IEC TR 63401-1

Edition 1.0 2022-11

TECHNICAL REPORT

colour inside

Dynamic characteristics of inverter-based resources in bulk power systems – Part 1: Interconnecting inverter-based resources to low short circuit ratio AC networks

IEC TR 63401-1:2022-11(en)

IEC Secretariat
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

About the IEC
The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications
The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigendum or an amendment might have been published.

IEC publications search - webstore.iec.ch/advsearchform
The advanced search enables to find IEC publications by a variety of criteria (reference number, text, technical committee, …). It also gives information on projects, replaced and withdrawn publications.

IEC Just Published - webstore.iec.ch/justpublished
Stay up to date on all new IEC publications. Just Published details all new publications released. Available online and once a month by email.

IEC Customer Service Centre - webstore.iec.ch/csc
If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: sales@iec.ch.

IEC Products & Services Portal - products.iec.ch
Discover our powerful search engine and read freely all the publications previews. With a subscription you will always have access to up to date content tailored to your needs.

Electropedia - www.electropedia.org
The world's leading online dictionary on electrotechnology, containing more than 22 300 terminological entries in English and French, with equivalent terms in 19 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

IEC TR 63401-1

Edition 1.0 2022-11

TECHNICAL REPORT

Dynamic characteristics of inverter-based resources in bulk power systems – Part 1: Interconnecting inverter-based resources to low short circuit ratio AC networks

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 29.020

ISBN 978-2-8322-6143-9

Warning! Make sure that you obtained this publication from an authorized distributor.

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

____

DYNAMIC CHARACTERISTICS OF INVERTER-BASED RESOURCES IN BULK POWER SYSTEMS –

Part 1: Interconnecting inverter-based resources to low short circuit ratio AC networks

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

IEC TR 63401-1 has been prepared by subcommittee SC 8A: Grid integration of renewable energy generation, of IEC technical committee TC 8: Systems aspects of electrical energy supply. It is a Technical Report.

The text of this Technical Report is based on the following documents:

Draft TR	Report on voting
8A/109/DTR	8A/113/RVDTR

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts in the IEC 63401 series, published under the general title *Dynamic characteristics of inverter-based resources in bulk power systems*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

IMPORTANT – The "colour inside" logo on the cover page of this document indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

As the penetration of inverter-based energy generating resources increases, huge challenges to all sections of the power system including planning, operation, control, etc. have been created. The impact on the power grid extends from local to the whole power system. New technical solutions are needed to address the different challenges. The solutions will include the new technologies, methods and practices, to provide more flexibility and improve the efficiency of power systems, constantly balancing generation and load.

The purpose of this document (TR) is to specifically focus on information collection from regulatory agencies, including specifying low short circuit ratio AC networks and the challenges they pose for inverter-based resources, and methods, indexes, and characteristics of low short circuit ratio AC networks. This TR addresses renewable energy (RE) integration in low short circuit ratio AC networks, mainly focusing on the technology development trends, best practices of RE grid integration, and future standardization activities.

The aim of this TR is to create a strategic, technically oriented and referenced document, which presents the core and key issues of interconnecting inverter-based resources to low short circuit ratio AC networks. Renewable energy station developers and owners, transmission systems operators need to have a common understanding of the key issues based on practices and challenges between inverter-based resources and AC networks.

DYNAMIC CHARACTERISTICS OF INVERTER-BASED RESOURCES IN BULK POWER SYSTEMS –

Part 1: Interconnecting inverter-based resources to low short circuit ratio AC networks

1 Scope

As the use of inverter-based RE power generation resources increases, the use of low short circuit ratio AC networks is becoming more common. Considering the advantages of short circuit ratio in stability analysis, the low short circuit ratio is an important indication for describing weak AC networks. This document focuses on technologies and standardization aspects of interconnecting inverter-based resources to low short circuit ratio AC networks. A clear definition of low short circuit ratio AC networks with or without a high proportion of inverter-based resources and the calculation method is described. The adaptability of traditional modelling and analytical method for low short circuit ratio AC networks are discussed. Some new characteristics and challenges will be re-examined, and some adapted control strategies will be studied. This document covers the following major aspects.

In terms of defining a weak AC network, for example the (X/R) ratio, voltage sensitivity, system inertia and the short circuit ratio (SCR) are important characteristics. The definition of low short circuit ratio AC networks in IEEE Std 1204™-1997 [1][1] and in CIGRE B4.62 TB671 [2] is used. Some stability challenges for inverter-based resources in a low short circuit ratio AC network (SCR AC) will be analyzed. There are stability challenges in a low short circuit ratio (SCR) AC network, typically complex static voltage control, risk of failure in fault ride-through situations, strong control interactions and instability.

In terms of identification of low short circuit ratio (SCR) AC networks, some short circuit ratio - like index for various applications is introduced. A wind power plant (WPP) is a power station consisting of a batch of wind turbines or groups of wind turbines, collection lines, main step-up transformers and other equipment. For a single grid-connected WPP system, a fault current based calculation method and an equivalent circuit based calculation method are introduced to make an SCR calculation possible for any given WPP and network topology. For multi grid-connected WPP systems, eigenvalue decomposition based generalized short circuit ratio (gSCR) is then proposed and compared against other approaches referred to as equivalent short circuit ratio (ESCR), composite short circuit ratio (CSCR), and weighted short circuit ratio (WSCR).

In terms of large scale inverter-based resources integration, the steady-state stability analysis methods, including the P-V curve, Q-V curve, and voltage sensitivity analysis, are illustrated. The conventional control strategies of the renewable energy sources are explained. An adaptive controller designed for the photovoltaic (PV) panels, which can maximize the power output capability of PV stations under weak-grid conditions, is presented. Finally, the steady-state voltage stability problem in China that happened recently is illustrated.

1 Numbers in square brackets refer to the Bibliography.

In terms of the transient state stability issue for low short circuit ratio AC networks after large scale inverter-based resources integration, related issues and phenomena that occur need to be discussed. Undervoltage ride-through (UVRT), overvoltage ride-through (OVRT) and multiple fault ride-through occur easily in a low SCR AC network, which bring risk of failure to fault ride-through. Electromagnetic transient simulations to supplement positive sequence root-mean-square (RMS) simulations are described, and shortfalls of the RMS models and how to identify them in simulations are considered.

In terms of the oscillatory stability issue for low short circuit ratio AC networks after large scale inverter-based resources integration, the impedance-based method is used to analyze the system stability. For the inverter modelling, three typical inverter models are established, including: a) only considering the current controller (CC); b) considering CC and phase-locked loop (PLL); c) considering CC, PLL and voltage controller (VC). Relying on the impedance analysis method, the effect of PLL, CC, number of inverters, SCR of AC grid is discussed. Finally, the additional active damping control method is proposed for suppressing the oscillation phenomenon.

This document discusses the challenges of connecting inverter-based resources to low short circuit ratio AC networks, key technical issues and emerging technologies. There are the steady-state stability issue, transient state stability issue, and oscillatory stability issue, which are the most distinct differences compared to inverter-based resources or traditional generators, and accordingly brings new challenges to operation, control, protection, etc. Therefore, technical solutions are needed. The potential solutions will include new technologies, methods and practices, in order to provide more flexibility and improve the efficiency of power systems. It is expected that this document can also provide guidance for further standardization on relevant issues.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 62934, *Grid integration of renewable energy generation – Terms and definitions*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 62934 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
renewable energy
RE
primary energy, the source of which is constantly replenished and will not become depleted

Note 1 to entry: Examples of renewable energy are: wind, solar, geothermal, hydropower, etc.

Note 2 to entry: Fossil fuels are non-renewable.

[SOURCE: IEC 60050-617:2009, 617-04-11]

3.2
inverter
electric energy converter that changes direct electric current to single-phase or polyphase alternating currents

[SOURCE: IEC 60050-151:2001, 151-13-46]

3.3
point of common coupling
PCC
point in an electric power system, electrically nearest to a particular load, at which other loads are, or may be, connected

Note 1 to entry: These loads can be either devices, equipment or systems, or distinct customer's installations

[SOURCE: IEC 60050-614:2016, 614-01-12]

3.4
short circuit current of renewable energy power plant
current that a renewable energy power plant delivers to the point of connection resulting from a short circuit in the external electric power system

3.5
short circuit ratio
SCR
ratio of the three-phase short circuit power at PCC to the nominal active power of a renewable energy power plant or generating unit

Note 1 to entry: SCR is a common analytical indicator used in the industry to quantify system strength.

Note 2 to entry: There is no industry consensus on the exact definition and methodology for calculating the SCR, particularly for applications with several adjacent renewable energy power plants, or for a renewable energy power plant adjacent to HVDC terminals, see CIGRE B4.62 TB 671 [2].

3.6
voltage dip
sudden voltage reduction at a point in an electric power system, followed by voltage recovery after a short time interval, from a few periods of the sinusoidal wave of the voltage to a few seconds

[SOURCE: IEC 60050-614:2016, 614-01-08]

3.7
fault ride-through
FRT
ability of a generating unit or power plant to stay connected during specified faults in the electric power system

3.8
electrical simulation model
set of mathematical formulae or logical functions used in time or frequency domain digital simulations which describe the dynamic characteristics of a facility or certain equipment

3.9
electromechanical simulation
RMS simulation
dynamic simulation method based on the RMS model, which usually focuses on the electromechanical processes of the electric power system under disturbance, and where the typical observation time interval is from several seconds to tens of seconds after disturbance

3.10
electromagnetic transient simulation
EMT simulation
dynamic simulation method to model the electromagnetic transient behaviour of an electric power system, where instantaneous values are used in the process, and the typical observation time interval is from several microseconds to several seconds after a disturbance

3.11
steady state stability
ability of generators in a system to keep operating synchronously and transit to a new stable operating state or recover to the original stable operating state under a small power system disturbance

3.12
transient stability
ability of generators in a system to keep running synchronously and transit to a new stable operating state or recover to the original stable operating state under a large power system disturbance

3.13
sub-synchronous oscillation
electrical oscillation occurring in an electric power system at a frequency smaller than the nominal system frequency and generally sustained for a minute or more

3.14
sub-synchronous resonance
resonance between adjacent equipment in an electric power system, generating oscillations at a frequency smaller than the nominal system frequency and generally sustained for a minute or more

3.15
low-frequency oscillation
electrical oscillation occurring in an electric power system at a frequency usually between 0,1 Hz and 3 Hz

Note 1 to entry: According to an extensive survey of IEEE technical literature, the range 0,1 Hz to 3 Hz covers the majority of low-frequency oscillation events.

4 Characteristics of low short circuit ratio AC networks

4.1 Definition of low short circuit ratio

4.1.1 General

The strength of a power system is a metric used to describe the ability of a power system to maintain the core characteristics through which it interacts with a connection, namely voltage and frequency, as steadily as possible, under all operating conditions. The strength or weakness of a power system is a relative concept and needs to be addressed both in terms of the system characteristics at a given connection point as well as the size of renewable energy to be connected to the connection point.

As indications of system strength, the (X/R) ratio of the system impedance seen from the connection point and the concept of available fault level have also been used. The ability to stably transfer power over a weak transmission system, from a renewable energy station connecting point to stronger parts of a network (where generally the load is) has been quantified by using the sensitivity of the connection point's voltage to the active and reactive power outputs of the renewable energy station. The maximum stable power transfer capability has been derived, providing an insight for renewable energy station designers of the potential issues to be anticipated when power transfer reaches the maximum transfer limits.

Short circuit ratio (SCR), which is a commonly used metric for quantifying the relative power system impedance seen from a connection point, is an important indication of the strength of AC networks. The SCR seen by a generator strongly influences its ability to operate satisfactorily both in steady state and after system disturbances. While this is a very powerful and simple concept, extending its use to describe the shared impedance seen by multiple renewable energy power plants (REPPs) connecting to the same part of a network, electrically close to each other, or close to other power electronic plants such as HVDC converters, has not been unified across the industry.

4.1.2 Low SCR in IEEE Std 1204-1997

SCR is a widely used index for assessment of the strength of the connection point for HVDC links, and in particular for the line current commutated (LCC) and capacitor commutated converter (CCC) technologies. For an HVDC link it is defined as the ratio of fault level at the connection point to the nominal output active power of the link. It is commonly used at the planning stage to give an idea of the likely issues caused by integration of the HVDC link into the network. The SCR seen by a generator strongly influences its ability to operate satisfactorily both in steady state and following system disturbances. While this is a very powerful and simple concept, extending its use to describe the shared impedance seen by multiple REPPs connecting to the same part of a network, electrically close to each other, or close to other power electronic plant such as HVDC converters, has not been unified across the industry.

The SCR can be often obtained from the following formula:

$$SCR = \frac{S}{P_{\mathrm{N}}} \tag{1}$$

where

S is the AC system three-phase symmetrical short circuit level in megavolt-amperes (MVA) at the convertor terminal AC bus with 1,0 p.u. AC terminal voltage;

P_{N} is the rated AC power in megawatts (MW).

Based on that definition and on typical inverter characteristics (such as the value of the convertor transformer reactance), the following SCR values can be used to classify an AC/DC system:

- a high SCR AC/DC system is categorized by a SCR value greater than 3;
- a low SCR AC/DC system is categorized by a SCR value between 2 and 3;
- a very low SCR AC/DC system is categorized by a SCR value lower than 2.

4.1.3 Low SCR in CIGRE B4.62 TB671

Compared to an HVDC link, a WPP has a significantly more complex topology due to the use of several wind turbines (which may or may not be identical), and the common use of static reactive support plants such as capacitor banks and dynamic reactive support plants such as STATCOMs and synchronous condensers. Additionally, it sometimes happens that several REPPs are located adjacent to each other, or even sometimes connected to the same connection point. This makes it imperative to evaluate the impact of all connected REPPs. The two aspects addressed above are difficult to account for using the conventional calculation method for the SCR. To make it applicable to any given REPP and network topology, an equivalent circuit based calculation method (ESCR) is proposed as elaborated below for various configurations. For multi REPP applications results obtained from this approach will then be compared against two other approaches referred to as composite short circuit ratio (CSCR) and weighted short circuit ratio (WSCR).

1) Composite short circuit ratio (CSCR)