storage systems are allowed to continue charging but are allowed to cease from actively charging when the maximum state of charge (maximum stored energy) has been achieved.” This apparent conflict can be difficult to interpret. As the clause language is normative, it can be understood that ES DER are allowed to charge only for continuation of supply to housekeeping and auxiliary loads. As many energy storage technologies require some power to maintain their operational state of charge or to supply power to cell balancing to maintain safety and reliability, the intent of NOTE 4 is to allow limited import of active power for this purpose.

NOTE—In the context of 4.5 [1547], “steady state and transient” means “all steady-state and non-steady-state operating conditions,” and the “cease to energize” requirements continue to apply if the ES DER is also required to trip (i.e., “cease to energize and trip”).

4.6 Control capability requirements [1547]

4.6.1 Capability to disable permit service [1547]

Subclause 4.6.1 [1547] applies to ES DER without further guidance.

4.6.2 Capability to limit active power [1547]

Subclause 4.6.2 [1547] applies to ES DER without further guidance.

4.6.3 Execution of mode or parameter changes [1547]

ES DER control modes may be defined from multiple perspectives:

- Connection with grid (e.g., grid connected, islanded)
- Operational hierarchy (e.g., remote, auto, manual)
- Operational status (e.g., idle, under charge/discharge)

Depending on the prevailing operational situation, an ES DER may need to be able to operate within more than one control mode (e.g., grid connected versus islanded mode) within a given period and switch between modes with minimal unwanted impacts. In some cases, this type of mode switching may need the ES DER to respond differently (e.g., faster or at a higher magnitude of active/reactive power) than the default or standard settings as defined in IEEE Std 1547-2018. ES DER control capabilities should be able to accommodate such needs.

4.6.4 Changes in available power over time

Conditions related to the energy storage medium in an ES DER (such as aging) may limit its ability to exchange power, both charging and discharging (see discussion of energy storage medium in 4.4.2). This power-capability limitation may cause unwanted impacts, such as an inability to meet service or application requirements. This deviation from application requirements may exceed an acceptable level. The impact of such deviations can be mitigated through implementation of a robust operational model as discussed in 4.4.2.

4.6.5 Active power production requirements

Active power production requirements, such as magnitude, ramp rate, and duration of ES DER, may vary widely to meet application needs. Depending on the technology, there may be necessary limitations that override use case or application requirements. Battery management systems (BMS) are typically equipped with control and protection features to manage these limitations. However, a higher level control system (e.g., at inverter or EMS) should be informed by those management systems that such limitations are active, and to what degree.

4.6.6 Charging limitations

Some ES DER are required or desired to be charged only from Local EPS generation sources. For example, ES DER that take advantage of a solar-linked investment tax credit may be required to charge only from that local solar resource. The Area EPS operator should be made aware of such limitations, and coordinate with the DER owner/operator in cases of Area EPS limitations imposed on the ES DER.

4.6.7 Standardization of control modes in service to the Area EPS

With growing interest to utilize ES DER for various applications during normal and abnormal (e.g., overstressed or faulted) grid conditions, it would be useful to standardize control modes and features under each mode for better planning and use of ESS capabilities. For instance, standardizing a control mode that can be enabled or disabled remotely by the Area EPS operator to contribute fault current from an ES DER when operating in idle mode could be useful for utilities when utilizing assets in a more coordinated fashion. Similarly, standardizing a control mode that can be enabled or disabled by the Area EPS operator to contribute fast reactive power support from an ES DER inverter during a severe voltage or frequency disturbance or voltage collapse could be beneficial for the local grid. This capability may help utilities to plan and operate their voltage management resources more effectively.