# IEC TR 61000-2-15

Edition 1.0 2023-02

# TECHNICAL REPORT

colour inside

## Electromagnetic compatibility – Part 2-15: Description of the characteristics of networks with high penetration of power electronic converters

INTERNATIONAL ELECTROTECHNICAL COMMISSION

ICS 29.240.01; 33.100.01

ISBN 978-2-8322-6550-5

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

® Registered trademark of the International Electrotechnical Commission

# CONTENTS

FOREWORD ..... 8
INTRODUCTION ..... 10
1 Scope ..... 11
2 Normative references ..... 11
3 Terms and definitions ..... 11
4 Resonance phenomena with network and power electronics equipment based on actual cases ..... 12
4.1 Operation of overvoltage protection of earth leakage circuit breaker in Japanese LV systems ..... 12
4.1.1 General ..... 12
4.1.2 Circuit modelling ..... 13
4.1.3 Measurements on site ..... 14
4.1.4 Technical or regulatory aspects ..... 16
4.2 Analysis and modelling of an EV charging hub with PV production ..... 17
4.3 Impact of power electronic household equipment on the impedance characteristics in residential networks ..... 21
4.4 Harmonic resonance in an urban, residential low voltage grid ..... 25
4.5 Harmonic distortion and impedance characteristics in an islanded microgrid ..... 28
5 Impact of modern power electronics on the propagation and amplification of voltage distortion ..... 31
5.1 Harmonic propagation in a residential LV network ..... 31
5.1.1 General ..... 31
5.1.2 Measurements ..... 31
5.1.3 Modelling issues ..... 33
5.2 Supraharmonic amplification in a residential LV network with a fast charging station ..... 34
5.2.1 Measurement procedures ..... 34
5.2.2 Measurement results ..... 36
5.2.3 Simulation results ..... 39
5.3 Supraharmonic amplification in a residential low voltage network with PV converters ..... 41
5.4 Generic supraharmonic emission models for PWM based converters ..... 42
5.5 Assessment of optimal impedance angles for power electronic devices to minimize risk of amplification ..... 43
6 Cases of a large amount of converters ..... 47
6.1 General ..... 47
6.2 Large PV installations ..... 48
6.3 Industrial grids ..... 53
6.4 Multiple EV chargers in a central charging infrastructure ..... 57
6.4.1 General ..... 57
6.4.2 Measurements ..... 58
6.4.3 Modelling of interactions between $N$ similar single-phase power converters ..... 59
7 Impact of grid conditions on the operation of converters ..... 66
7.1 Analysis of a single-phase inverter model with an LCL filter using the Nyquist criterion ..... 66
7.2 Probabilistic stability analysis for commercial low power inverters based on measured grid impedances ..... 74

7.3 Description of electric vehicles connected to a weak network ..... 77
7.3.1 General ..... 77
7.3.2 Modeling of the equipment involved ..... 77
7.3.3 Determination of the voltage at the entrance of the charger, for different impedance values of the upstream network ..... 79
7.3.4 Measurements performed at the manufacturer's laboratory ..... 81
7.4 Other interactions between the grid and power converters ..... 82
7.4.1 PV connected to a weak network ..... 82
7.4.2 Windfarms connected to a grid ..... 88
7.4.3 Microgrid during the islanding phase ..... 89
7.4.4 Impact of the operating conditions ..... 93
8 Harmonic emission characteristics of power electronic equipment for the mass-market ..... 94
9 Conclusion and perspectives ..... 97
9.1 General ..... 97
9.2 Challenges ..... 97
9.3 Main findings ..... 98
9.4 Consequences ..... 98
9.5 Recommendations ..... 99
9.6 Future work ..... 99
Bibliography ..... 100

Figure 1 – Schematic illustration of a harmonic resonance issue in a LV system ..... 12
Figure 2 – Waveform of the overvoltage at the neighbour side ..... 13
Figure 3 – Description of an equivalent circuit modelling for harmonic resonances ..... 13
Figure 4 – Electrical circuit used in simulations, and results of resonance magnification factors (RMFs) ..... 14
Figure 5 – Description of the experimental test configuration ..... 14
Figure 6 – Measurement performed during the experimental tests ..... 15
Figure 7 – Resonance magnification factors (RMFs) using measurement and simulation ..... 15
Figure 8 – Flowchart to assess an appliance's compliance with JIS TS C 0058 [2] ..... 16
Figure 9 – Harmonic current limits for measurement assessment ..... 17
Figure 10 – Trends of the number of inquiries regarding current emission limits in Japan ..... 17
Figure 11 – Bloc scheme of the measured EV charging hub with PV production ..... 18
Figure 12 – Power line impedance magnitude (top) and phase (bottom) measured at the point of common connecting (PCC) of an EV charger hub with PV production ..... 19
Figure 13 – Resulting simplified model of the charging hub with distribution lines and feeder ..... 19
Figure 14 – Impact of a super-fast EV charger on grid impedance ..... 20
Figure 15 – Impedance characteristics of an urban LV network, ..... 24
Figure 16 – Schema of the network ..... 25
Figure 17 – Network harmonic impedance measured at different locations (L1-N) ..... 26
Figure 18 – Simulated network harmonic impedance at different locations (L1-N) using default element representations ..... 26
Figure 19 – Equivalent impedance model of a domestic customer ..... 27

Figure 20 – Measured and simulated network harmonic impedance at different locations (L1-N) using the developed customer impedance model ..... 27
Figure 21 – Schematic representation of system under test ..... 28
Figure 22 – Impedance characteristics (magnitude and phase angle) ..... 29
Figure 23 – Voltage harmonic levels in ICM (a) and ISM (b) ..... 30
Figure 24 – Simplified line diagram of the grid with marked measuring points ..... 31
Figure 25 – Connection of a PQ measuring device ..... 32
Figure 26 – Measured $15^{th}$ current and voltage harmonic on phase L1 during operation of the heat pumps at the heat pumps' point of connection without active filter ..... 32
Figure 27 – Measured voltage amplitudes of the $15^{th}$ harmonic for each phase L1 to L3 during three different operating states without active filter ..... 33
Figure 28 – Comparison of measured and simulated voltage levels ($15^{th}$ harmonic voltage) at each measuring point ..... 33
Figure 29 – Modelled voltage vectors of the $15^{th}$ harmonic at on- and off-state of the large heat pump without active filtering ..... 34
Figure 30 – Spectrogram of the voltage at the point of injection of supraharmonic currents in a residential low voltage network ..... 35
Figure 31 – Single-line diagram of relevant parts of the low voltage network ..... 36
Figure 32 – Transfer ratio of supraharmonic voltage along the low voltage cable for phase L1 in case of single-phase injection at the transformer busbar BB ..... 37
Figure 33 – Crosstalk ratio of supraharmonic voltage between phase L1 (phase of injection) and phase L2 at the junction box JB ..... 38
Figure 34 – Measured impedance (magnitude and phase) of the DC charger in idle mode ..... 38
Figure 35 – Transfer ratio along the cable for all three phases in case of three-phase injection at the transformer busbar BB ..... 39
Figure 36 – Fully coupled three-phase simulation model ..... 39
Figure 37 – Simplified simulation model for supraharmonic transmission along a low voltage cable ..... 40
Figure 38 – Comparison of measured and simulated transfer ratios along a low voltage cable ..... 40
Figure 39 – Transfer ratio of supraharmonic voltages along a low voltage cable of varying length ..... 41
Figure 40 – Single-line diagram of the analysed low voltage network, two routes, and measurement locations on each route in red, green and blue ..... 41
Figure 41 – Transfer ratios along two routes in a low voltage network with residential customers, upstream direction as circles, downstream direction as crosses ..... 42
Figure 42 – Equivalent circuit (model) for the supraharmonic emission of single-phase voltage-source power converters for the $m^{th}$ emission band ..... 43
Figure 43 – RMS voltage spectrum $U_S$ at the output terminals of a single-phase power converter H-bridge using unipolar PWM ..... 43
Figure 44 – Amplification and damping of supraharmonic emission at the POC relatively to the source voltage depending on the network to source impedance ..... 45
Figure 45 – Circles of constant POC voltage in the dominant emission band of two photovoltaic inverters [29] ..... 46
Figure 46 – Prevailing phase angle of 187 measured network loop impedances [34]between 2 kHz and 150 kHz, phase angle of the line impedance stabilization network from CISPR 16-1-2 ..... 46

Figure 47 – Cumulative distribution function (CDF) of non-intentional emissions due to distributed energy sources at two different frequencies (45,7 kHz and 118,4 kHz) and noise present in the electrical grid (122,9 kHz) ..... 47

Figure 48 – Identification of the frequencies in the frequency response ..... 47

Figure 49 – Identification of the frequencies in the spectrogram of the measurements (see case study [23]) ..... 48

Figure 50 – Parallel-connect configuration in large photovoltaic (PV) farm ..... 49

Figure 51 – Simplified parallel of two converters featuring LCL filter and capacitor on common bus for reactive compensation in the grid (see Table 7) ..... 49

Figure 52 – Frequency domain results of parallel LCL filter system with reactive power compensation capacitor represented in two frequency ranges ..... 50

Figure 53 – $N$ parallel connected equivalent inverter models equipped with LCL filter interfaces connected to common grid impedance $\boldsymbol{Z}_{\mathrm{g}}$ as parallel connection of Thévenin's equivalent voltage sources and equivalent impedances ..... 51

Figure 54 – Change in Bode plot of $i_{\mathrm{sg}}/i_{\mathrm{s11}}$ (ratio of grid and inverter side currents respectively) or LCL-filter topology when the number of parallel connected inverters $n$ increases from 2 to 8 with increments of 2 ..... 51

Figure 55 – Time domain simulations of parallel LCL system without reactive power compensation capacitor dependent on (in dependency of) a small sinusoidal disturbance term added in the control loop – Duty cycle ..... 51

Figure 56 – Power line impedance in lower frequency range measured with 0 to 59 inverters activated in a 2,1 MW PV plant ..... 52

Figure 57 – Power line impedance measured with 0 to 59 inverters activated in a 2,1 MW PV plant ..... 53

Figure 58 – Configuration of an industrial grid ..... 54

Figure 59 – Interaction between two converters, which can lead to resonances and generate non-intentional emissions in the 2 kHz to 150 kHz frequency range ..... 54

Figure 60 – Modeling of a simple configuration of noise source and noise sink, where the EMI filter of the sink converter can be of $2^{\mathrm{nd}}$, $3^{\mathrm{rd}}$ or $4^{\mathrm{th}}$ order [25] ..... 55

Figure 61 – Impedance into the noise sink converter $Z_{\mathrm{sink}}$ with different EMI filter types with simple choke interface only and different EMI filter configurations ..... 55

Figure 62 – Impedance into the noise sink converter $Z_{\mathrm{sink}}$ with different EMI filter types with LCL interface and different EMI filter configurations ..... 56

Figure 63 – Ratio of voltage and current in phase 1 with a third-order EMI filter and different cables with: a) DM excitation and b) CM excitation ..... 57

Figure 64 – Voltage at 10 kHz of one to four BEVs charging at a common POC, time varying values as solid line (20 ms measurement windows), overall RMS as dotted line ..... 58

Figure 65 – Supraharmonic voltages and currents at the POC of multiple AC charging points, first emission band (800 Hz) centred around 10 kHz ..... 59

Figure 66 – Single-line diagram of an arbitrary number $N$ of power converters operating in parallel on a single network phase ..... 60

Figure 67 – Supraharmonic emission model for an arbitrary number $N$ of power converters operating in parallel ..... 60

Figure 68 – Simulation of supraharmonic beating using summation of rotating phasors, for one up to three sources with different frequencies and magnitudes of contribution, first emission band ..... 61

Figure 69 – Exemplary assessment of the supraharmonic emission of two photovoltaic inverters using the criteria in Formula (19) to Formula (21), and photovoltaic inverters from [15] ..... 64

Figure 70 – Dependency of the POC voltage on the number of sources $N$ for different magnitude ratios of source impedance to network impedance assuming phase angles of source impedance and network impedance are equal ..... 65
Figure 71 – Single phase inverter with an LCL filter and corresponding state variables ..... 66
Figure 72 – Block scheme equivalent to the formula system of Figure 71 ..... 67
Figure 73 – Linearized control loop for the in-feed converter and transfer functions for feed forward and current measurement filter ..... 68
Figure 74 – Norton equivalent circuit of the single-phase inverter ..... 69
Figure 75 – Nyquist stability analysis of the control loop with parameters listed in Table 8 ..... 70
Figure 76 – PLECS model of the single-phase inverter with LCL filter ..... 71
Figure 77 – PLECS model of the single-phase inverter controller with Feedforward of the connecting point voltage ..... 71
Figure 78 – Simulation result of a current reference step of 0 A to 10 A for the converter ..... 72
Figure 79 – Impedance magnitude (a) and phase angle characteristic (b) of commercially available single-phase inverter (black), network impedance with inductance of 2,3 mH (blue) and 3,2 mH (red) ..... 73
Figure 80 – Grid-side current measurements for $LR$-equivalent network impedance with inductance values of 2,3 mH (a) and 3,2 mH (b) ..... 74
Figure 81 – Small signal model of an inverter and the low voltage network ..... 74
Figure 82 – Magnitude (a) and phase angle of low voltage network impedance measurements at 120 measurement sites ..... 75
Figure 83 – Magnitude (a) and phase angle of the impedance of six commercially available inverters ..... 75
Figure 84 – Critical frequency regions of commercially available inverters (a) and measurement sites in LV networks (b) ..... 76
Figure 85 – Electrical network including the network and four electrical vehicles connected (described in the EMTP program) ..... 77
Figure 86 – Description of the different elements considered ..... 78
Figure 87 – Description of the filter connecting the boost to the electrical network ..... 78
Figure 88 – Description of the low frequency filter ..... 78
Figure 89 – Description of the converter of the boost PFC converter, including its AC/DC rectifier ..... 79
Figure 90 – Current $i_{\mathrm{d}}$ flowing in the electronic components (diodes, IGBTs) versus positive values of the applied voltage $V_{\mathrm{d}}$ ..... 79
Figure 91 – Voltage $V_{\mathrm{c}}$ at the entrance of the charger, obtained by simulations, for different values of the upstream network ..... 80
Figure 92 – Description of the phase-space diagram corresponding to the main state-variables of the system ..... 80
Figure 93 – Current crossing an IGBT obtained by simulations, with an inductance value of 600 μH for the upstream network ..... 81
Figure 94 – Voltage $V_{\mathrm{cmeas}}$ at the entrance of the charger, measured at the manufacturer's laboratory, for a value of 750 μH for the inductance of the upstream network ..... 81
Figure 95 – Description of the circuit including a solar PV–micro turbine based power system with battery backup ..... 83
Figure 96 – PCC (grid) voltage with linear and non-linear loads in the absence of any VSI (voltage source inverter) ..... 83
Figure 97 – Grid working and VSI switched on at $t$ = 0,5 s ..... 84

Figure 98 – Grid working and VSI switched on at $t$ = 0,5 s ..... 85
Figure 99 – Frequency characteristic of the 3 kW PV system with L-C-L filter in the following grid conditions: A) 0,1 mH, B) 3 mH, C) 0,1 mH, 100 µF and D) 3 mH, 100 µF ..... 85
Figure 100 – Resonance frequency variation in per cent of the rated resonance frequency as a function of grid inductance in per cent ..... 86
Figure 101 – Illustration of a quasi-periodic route to chaos in a buck-boost converter, with the input voltage as a bifurcation parameter ..... 87
Figure 102 – Experimental illustration of period doubling route to chaos in buck-boost converter ..... 87
Figure 103 – Grid-connected DFIG WT system ..... 88
Figure 104 – DFIG PQ limitation due to $SCR$ and $X/R$ variation ..... 88
Figure 105 – System response to different network strength ..... 89
Figure 106 – Structure of a hybrid system proposed for a microgrid application ..... 90
Figure 107 – Control for a hybrid PV-battery system ..... 90
Figure 108 – Variation of the voltage at the PV terminals and current in the battery ..... 90
Figure 109 – Regulation of the voltage when the load is changing ..... 91
Figure 110 – Current in the battery during variation of the voltage at the PV terminals during the change of load ..... 91
Figure 111 – Microgrid system configuration and main features ..... 92
Figure 112 – Designed PV microgrid system (left) and control set up of the PV microgrid at the Griffith University, Australia (right) ..... 92
Figure 113 – Disturbance rejection response comparison in the intentional islanding scenario ..... 93
Figure 114 – Description of a “test bench” at the laboratory ..... 93
Figure 115 – Evolution of the measured current as a function of the charging setpoint ..... 94
Figure 116 – Normalized input AC current waveforms of typical electronic appliances for sinusoidal (left) and flat-top (right) supply voltage waveforms ..... 95
Figure 117 – Impact of voltage magnitude on harmonic current emission for different topology categories (sinusoidal waveform) ..... 96
Figure 118 – Impact of flat top voltage waveform on harmonic current emission for different topology categories (nominal RMS voltage) ..... 96

Table 1 – Relation between measured current and respective impedance for each feeder ..... 21
Table 2 – Devices and topologies used in the different evolution stages ..... 22
Table 3 – Load scenarios depending on the evolution stages and loading conditions ..... 22
Table 4 – Equivalent $R_{L1}L_1 || R_{L2}L_2C_2$ parameter values ..... 23
Table 5 – Ratio between network harmonic impedance and extrapolated impedance for various cases ..... 24
Table 6 – Load scenarios ..... 29
Table 7 – Values of the system parameters [23] ..... 49
Table 8 – Example of system parameters and components for the Nyquist stability analysis ..... 71
Table 9 – Grid-compatibility index of commercially available single-phase inverters ..... 76

INTERNATIONAL ELECTROTECHNICAL COMMISSION

_____

# ELECTROMAGNETIC COMPATIBILITY –

# Part 2-15: Description of the characteristics of networks with high penetration of power electronic converters

## 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 61000-2-15 has been prepared by subcommittee 77A: EMC – Low frequency phenomena, of IEC technical committee 77: Electromagnetic compatibility. It is a Technical Report.

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

| Draft | Report on voting |
|---|---|
| 77A/1153A/DTR | 77A/1159/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/publications.

A list of all parts in the IEC 61000 series, published under the general title *Electromagnetic compatibility*, 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

IEC 61000 is published in separate parts according to the following structure:

**Part 1: General**

General considerations (introduction, fundamental principles)

Definitions, terminology

**Part 2: Environment**

Description of the environment

Classification of the environment

Compatibility levels

**Part 3: Limits**

Emission limits

Immunity limits (insofar as these limits do not fall under the responsibility of the product committees)

**Part 4: Testing and measurement techniques**

Measurement techniques

Testing techniques

**Part 5: Installation and mitigation guidelines**

Installation guidelines

Mitigation methods and devices

**Part 6: Generic standards**

**Part 9: Miscellaneous**

Each part is further subdivided into several parts, published either as international standards or as technical specifications or technical reports, some of which have already been published as sections. Others will be published with the part number followed by a dash and a second number identifying the subdivision (example: IEC 61000-6-1).

This part of IEC 61000-2 describes the main phenomena which affect the power quality of modern distribution systems with high penetration of power electronics converters.

It focuses on the following main aspects: resonances in LV network, impact of increased number of power electronic converters, instability issues for the equipment to be connected to the LV networks.

Those new aspects, organized and described in this document, can lead to new IEC specifications; that is why a state of the art on this topic is necessary.

# ELECTROMAGNETIC COMPATIBILITY –

# Part 2-15: Description of the characteristics of networks with high penetration of power electronic converters

## 1 Scope

This part of IEC 61000, which is a Technical Report, addresses in particular the following main phenomena, which affect the power quality in modern distribution systems with high penetration of power electronics converters. As some aspects of the subject have already been addressed in the past, considering the evolution of the LV and MV networks, this document focuses on the following aspects:

- resonances in the network, modelling and on-site validation;
- supraharmonics and measurements issues;
- impact of increased number of power electronic converters;
- stability and instability issues for the equipment to be connected

The target phenomena and conditions of this document are the following:

- frequency: ≤ 2 kHz, 2 kHz to 9 kHz, ≥ 9 kHz;
- voltage levels: LV, MV;
- harmonic sources: all types of converters (EV battery chargers, appliances, etc.…).

Some of these frequency ranges have already been standardized in some countries (Japan, Germany, Switzerland, etc.), but the resulting phenomena developed will benefit being described in more details, with a focus on the interaction between the converters and the electrical networks. The case of the presence of a large number of converters is also at stake. Some complex phenomena can also arise when the full system is not stable anymore.

NOTE Whereas it is expected that the models and derived calculations form this document can be applied to the Americas electrical systems its formal validation studies are still pending.

## 2 Normative references

There are no normative references in this document.