



IEEE Recommended Practice for Use and Functions of Virtual Synchronous Machines

IEEE Power Electronics Society

Developed by the
Standards Committee

IEEE Std 2988™-2024

STANDARDS

IEEE Recommended Practice for Use and Functions of Virtual Synchronous Machines

Developed by the

Standards Committee
of the
IEEE Power Electronics Society

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IEEE SA Standards Board

Abstract: The fundamental principles, essential functions, and optional functions of a virtual synchronous machine (VSM) to make power electronic converters standardized for different applications and suitable for single-unit operation, multi-unit operation, islanded/off-grid operation, and grid-tied operation, facilitating the large-scale utilization of DER and the integration of power electronic converters into the grid, and advancing energy freedom and energy access are defined in this standard.

Keywords: black-start, centralized control, damping, democratized interaction, distributed energy resources (DER), droop control, electrification, energy access, energy freedom, fault ride-through, frequency regulation, fundamental challenge, grid-following, grid-forming, IEEE 2988™, inertia, islanding detection, paradigm shift, phase-locked loop, power electronic converters, rate of change of frequency (RoCoF), reclosing, solar energy, stability, storage systems, synchronous machines (SM), synchronization, virtual synchronous machines (VSM), voltage regulation, wind energy

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Introduction

This introduction is not part of IEEE Std 2988™-2024, IEEE Recommended Practice for Use and Functions of Virtual Synchronous Machines.

Electrification is the greatest engineering achievement of the 20th century and power systems are arguably the most important infrastructure that underpins social life and economic growth. The generation of electricity has been dominated by centralized large power plants, but power systems are going through a paradigm shift. Centralized large generating facilities are being replaced with distributed, incompatible, non-synchronous and relatively small renewable wind turbines, solar panels, plug-in EVs, and energy storage units etc., interfaced through power electronic converters (PECs). At the same time, different types of loads, such as motors, lighting devices, and electronic devices, are connected to power systems at an ever-increasing speed, also interfaced through PECs as well. This paradigm shift, referred to as the democratization of power systems, is comparable to the great historical event of personal computers replacing mainframes in the technology domain or republics replacing monarchies in the political domain. It brings unprecedented challenges to grid stability, reliability, security, and resiliency. The fundamental challenge behind the scene is that future power systems are power electronics based, rather than electrical machines based, with millions of non-synchronous heterogeneous players (see Zhong).

While electrification is the greatest engineering achievement of the 20th century, about one billion people still do not have access to electricity. Many of those who do still do not have the freedom to choose the supplier of reliable and affordable electricity. The large-scale utilization of renewable distributed energy resources (DERs), such as wind and solar energy, has provided an affordable means and freedom for these people to access electricity.

It has been revealed that the synchronization mechanism of synchronous machines (SMs), which has underpinned power systems operation and growth for over 100 years, can continue to be adopted to bring backward compatibility to the current power systems, by turning PECs into virtual synchronous machines (VSM). They can be controlled to mimic and, in some cases, to surpass the dynamics and behavior of conventional SMs through the inherent synchronization mechanism of SMs, while accounting for equipment limitations. This allows millions of non-synchronous heterogeneous players, including DERs and flexible loads that have PECs at the front end, to unify and harmonize their interface and interaction with the grid. This will significantly smooth the paradigm shift of power systems, transitioning from the *centralized control* of a small number of large facilities to *democratized interaction* of a large number of relatively small generators and flexible loads (see Zhong).

This standard defines the fundamental principles, essential functions, and optional functions of a VSM to make PECs standardized for different applications and suitable for single-unit operation, multi-unit operation, islanded/off-grid operation, and grid-tied operation. It does not describe or specify power semiconductor devices, hardware topologies, or micro-controllers that are used to build a VSM.

This standard is about equipment operation rather than grid requirements. Equipment complying with this standard are able to work individually, to form a grid, and to interact with the grid. This standard focuses on VSM only, rather than generic criteria that apply irrespective of the specific control implementation. The boundary of this standard is at the equipment terminal and, hence, anything outside of the equipment terminal, such as the energy source, the load, and/or the grid, are not covered in this standard.

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IEEE Recommended Practice for Use and Functions of Virtual Synchronous Machines

1. Overview

1.1 Scope

This recommended practice defines the fundamental principles, essential functions, and optional functions of a virtual synchronous machine (VSM). A VSM is a piece of equipment that includes a dc/ac power electronic converter (PEC) controlled to mimic and, in some cases, to surpass the dynamics and behavior of conventional synchronous machines (SM) through the inherent synchronization mechanism of SM. It does not describe or specify power semiconductor devices, hardware topologies, or micro-controllers that are used to build a VSM.

This standard is about equipment operation rather than grid requirements, which are covered by IEEE Std 1547-2008 [B2] and IEEE Std 2800-2022 [B3].⁶ Equipment complying with this standard are able to work individually, to form a grid, and to interact with the grid.

This standard focuses on VSM only, rather than generic criteria that apply irrespective of the specific control implementation.

The boundary of this standard is at the equipment terminals, which includes the phase terminals, plus a neutral terminal, plus a ground terminal on the ac side and the dc-bus terminals on the dc side, while IEEE Std 1547-2008 [B2] and IEEE Std 2800-2022 [B3] consider the point of connection (PoC) or point of common coupling (PCC) as the boundary. As a result, anything outside of the equipment terminals, such as the energy source, the load, and/or the grid, are not covered in this standard.

1.2 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*).^{7,8}

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*).

⁶The numbers in brackets correspond to those of the bibliography in Annex A.

⁷The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁸The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

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*).

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.

Heffron, W. G. and R. A. Phillips, “Effect of a Modern Amplidyne Voltage Regulator on Underexcited Operation of Large Turbine Generators,” [includes discussion], Transactions of the American Institute of Electrical Engineers. Part III: Power Apparatus and Systems, vol. 71, no. 3, pp. 692–697, August 1952.^{9,10}

IEEE Std 421.5TM-2005, IEEE Recommended Practice for Excitation System Models for Power System Stability Studies.

IEEE Std 1110TM-2019, IEEE Guide for Synchronous Generator Modeling Practices and Parameter Verification with Applications in Power System Stability Analyses.

IEEE Std 1662TM-2016, IEEE Recommended Practice for the Design and Application of Power Electronics in Electrical Power Systems.

IEEE Std C37.96TM-2012, IEEE Guide for AC Motor Protection.

IEEE Std C37.102TM-2006, IEEE Guide for AC Generator Protection.

IEEE Std C50.13TM-2014, IEEE Standard for Cylindrical-Rotor 50 Hz and 60 Hz Synchronous Generators Rated 10 MVA and Above.

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Zhong, Q.-C. and T. Hornik, Control of Power Inverters in Renewable Energy and Smart Grid Integration. Wiley-IEEE Press, 2013.¹¹

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¹⁰IEEE publications are available from The Institute of Electrical and Electronics Engineers (<https://standards.ieee.org/>).

¹¹Available at <http://dx.doi.org/10.1002/9781118481806>.

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.¹²

black-start: Black-start is the process of establishing the voltage from around zero, in terms of root mean square (rms), when an energy source is available.

current-source converter (CSC): A current-source converter is a power electronic converter (PEC) that is fed from a current source.

fault ride-through (FRT): Fault ride-through is the capability of staying connected during the occurrence of a fault beyond the equipment output terminals.

grid-forming: Grid-forming is the capability of connecting one or more voltage sources to form a grid.

grid-following: Grid-following is the capability of following the grid frequency and voltage.

natural (abc) frame: A reference frame in which signals are represented as three-dimensional vectors in its natural order.

power electronic converter (PEC): A power electronic converter utilizes semiconductor switching devices to convert electrical energy from one type to another. Since there are dc-type and ac-type electrical systems, there are a total of three main types of PECs: ac/dc, dc/dc and ac/ac.

proportional integral (PI) control: A controller that combines proportional control with integral control to automatically compensate system changes. A PI controller can achieve zero steady-state error for a dc signal.

proportional resonance (PR) control: A controller that combines proportional control with resonant control to automatically compensate system changes. A PR controller can achieve zero steady-state error for a sinusoidal signal at the given frequency.

saliency: Saliency of a synchronous machine (SM) indicates the effect that a physical quantity is not evenly distributed along all directions.

seamless mode change: Seamless mode change means the instantaneous voltage stays within the desired range during the transition between different modes of operation, such as islanded mode, grid-connected mode, and set mode.

set mode: set mode is the capability of exchanging set real power and/or reactive power with the grid.

stationary reference ($\alpha\beta$) frame: A stationary reference frame in which three-dimensional variables are represented as two-dimensional vectors for a balanced three-phase system. The vectors are converted from their natural (abc) frame representations by a Clarke transformation, in which the third element is 0 or neglected.

synchronization process: Synchronization process is the process of the equipment to synchronize its terminal voltage with another voltage source, so that the difference between the two voltages is small, which includes some or all of the following: frequency synchronization to have the same frequency, phase synchronization to have the same phase, amplitude synchronization to have the same voltage amplitude, and phase sequence synchronization to have the same phase sequence.

¹²*IEEE Standards Dictionary Online* is available at: <http://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.

synchronization mechanism: The mechanism that a voltage source keeps synchronization with another voltage source.

synchronous machine (SM): A synchronous machine is an ac electrical machine operated with a constant electromagnetic field. Its instantaneous speed of normal operation is exactly proportional to the frequency of its ac voltage. An SM with a round rotor has a uniform air gap, so that the reluctance does not depend on the flux position. Contrarily, the air gap of an SM with a salient-pole rotor varies circumferentially around the rotor, resulting in a non-uniform reluctance.

synchronously rotating reference (dq) frame: A rotating reference frame in which variables are represented as two-dimensional vectors for a balanced three-phase system. The vectors are converted from their stationary reference ($\alpha\beta$) frame representations by a Park transformation. The rotating frequency of the synchronously rotating reference frame is generally synchronized with the frequency of the variables, so that balanced three-phase sinusoidal variables are expressed as two constants in this frame.

virtual damping: The damping effect that is implemented through a control function.

virtual impedance: The impedance that is implemented through a control function.

virtual inertia: The inertia that is implemented through a control function to emulate the physical inertia of an SM.

virtual synchronous machine (VSM): A virtual synchronous machine is a piece of equipment that includes a dc/ac power electronic converter (PEC) controlled to mimic and, in some cases, to surpass the dynamics and behavior of a conventional synchronous machine (SM) through the inherent synchronization mechanism of SM.

voltage-source converter (VSC): A voltage-source converter is a power electronic converter (PEC) that is fed from a voltage source.

3.2 Acronyms and abbreviations

AVR	automatic voltage regulator
CSC	current-source converter
<i>emf</i>	electromotive force
FRT	fault ride-through
PCC	point of common coupling
PEC	power electronic converter
PI	proportional integral (control)
PLL	phase locked loop
PR	proportional resonance (control)
PSS	power system stabilizer
PWM	pulsewidth modulation
rms	root mean square
RoCoF	rate of change of frequency
SG	synchronous generator