



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

| | |
|---|----|
| FOREWORD..... | 6 |
| INTRODUCTION..... | 8 |
| 1 Scope..... | 9 |
| 2 Normative references | 10 |
| 3 Terms and definitions | 10 |
| 4 Characteristics of low short circuit ratio AC networks..... | 12 |
| 4.1 Definition of low short circuit ratio | 12 |
| 4.1.1 General | 12 |
| 4.1.2 Low SCR in IEEE Std 1204-1997..... | 13 |
| 4.1.3 Low SCR in CIGRE B4.62 TB671 | 13 |
| 4.2 Stability issues posed by inverter-based resources | 15 |
| 4.2.1 General | 15 |
| 4.2.2 Static voltage control | 16 |
| 4.2.3 Fault ride-through | 16 |
| 4.2.4 Multi-frequency oscillation | 16 |
| 4.3 Summary | 17 |
| 5 Identification of low short circuit ratio AC networks | 17 |
| 5.1 Problem statement..... | 17 |
| 5.2 Short circuit ratio for a single-connected REPP system..... | 18 |
| 5.2.1 SCR calculation with fault current | 18 |
| 5.2.2 SCR calculation with equivalent circuit | 19 |
| 5.3 Short circuit ratio for multi grid-connected WPP system | 26 |
| 5.3.1 General | 26 |
| 5.3.2 Modal decoupling method..... | 27 |
| 5.3.3 Circuit aggregation method..... | 38 |
| 5.4 Summary | 45 |
| 6 Steady state voltage stability issue for low short circuit ratio AC networks..... | 47 |
| 6.1 Problem statements | 47 |
| 6.2 Steady state stability analysis method..... | 47 |
| 6.2.1 <i>P-V</i> curve..... | 47 |
| 6.2.2 <i>Q-V</i> curve | 48 |
| 6.2.3 Voltage sensitivity analysis..... | 49 |
| 6.2.4 Relation to short circuit ratio..... | 54 |
| 6.3 Control strategy for inverter-based resource | 56 |
| 6.3.1 Active power and reactive power control..... | 56 |
| 6.3.2 Voltage control | 58 |
| 6.4 Case study..... | 59 |
| 6.4.1 Steady state voltage stability problem – China..... | 59 |
| 6.4.2 Low SCR interconnection experience – Vestas | 62 |
| 6.5 Summary | 63 |
| 7 Transient issue for low short circuit ratio AC networks | 64 |
| 7.1 Problem statement..... | 64 |
| 7.2 Transient characteristic modelling and analysis | 65 |
| 7.2.1 Transient stability analysis tools and limitations..... | 65 |
| 7.2.2 Electromagnetic transient (EMT) type models | 66 |
| 7.2.3 Transient stability analysis model requirements | 67 |

| | | |
|-------|--|-----|
| 7.3 | Fault ride-through protection and control issue..... | 67 |
| 7.3.1 | General | 67 |
| 7.3.2 | Hardware protection of inverter-based resource during fault | 68 |
| 7.3.3 | Unbalancing-voltage ride-through issue | 71 |
| 7.3.4 | Overvoltage ride-through control strategy | 73 |
| 7.3.5 | Multiple fault ride-through | 75 |
| 7.3.6 | Under and over -voltage ride-through in time sequence | 78 |
| 7.3.7 | Active/reactive current support of inverter-based resource during fault | 79 |
| 7.4 | Operating experiences | 80 |
| 7.4.1 | Operating experience – China | 80 |
| 7.4.2 | Operating experience | 81 |
| 7.5 | Summary | 83 |
| 8 | Oscillatory instability issue for low short circuit ratio AC networks..... | 83 |
| 8.1 | Problem statement..... | 83 |
| 8.2 | Modelling and stability analysis..... | 86 |
| 8.2.1 | Analysis and modelling of the inverter in the time-domain..... | 86 |
| 8.2.2 | Analysis and modelling of the inverter in the frequency-domain | 86 |
| 8.3 | Mitigation of the oscillation issues by active damping control | 93 |
| 8.4 | Cases study based on the benchmark model | 94 |
| 8.5 | Summary | 99 |
| 9 | Conclusions..... | 100 |
| | Bibliography..... | 101 |
| | Figure 1 – Measured voltage and current curves of sub-synchronous oscillation | 15 |
| | Figure 2 – Schematic diagram of a WPP with no static or dynamic reactive support..... | 19 |
| | Figure 3 – Equivalent circuit representation of the WPP shown in Figure 2 | 20 |
| | Figure 4 – A typical SIPES..... | 24 |
| | Figure 5 – Changes of system eigenvalues, and the weakest system eigenvalue’s damping ratio with SCR in a SIPES..... | 24 |
| | Figure 6 – Schematic diagram of a WPP with static reactive support plant (capacitor banks) | 25 |
| | Figure 7 – Equivalent circuit representation of the WPP shown in Figure 6 | 25 |
| | Figure 8 – Schematic diagram of a WPP with dynamic reactive support plant (synchronous condensers)..... | 26 |
| | Figure 9 – Equivalent circuit representation of the WPP shown in Figure 8 | 26 |
| | Figure 10 – Mechanism illustration of decoupling a MIPES into a set of equivalent SIPESs | 28 |
| | Figure 11 – A typical MIPES | 29 |
| | Figure 12 – A test wind farm system that contains nine wind turbines | 33 |
| | Figure 13 – One-line diagram of 5-infeed PES | 35 |
| | Figure 14 – Eigenvalue comparison of 5-infeed PES and its 5 equivalent SIPESs..... | 36 |
| | Figure 15 – The 9-converter heterogeneous system with a IEEE 39-bus network topology..... | 37 |
| | Figure 16 – The dominant eigenvalues and the damping ratios | 38 |
| | Figure 17 – Nearby WPP connected to the same region in a power system..... | 39 |
| | Figure 18 – Equivalent representation of multiple windfarms connecting to a power system with its Z matrix..... | 40 |

| | |
|---|----|
| Figure 19 – Equivalent circuit representation of two WPPs connected to the same connection point-configuration 2 | 41 |
| Figure 20 – Four WPPs integrated into the system with weak connections | 42 |
| Figure 21 – Multiple WPPs connecting to the same HV bus or HV buses in close proximity | 43 |
| Figure 22 – Equivalent circuit representation of WPPs connecting to the same HV bus | 43 |
| Figure 23 – Approximate equivalent representation assumed for CSCR method | 43 |
| Figure 24 – System topology | 47 |
| Figure 25 – Typical $P-V$ curve | 47 |
| Figure 26 – System topology | 48 |
| Figure 27 – Typical $Q-V$ curve | 48 |
| Figure 28 – Simplified equivalent circuit of large-scale wind power integration system | 49 |
| Figure 29 – Voltage sensitivity at PCC of large-scale wind power integration system | 51 |
| Figure 30 – Single generator connected to an infinite bus via grid impedance | 52 |
| Figure 31 – $P-V$ curves for a typical generator in a weak grid | 53 |
| Figure 32 – Power limit curve of DFIG | 58 |
| Figure 33 – Voltage control block diagram of the doubly-fed wind turbine | 59 |
| Figure 34 – Network structure of Baicheng grid | 59 |
| Figure 35 – Short circuit capacity of Baicheng network | 60 |
| Figure 36 – $P-V$ curves and $V-Q$ curves | 61 |
| Figure 37 – Reactive power of the wind farm and voltage level at the PCC | 62 |
| Figure 38 – Schematic representation of the study system | 63 |
| Figure 39 – Fault characteristics | 64 |
| Figure 40 – Comparison of VER fault response between transient stability and EMT models | 66 |
| Figure 41 – Doubly-fed wind turbine rotor-side crowbar protection circuit topology | 69 |
| Figure 42 – Schematic diagram of positive and negative sequence current control of DFIG converter under grid unbalanced fault | 72 |
| Figure 43 – Comparative analysis of simulation results | 73 |
| Figure 44 – Overvoltage ride-through control flow diagram | 74 |
| Figure 45 – Multiple fault conditions | 75 |
| Figure 46 – Pitch angle control strategy | 76 |
| Figure 47 – Typical characteristics of P_m and P_e under multiple fault ride-through | 77 |
| Figure 48 – Characteristics of P_m and P_e under multiple fault ride-through | 78 |
| Figure 49 – Under/overvoltage ride-through curve | 78 |
| Figure 50 – Circuit diagram in Jiuquan | 80 |
| Figure 51 – Analysis of wind power disconnection incident | 81 |
| Figure 52 – Demonstration of voltage regulation performance during variable power output conditions | 82 |
| Figure 53 – Configuration of a system of multiple grid-tied VSIs | 85 |
| Figure 54 – Control schematic diagram and structure of inverter | 87 |
| Figure 55 – Frequency coupling in different frequency range | 90 |
| Figure 56 – Negative resistor caused by PLL | 91 |
| Figure 57 – Negative resistor caused by DVC | 92 |

| | |
|--|----|
| Figure 58 – Equivalent circuits of the LC-filter considering the virtual resistor | 93 |
| Figure 59 – Active damping control methods..... | 94 |
| Figure 60 – Impact of virtual resistance control on the stability | 95 |
| Figure 61 – Impact of line length on the stability | 97 |
| Figure 62 – Impact of PLL on the stability | 98 |
| Figure 63 – Impact of current control loop on the stability | 99 |
| | |
| Table 1 – Rated capacity of PEDs in 5-infeed PES in p.u..... | 35 |
| Table 2 – Network parameters of 5-infeed PES in p.u. | 36 |
| Table 3 – Relationship between equivalent SIPESs and eigenvalues of Y_{eq} in 5-infeed PES | 36 |
| Table 4 – Control parameters of converters | 37 |
| Table 5 – Wind capacity and SCR values assuming no interaction | 42 |
| Table 6 – The definition of different MISCRs..... | 45 |
| Table 7 – Comparison of SCR methods | 46 |
| Table 8 – Wind farm’s maximum power under different conditions | 61 |
| Table 9 – New oscillation issues of power systems in the world | 83 |
| Table 10 – Detailed influence frequency ranges of every loop..... | 89 |
| Table 11 – Approximate distribution of high frequency negative damping range | 93 |
| Table 12 – Typical cases of weak grid parameters | 96 |

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 1204TM-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*