



BSI Standards Publication

Power quality management

Part 100: Impact of power quality issues on electric equipment and power system

National foreword

This Published Document is the UK implementation of IEC TR 63222-100:2023.

The UK participation in its preparation was entrusted to Technical Committee GEL/8, Systems Aspects for Electrical Energy Supply.

A list of organizations represented on this committee can be obtained on request to its committee manager.

Contractual and legal considerations

This publication has been prepared in good faith, however no representation, warranty, assurance or undertaking (express or implied) is or will be made, and no responsibility or liability is or will be accepted by BSI in relation to the adequacy, accuracy, completeness or reasonableness of this publication. All and any such responsibility and liability is expressly disclaimed to the full extent permitted by the law.

This publication is provided as is, and is to be used at the recipient's own risk.

The recipient is advised to consider seeking professional guidance with respect to its use of this publication.

This publication is not intended to constitute a contract. Users are responsible for its correct application.

This publication is not to be regarded as a British Standard.

© The British Standards Institution 2023
Published by BSI Standards Limited 2023

ISBN 978 0 539 19831 7

ICS 29.020

Compliance with a Published Document cannot confer immunity from legal obligations.

This Published Document was published under the authority of the Standards Policy and Strategy Committee on 30 September 2023.

Amendments/corrigenda issued since publication

Date	Text affected
------	---------------

TECHNICAL REPORT



Power quality management – Part 100: Impact of power quality issues on electric equipment and power system

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 29.020

ISBN 978-2-8322-7443-9

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

CONTENTS

FOREWORD.....	6
INTRODUCTION.....	8
1 Scope.....	9
2 Normative references	9
3 Terms and definitions	9
4 General impacts of power quality issues.....	12
4.1 General.....	12
4.2 Harmonic distortion	12
4.3 Voltage unbalance	13
4.4 Voltage deviation	13
4.5 Frequency deviation.....	13
4.6 Flicker and rapid voltage change	14
4.7 Voltage dip	14
4.8 Transient over-voltages	14
4.9 Voltage swell	14
5 Continuous power quality disturbances impact.....	14
5.1 The impact of voltage deviation.....	14
5.1.1 General	14
5.1.2 Impact on equipment	16
5.1.3 Impact on power system	17
5.2 The impact of frequency deviation.....	18
5.2.1 General	18
5.2.2 Impact on electrical equipment	19
5.3 The impact of voltage unbalance.....	21
5.3.1 General	21
5.3.2 Impact on electrical equipment	22
5.3.3 Impact on power system	27
5.3.4 Impact on electrical equipment	30
5.3.5 Impact on power system	32
5.3.6 Impact on electrical equipment	34
5.3.7 Impact on electrical equipment	40
6 Discontinuous power quality disturbances impact	41
6.1 The impact of voltage dip and short time interruptions	41
6.1.1 General	41
6.1.2 Impact on power system equipment	42
6.1.3 Effects on end users' devices	43
6.1.4 Useful impacts assessment indices.....	45
6.2 The impact of voltage swell.....	47
6.2.1 General	47
6.2.2 Impact on power system	48
6.2.3 Effects on some electrical equipment.....	48
6.3 The impact of transient over-voltage	49
6.3.1 General	49
6.3.2 Impact on power system equipment	49
6.3.3 Effects on some electrical equipment.....	50
Annex A (informative) Case analysis: Voltage deviation impact on power loss	52

A.1	Loss of low voltage distribution network	52
A.1.1	Transformer iron loss	52
A.1.2	Transformer copper loss	52
A.2	LED Lights	55
Annex B (informative)	Case analysis: Voltage unbalance impact	57
B.1	Three-phase unbalance leads to voltage deviation	57
B.2	Increases the loss of power network	58
Annex C (informative)	Case analysis: flicker and rapid voltage change impact	61
C.1	The impact of RVC on induction motor	61
C.2	The impact of RVC on electrolytic capacitor lifetime	63
C.3	The experiment of the impact of voltage fluctuation on induction motor life	64
C.4	Voltage fluctuation reduces the energy efficiency	67
Annex D (informative)	Case analysis: Harmonic, inter-harmonic and the high frequency component impact	70
D.1	Harmonic impact on tripping time of relay protection device	70
D.2	The impact of harmonics on billable meters in Markal, Dist. Pune Steel Mill	71
D.3	The impact of harmonics on power cable	72
D.3.1	Parameter aspect	72
D.3.2	Performance aspect	73
D.4	The impact of inter-harmonics on sub-synchronous oscillation of power system	74
Annex E (informative)	Case: Voltage dip impact	76
E.1	Voltage dip sensitive equipment tolerance test	76
E.1.1	Alternating current contactor (ACC) voltage dip tolerance results	76
E.1.2	PLC voltage dip tolerance test and test results	78
E.1.3	Relay voltage dip tolerance test and test results	81
E.2	Voltage dip sensitive industrial customers	87
Annex F (informative)	Case: Voltage swell impact	88
Annex G (informative)	Case: Transient over-voltage impact	89
G.1	Test waveform	89
G.2	Case of interaction between the power system and communications system	89
G.3	Case of 10kV hybrid OHL-cable system during energization	89
Bibliography		90
Figure 1	–The influence of under-voltage deviation on transmission loss	18
Figure 2	– Derating factor for motors operating with phase voltage unbalance	23
Figure 3	– Percentage changes in torques of induction motor	24
Figure 4	– Standard drive with DC-link LC filter under 5 % grid voltage amplitude unbalanced condition	27
Figure 5	– Proportion of neutral line additional loss (%)	28
Figure 6	– Neutral shift vector diagram	29
Figure 7	– Capacitor current value under different voltage fluctuations condition	32
Figure 8	– Current waveform and spectrum, transformer derating due to current harmonic losses up to 2 kHz	35
Figure 9	– Effect of harmonics on power loss	38
Figure 10	– Effect of harmonics on temperature rise	39

Figure 11 – Effect of harmonics on expected useful life	39
Figure 12 – ITIC (CBEMA) curve for equipment connected to 120 V 60 Hz systems...	44
Figure 13 – Region of uncertainty for sensitivity curves of equipment	45
Figure A.1 – Equivalent circuit diagram of low voltage distribution network	52
Figure A.2 – The relationship between the ratio of constant impedance load to constant power load and voltage deviation in the connected system when the additional copper loss is 0	54
Figure A.3 – U-I curves of four LED lamps	56
Figure A.4 – P-U curves of four LED lamps	56
Figure B.1 – Guowan #2 station	57
Figure B.2 – Voltage curve of Guowan #2 station on January 27	57
Figure B.3 – Three – phase power curve of Guowan #2 station on January 27	58
Figure B.5 – Losses vs. unbalance factor	60
Figure C.1 – Energy efficiency indexes of A phase when the frequency of am wave is 8,8 Hz	61
Figure C.2 – Energy efficiency indexes of A phase when the amplitude modulation is 10 % (based on 50Hz system)	62
Figure C.3 – Motor lifetime estimation with load torque gradually increase subject to 10 % voltage magnitude change and different modulation frequency	64
Figure C.4 – Motor lifetime estimation with load torque gradually increase subject to 10 % voltage magnitude change and different modulation frequency	64
Figure C.5 – The comparison of motor lifetime between voltage fluctuations condition and normal condition	65
Figure C.6 – Motor lifetime estimation with light load subject to various voltage fluctuations	66
Figure C.7 – Motor lifetime estimation with heavy load subject to various voltage fluctuations	67
Figure C.8 – Three-dimensional diagram of copper loss of A phase stator	68
Figure C.9 – Three-dimensional diagram of copper loss of A phase rotor	68
Figure C.10 – Three-dimensional diagram of iron loss of A phase	68
Figure C.11 – Three-dimensional diagram of energy efficiency of A phase	69
Figure D.1 – Test setup	70
Figure D.2 – Tripping time with distortion current (each test for each order harmonic with 20% distortion)	71
Figure D.3 – Recording kWh consumption at HT consumer metering installation	72
Figure D.4 – Effect of harmonics on resistance (R)	72
Figure D.5 – Effect of harmonics on inductance (L)	72
Figure D.6 – Effect of harmonics on power loss	73
Figure D.7 – Effect of harmonics on temperature rise	74
Figure D.8 – Effect of harmonics on expected lifetime	74
Figure E.1 – VTC (voltage tolerance curve) under different POW	76
Figure E.2 – VTC (voltage tolerance curve) under different PAJ	77
Figure E.3 – Voltage tolerance curve of each PLC	78
Figure E.4 – Voltage tolerance curves of P1 and P3 at different starting phases	79
Figure E.5 – Voltage tolerance curve of P1 at different supply voltages	80
Figure E.6 – The relation curve between different harmonic phases and U_{dc}	80

Figure E.7 – When THD is 5 % and 10 %, the voltage tolerance curve of P3 of different sub-harmonics is tested at 0° of harmonic phase	81
Figure E.8 – Voltage dip sensitivity curve of R1 relay at the starting point of 0°-360°	82
Figure E.9 – The maximum normal operating duration curve of R1 relay obtained at voltage dip starting point from 0° to 360°	83
Figure E.10 – Sensitivity curves of 8 relays obtained at voltage dip starting point of 0° and 90°	84
Figure E.11 – Critical voltage difference	85
Figure E.12 – VTC under voltage dips with/without harmonics	85
Figure E.13 – Sensitivity curves of R1 and R4 relays influenced by operation voltage before voltage dip occurring at voltage dip starting point 0°/90°	86
Table E.4 – Successive dips testing information	86
Table 1 – reference information of voltage deviation impacts	15
Table 2 – reference documents on impact of frequency deviation	19
Table 3 – reference documents on the impact of voltage unbalance	22
Table 4 – Effect of voltage Unbalance on motors at full load	24
Table 5 – Line loss and additional loss increase under three-phase current unbalance	28
Table 6 – Reference documents on the impact of flicker and RVC	30
Table 7 – Reference documents on impact of harmonic and inter-harmonic	33
Table 8 – The actual measured capacitance value change rate	37
Table 9 – Reference documents on impact of voltage dip and short time interruption	42
Table 10 – reference documents on impact of voltage swell	48
Table 11 – Reference documents for impact evaluation of transient over-voltages	49
Table A.1 – Test object parameters	55
Table A.2 – Raw data of fluorescent lamp under AC power supply	55
Table B.1 – Simulation results of output voltage	58
Table B.2 – Load distribution (L1, L2 and L3) and unbalance index D (%) for the 6 KVA network	59
Table B.3 – Load distribution (L1, L2 and L3) and unbalance index D (%) for the 18 KVA network	59
Table B.4 – Load distribution (L1, L2 and L3) and unbalance index D (%) for the 180 KVA network	59
Table C.1 – The variation trend of motor energy efficiency η with voltage fluctuation (%)	69
Table D.1 – Test 1 THD=20 %	71
Table E.1 – Tested ACC	76
Table E.2 – Tested PLC equipment	78
Table E.3 – Number and type of low voltage relay	81

INTERNATIONAL ELECTROTECHNICAL COMMISSION

POWER QUALITY MANAGEMENT –

**Part 100: Impact of power quality issues
on electrical equipment and power system**

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 63222-100 has been prepared by IEC technical committee 8: System aspects of electrical energy supply. It is a Technical Report.

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

Draft	Report on voting
8/1648/DTR	8/1660/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 63222 series, published under the general title *Power quality management*, 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

The impacts of power quality issues increasingly attract much attention with modern industrial development. The integration of nonlinear loads, such as power-electronic based equipment, electric arc furnace, electric locomotive, etc., and faults or other events such as short-circuit and lightning strikes directly or indirectly cause power quality issues.

If public supply system power quality is not within the reasonable range defined in IEC TS 62749, and/or the demand-side power quality is not appropriately managed (e.g. IEC TR 63191) and/or the equipment immunity does not accommodate the expected environment, the performance of equipment may be impacted, likely causing malfunction, maloperation, or damage, and likewise the power system itself.

On the other hand, the quality of power is not absolute. Regarding the levels of power quality, the situation differs. So called “poor” power quality level for one grid may be acceptable or good for another internal application depending on the system configuration, the transfer characteristics between the different voltage levels (attenuation or amplification), the immunity of the equipment /installations/appliances, the actual disturbance levels on the system, etc.

In terms of power quality, the situation in micro-grid on islanding mode, off grid, mini-grid or weak grid may differ from that in public supply system. The level of power quality may worsen even far outside the recommended values defined by IEC TS 62749. In those forementioned grids, appliances may need to be better designed for immunity to power quality issues.

This document, which is a Technical Report, collects relevant information on power quality impact from, e.g., CIGRE reports, case study, research findings, etc., in order to uncover the mechanism of how electrical equipment/installations are impacted under specific power quality condition, as well as to fully understand the reasons of power quality management.

This document focuses on the public supply system. Notionally, the mechanisms of how electrical equipment/installations/system are impacted by power quality disturbances are applicable for so-called weak grids.

The contents of this document can help network users and equipment suppliers make rational investments and actively cooperate with network operators to take specific measures to improve power quality.

The contents of this document can also support IEC TR 63222-101, namely, power quality management-power quality data applications.

POWER QUALITY MANAGEMENT –

Part 100: Impact of power quality issues on electrical equipment and power system

1 Scope

This part of IEC 63222, which is a Technical Report, collects relevant information on power quality impacts from, e.g., CIGRE reports, case studies, research findings, etc., in order to uncover the mechanisms of how electrical equipment/installations/system are impacted by power quality disturbances, as well as to fully understand the guidelines for power quality management.

The contents of this document aim to help network operators, network users and equipment suppliers make rational investments and actively cooperate to manage power quality and keep it consistent with relevant EMC standards.

NOTE 1 The boundaries between the various voltage levels may be different for different countries/regions. In the context of this document, the following terms for system voltage are used:

- low voltage (LV) refers to $U_N \leq 1 \text{ kV}$
- medium voltage (MV) refers to $1 \text{ kV} < U_N \leq 35 \text{ kV}$
- high voltage (HV) refers to $35 \text{ kV} < U_N \leq 230 \text{ kV}$

NOTE 2 Because of existing network structures, in some countries/regions, the boundary between medium and high voltage can be different.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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

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

3.1

electricity

set of phenomena associated with electric charges and electric currents

Note 1 to entry: In the context of electric power systems, electricity is often described as a product with particular characteristics.

[SOURCE: IEC 60050-121:1998, 121-11-76]

3.2

flicker

impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time

[SOURCE: IEC 60050-161:1990, 161-08-13]

3.3

frequency deviation

difference between power supply frequency ($f_{h,1}$) and nominal frequency (f_n)

[SOURCE: IEC 60050-614:1990, 614-01-10, modified]

3.4

harmonic frequency

$f_{H,h}$ (abbreviation)

the frequency which is an integer multiple of the power supply (fundamental) frequency

[SOURCE: IEC 61000-4-7:2009, 3.2.1, modified (removal of formula and Note to entry)]

3.5

Harmonic order

h (abbreviation)

(Integer) the ratio of a harmonic frequency ($f_{H,h}$) to the power supply frequency ($f_{H,1}$)

[SOURCE: IEC 60050-161:1990, 161-02-19, modified]

3.6

System operator

network operator

the party responsible for safe and reliable operation of a part of the electric power system in a certain area and for connection to other parts of the electric power system

[SOURCE: IEC 60050-617:2009, 617-02-09]

3.7

nominal frequency

f_N (abbreviation)

value of frequency used to designate or identify a system

3.8

nominal voltage (of a system)

U_N (abbreviation)

value of voltage used to designate or identify a system

[SOURCE: IEC 60050-601:1985, 601-01-21, modified (addition of abbreviation, removal of "suitable approximate" from the beginning of definition)]

3.9

point of common coupling

PCC (abbreviation)

point in a public power supply network, electrically nearest to a particular load, at which other loads are or may be connected

Note 1 to entry: These loads can be either device, equipment or systems, or distinct network user's installations.

[SOURCE: IEC 60050-161:1990, 161-07-15, modified ("consumer's installation" replaced by "load")]

3.10**supply terminals****point of supply**

point in a distribution network designated as such and contractually fixed, at which electric energy is exchanged between contractual partners

Note 1 to entry: Supply terminals may be different from the boundary between the electricity supply system and the user's own installation or from the metering point.

[SOURCE: IEC 60050-617:2009, 617-04-02, modified Note 1 to entry]

3.11**(power) network user**

party supplying electric power and energy to, or being supplied with electric power and energy from, a transmission system or a distribution system

[SOURCE: IEC 60050-617:2009, 617-02-07]

3.12**power quality**

characteristics of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters

Note 1 to entry: These parameters might, in some cases, relate to the compatibility between electricity supplied on a network and the loads connected to that network.

Note 2 to entry: In the context of this Technical Specification, power quality refers to supply terminals and focuses on defining the characteristics of the voltage and frequency.

[SOURCE: IEC 60050-617:2009, 617-01-05, modified ("electric current, voltage and frequencies" replaced by "electricity" and Note 2 to entry added)]

3.13**rapid voltage change****RVC (abbreviation)**

quick transition (that may last more than several cycles) in RMS voltage between two steady-state conditions while the voltage stays in-between the thresholds defined for voltage swells and dips (otherwise, it would be considered as a swell or a dip)

Note 1 to entry: For more information, see IEC 61000-4-30.

3.14**transient over-voltage****voltage surge**

transient voltage wave propagating along a line or a circuit and characterized by a rapid increase followed by a slighter decrease of the voltage

[SOURCE: IEC 60050-161:1990, 161-08-11]

3.15**voltage deviation**

difference between supply voltage (U) and nominal voltage (U_N), often expressed by relative value

Note 1 to entry: In some circumstance, U_N may be replaced by U_C by contract or agreement.

3.16**voltage dip**

sudden reduction of the voltage at a point in an electrical system followed by voltage recovery after a short period of time, usually from a few cycles to a few seconds

Note 1 to entry: The starting threshold of voltage dip generally is 90 % of the reference voltage.

[SOURCE: IEC 60050-161:1990, 161-08-10, modified (addition of Note 1 to entry)]

3.17

voltage fluctuation

series of voltage changes or a cyclic variation of the supply voltage envelope

Note 1 to entry: For the purpose of this document, the reference voltage is the nominal or declared voltage of the supply system.

[SOURCE: IEC 60050-161:1990, 161-08-05, modified (addition of "supply voltage" and Note 1 to entry)]

3.18

voltage swell

sudden increase of the voltage at a point in an electrical system followed by voltage recovery after a short period of time, usually from a few cycles to a few seconds

Note 1 to entry: The starting threshold of voltage swell generally is 110 % of reference voltage.

3.19

voltage unbalance

in a poly-phase system, a condition in which the magnitudes of the phase voltages or the phase angles between consecutive phases are not all equal (fundamental component)

[SOURCE: IEC 60050-161:1990, 161-08-09, modified ("RMS values" replaced by "magnitudes")]

3.20

voltage unbalance factor

in a three-phase system, the degree of unbalance is expressed by the ratio (in per cent) between the RMS values of the negative sequence (or, rarely, of the zero-sequence) component and the positive sequence component of voltage

[SOURCE: IEC 60050-604:1987, 604-01-30, modified (addition of "voltage" to term)]

4 General impacts of power quality issues

4.1 General

Generally, for electrical equipment exposing under continuous power quality phenomenon disturbances, the impacts of long-time accumulated effects may be the key aspect, while immediate impact may arise in case of events of discontinuous power quality phenomenon, e.g., voltage dip/swell/short time interruption.

IEC TS 62749:2020, Annex C describes the general impacts of power quality issues. This clause refers to IEC TS 62749:2020, Annex C.

4.2 Harmonic distortion

Generally, harmonic impacts due to long-time accumulated effects are often of concern, but harmonic resonance will lead to harmonic over-voltage which will lead to harmonic over-voltage which produces dielectric stress of electrical equipment, and even causes dielectric breakdown.

- Capacitors for power factor correction often act as sinks for a particular order of harmonic currents. In this case, it can lead to capacitor over current if no forethought is given at the designing stage.
- Non-sinusoidal power supplies result in the reduction of torque of induction motors.

- Harmonics will increase interference with telephone, communicating and analogue circuits.
- Excessive levels of harmonics can cause errors in the reading of induction type energy meters which are calibrated for pure sinusoidal AC power.
- High-order harmonics cause voltage stresses.
- Harmonic currents flowing through power system networks can cause additional losses.

It is reported that the level of inter-harmonics in power supply systems is increasing due to the development of frequency converters and similar electronically controlled equipment. Harmonic voltages and inter-harmonic voltages, if not controlled, might lead (among other effects) to overloading or disturbance of equipment on the supply networks and in electricity users' installations.

In some cases, inter-harmonic voltages, even at low levels, can give rise to flicker or cause interference in ripple control systems.

4.3 Voltage unbalance

Voltage unbalance is always a concern as it affects the transformers, electrical motors, electrical generators, transmission losses and relay protection.

- Voltage unbalance degrades the performance and shortens the life of a three-phase motor.
- Current unbalance caused by voltage unbalance essentially creates counter-torque (resisting torque). That is, it tries to make the motor turn in the opposite direction. This may create heating.
- Voltage unbalance may also reduce the capacity of equipment such as motors or generators if not properly taken into consideration at the design stage (equipment is normally designed and rated to account for some degree of voltage unbalance normally present in any power system).
- Voltage unbalance causes distance protection and negative-sequence protection to malfunction, which may result in abnormal starting or even tripping of relay protection.
- Current unbalance caused by voltage unbalance may cause additional losses of distribution lines and cable lines. It may also lead to the shift of neutral point of high voltage side of the transformer.
- Voltage unbalance may increase non-characteristics harmonics produced by converters.
- Voltage unbalance may transfer triple harmonic currents in the transmission system, normally blocked by delta-connected transformer windings.

4.4 Voltage deviation

Large voltage deviations from the nominal values may shorten the life of electrical equipment, lower the stable limit of the power system, increase the cost of network operation and reduce the output of reactive power compensation. Electrical equipment operating under this condition may malfunction, break down or be damaged.

4.5 Frequency deviation

Frequency deviation will endanger the reliability and stability of power system operation and production efficiency of end-users. The rapid change of frequency will bring great harm to the normal operation of the equipment of units, such as induction motor or feed water pump. The accuracy of the energy meter may be impacted by the frequency deviation. Frequency disturbances in the main network causing local electrical resonance may lead to a large-scale off-grid accident of renewable energy, e.g. sub-synchronous resonance.

If frequency deviation exceeds the limit, motors are usually protected by means of stopping their operation. Sustained operation will alter the speed of motors and potentially create unsafe conditions for the processes in which they function.

Where frequency deviations occur frequently, such as islanded power systems, users may notice time drift with their analogue clocks.

4.6 Flicker and rapid voltage change

Flicker is considered to be an annoying problem for network users. Most of the time, it does not have a high financial impact. However, at high levels it can cause inconvenience and adverse health effects to people when frequent flickering of lights (different technology of lamps may have different sensitivity to voltage fluctuation) occurs at their work-places or homes.

Flicker can cause photosensitive epileptic seizures, asthenopia (i.e. eyestrain) and stroboscopic effects (noting that stroboscopic effects pose a danger in industrial settings due to the possibility that rotating machinery can appear stationary).

Voltage fluctuations and rapid voltage change can cause a number of harmful technical effects such as data errors, memory loss, equipment shutdown, flicker, motors stalling and reduced motor life, resulting in disruption to production processes and substantial costs. In addition, large voltage fluctuations damage electrical equipment such as LED lamps.

4.7 Voltage dip

Motor drives, including variable speed drives, are particularly susceptible because the load still requires energy that is no longer available except the inertia of the drive. In processes where several drives are involved, individual motor control units may sense the loss of voltage and shut down the drive at a different voltage level from its peers and at a different rate of deceleration, resulting in a complete loss of process control. Data processing and control equipment is also very sensitive to voltage dips and can suffer from data loss and extended downtime.

4.8 Transient over-voltages

Transient over-voltage can cause large dV/dt values that can damage or reduce the lifetime of variable speed drives, motors, transformers, and cables. It also causes the abnormal operation of wind farms, HVDC systems and energy systems along with flash-over and partial discharge phenomena and damage their key equipment after events.

4.9 Voltage swell

Voltage swell can affect the operation of wind turbines and may lead it off the grid. When the grid voltage is disturbed by a temporary rise, the stator flux will generate positive (forced) component, negative (asymmetric temporary rise) component and DC (free) component, which will generate over-voltage at wind turbine.

Besides, the surge arresters can be exposed to swells during their lifetime. If the voltage is high enough, a swell is likely to damage or destroy the surge arrester. There are indications that swells can damage surge arresters more often than surges.

5 Continuous power quality disturbances impact

5.1 The impact of voltage deviation

5.1.1 General

Voltage deviations from nominal levels will affect electrical equipment for power suppliers and end-users. The performance of the equipment under different voltage deviation levels is identified using the equations and flowchart in the references in Table 1.

Table 1 – reference information of voltage deviation impacts

Equipment		Impact description	Reference
Electrical equipment	DC and AC Electric Motor	• An increase in power loss. • A reduction in load-carrying capacity. • An incremental change in winding temperature. • Under deviation results in reduced starting torque and increased full load temperature rise. • Over deviation results in increased torque, increased starting current, and decreased power factor. • Increase of even and triple harmonics (case saturation).	Ref.[1] P82,83 Ref. [2] P1095Ref. [10] P3
	Illumination Equipment	• The light output of Illumination equipment. • The lifetime of Illumination equipment. • Perform below the minimum acceptable illumination level.	Ref. [1] P84 Ref. [4] P53
	Household Appliances	• Perform less efficiently. • Higher losses and reduced lifetime. • Malfunction of the equipment. • Damage of the appliances	Ref. [1] P85 Ref. [3] P1064
	Transformer	• High voltage will increase the magnetizing current of a transformer. • Over deviation will accelerate insulation aging • Under deviation will increase winding loss. • More inrush current if high power supply voltage.	Ref. [4] P53 Ref. [5] P55
	Industrial Equipment	• Increase power loss. • The quality of the product is declining. • The output is reduced. • Equipment damage. • Reduced Lifetime.	Ref. [5] P55
	Power electronic Converter	• The current-carrying ability. • The firing order on the thyristor could be inefficient. • Damage of the component.	Ref. [1] P86
Power system	Reactive power compensation	• The reactive power output of capacitors varies with the square of the impressed voltage. • Under deviation reduces the output reactive power. • Over deviation reduces insulation life. • Increase temperature/cost of supply.	Ref. [5] P55,56
	Stability	• A large number of users may have power outages. • Power system instability. • System collapse. • Damage to appliances/equipment in line.	Ref. [1] P86 Ref. [5] P56
	Transmission losses	• Increasing the line loss rate. • Increasing the cost of power supply.	Ref. [5] P56
Numbers in square brackets refer to the Bibliography.			

5.1.2 Impact on equipment

5.1.2.1 DC and AC electric motor

Motor voltages less than the nameplate rating result in decreased starting torque and an increased temperature at full load. Increased torque, increased starting current, and a decreased power factor occur when motor voltages exceed the nameplate rating. Increased starting torque results in increased accelerating forces applied to couplings and driven equipment. Increased starting current results in a larger voltage drop in the supply circuit, which caused the voltage dips.

In general, voltage above the nameplate rating has a less detrimental effect on motor performance than voltage below the nameplate rating.

Synchronous motors behave similarly to induction motors, except that the speed remains constant (unless the frequency changes) and the maximum or pull-out torque varies directly with the voltage if the field voltage remains constant. If the field voltage varies in proportion to the line voltage, as in the case of a static rectifier source, the maximum or pull-out torque varies proportionally to the voltage squared, almost the same consequences as that of LED because the electronic part is similar.

5.1.2.2 Illumination equipment

Incandescent lamps: The voltage deviation has an effect on the light output and life of these kinds of lamps. A few percent increases in the voltage reduces the expected life of an incandescent lamp. While lower-than-nominal voltages extend the lifetime, but it cannot compensate for the decrease in lifetime caused by higher-than-nominal voltages. A large deviation in voltage results in a shorter lifetime when compared to a constant voltage.

LED equipment: Lower-than-nominal voltages affect the brightness of LED lamps, and LED equipment may not work normally. Higher-than-nominal voltages reduce the service life of LED equipment and even damage LED equipment.

Compact Fluorescent lamps (CFL): The voltage deviation affects the brightness and life of CFL.

Fluorescent lamps: The light output varies proportionally to the voltage. Voltage deviation has a smaller effect on the lifetime of fluorescent lamps than that of incandescent lamps.

5.1.2.3 Household appliances

Due to under-deviation, household appliances perform less efficiently. Under-deviation makes appliances more sensitive to voltage dips. An over-deviation makes the equipment more sensitive to transient over-voltages. Because the internal voltage control keeps the voltage of household appliances constant, an under-deviation in terminal voltage causes an increase in current, which results in higher losses and a shorter lifetime.

5.1.2.4 Transformer

A higher-than-nominal voltage between the transformer terminals increases the magnetizing current of a transformer. Because the magnetizing current is distorted, an increase in voltage magnitude amplifies the waveform distortion. The increase in electric field strength on the surface of transformer oil and winding accelerates the aging of these components. Serious voltage deviation damages the insulation.

Voltage deviation increases winding current under the same power transmission conditions, and winding loss is proportional to the square of the current. Since winding loss is proportional to the square of the current, voltage deviation increases winding loss.

5.1.2.5 Industrial equipment

Voltage deviation affects industrial equipment in different ways like power loss, product quality, equipment output, and equipment being damaged or forced to shut down. For instance, the output of thermal energy from electric heating equipment such as a resistance furnace is proportional to the square of the voltage. When the voltage is reduced, the melting and heating times become longer, resulting in a significant reduction in production efficiency. In addition, the electrolytic equipment supplies current through the rectifier device, and the reduction of voltage increases its electrical loss.

5.1.3 Impact on power system

5.1.3.1 Reactive power compensation

For the simple transmission system, the relationship between reactive power and voltage is as follows:

$$Q = \frac{U(E \cos \delta - U)}{X_{\Sigma}} \quad (1)$$

Where Q is the three-phase reactive power; U is the system line voltage; E is the electromotive force of the generator; δ is the phase angle between E and U ; X_{Σ} is the total line impedance (between E and U).

As shown in Formula (1), when $E \cos \delta > U$, the generator delivers reactive power to the power system. The greater the difference between E and U , the greater is the reactive power output. When $E \cos \delta < U$, the generator absorbs the reactive power from the system. From the perspective of the system's reactive power and voltage requirements, it is necessary for the generator to output or absorb reactive power in order to maintain the system's reactive power and voltage balances. At the peak of electricity consumption, the power system is carrying a heavy load and requires additional reactive power to maintain system line voltage U constant. To generate reactive power, the generator's electromotive force E must be increased. In terms of power grid economy, the transfer reactive power from the generator to the power system for the long-distance transmission lines could be avoided.

5.1.3.2 Stability

The transmission line's static stable power limit is proportional to the generator back-EMF and system voltage and inversely proportional to the reactance. The lower the system voltage, the lower the stable power limit, and the smaller the difference between the power limit and the transmission power, the more prone the system is to instability and serious system collapse. When the power grid is deficient in reactive power and its operating voltage is low, the system may collapse due to voltage instability, or a large number of users may experience power outages. For example, when the voltage is low, the reactive power emitted by the system is less than the reactive power absorbed by the load, resulting in an increase in current and a fall in voltage. The voltage reduction further aggravates the reactive power shortage. This vicious circle results in voltage collapse.

5.1.3.3 Transmission losses

If the transmission line's delivered power is constant, its voltage and current are inversely proportional. When the line voltage is increased, the current and network loss decrease proportionately. The decrease of line voltage leads to the current and network loss increase proportionately.

The transmission loss is determined by the relationship between active power, reactive power, and voltage deviation:

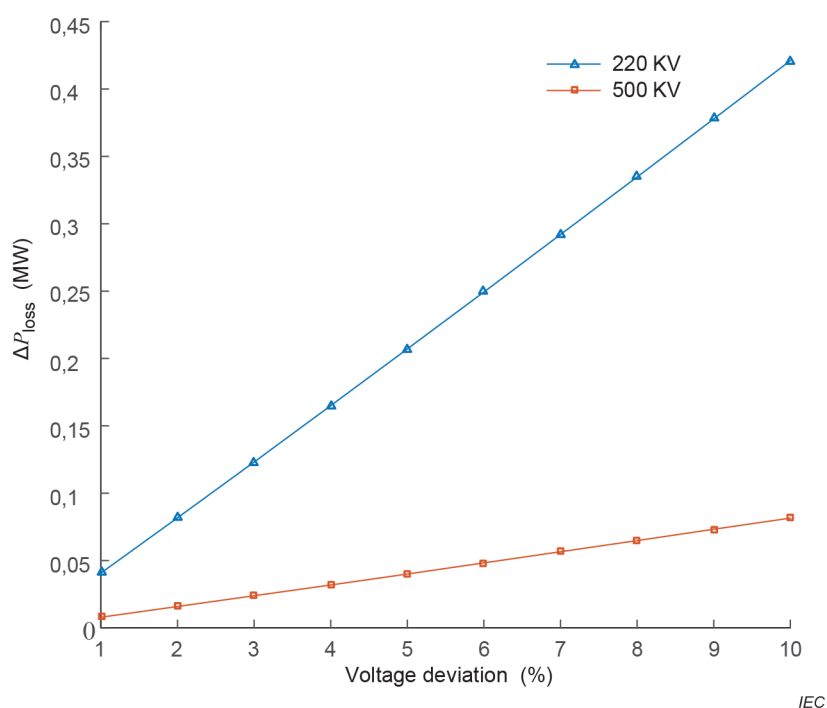
$$R_{\text{loss}} = \frac{Q^2 + P^2}{U^2} R_L = \frac{Q^2 + P^2}{U_N^2 (1 + \beta)^2} R_L \quad (2)$$

Where β is the voltage deviation; U is the system line voltage; R_L is the equivalent resistance of the transmission line; P is the active power and Q is the reactive power delivered. U_N is the rated voltage; P_{loss} is the line loss.

Therefore, the transmission loss caused by voltage deviation is obtained as follows:

$$\Delta P_{\text{loss}} = - \frac{(2\beta + \beta^2)(Q^2 + P^2)}{U_N^2 (1 + \beta)^2} R_L \quad (3)$$

Suppose the line impedance is 10 ohm and the transmission power is 100 MVA, the influence of under-voltage deviation on transmission loss is shown in Figure 1.



IEC

Figure 1 –The influence of under-voltage deviation on transmission loss

5.2 The impact of frequency deviation

5.2.1 General

The reference documents on impact of frequency deviation are listed in Table 2.

Table 2 – reference documents on impact of frequency deviation

Equipment	Impact description	Reference
Data processing equipment	• Cause abnormal function • Calculation error • Measurement error • Cause damages to power unit, supply cable	Ref. [6] P15 Ref. [7] P10
Electric feed pump	• Increase torque and reduce output • Increases power consumption • Decrease the efficiency and operational economic effectiveness • Mechanical vibration	Ref. [8] P2-3
Induction motor	• Temperature rise • Cause additional iron and mechanical loss • Impact output torque and speed • Mechanical vibration	Ref. [9] P2-3
Thyristor-based AC/DC converter	• Firing (commutation) error of thyristors • Thyristor damage if in generation mode of ASD • Important fluctuation of DC voltage • Stop of process	
Numbers in square brackets refer to the Bibliography.		

5.2.2 Impact on electrical equipment

5.2.2.1 Data processing equipment

Many new scientific equipment and precision instruments have stricter frequency requirements for data processing units. IEEE 446-1995 states that the maximum range of frequency deviation for many devices is 0,5 Hz; IEEE 1159-2019 further proposes the impact of frequency deviation on data processing equipment.

A ferromagnetic AC / DC power supply that works on the principle of a tuning circuit can only allow a 1 % frequency deviation in 50 Hz or 60 Hz system. Australian standard AS1284.5 points out that, for general electronic energy meters, the allowable frequency deviation tolerance of the level 1 meter is 0,3 % of the reference frequency, and the allowable frequency deviation tolerance of the level 2 meter is 0,5 % of the reference frequency. When the frequency deviation is up to 5 % of the reference frequency, the error of these electronic devices can reach 0,8 % to 1,5 %. When the frequency is changed by 1 %, the measurement error of the inductive energy meter increases by about 0,1 %. As the frequency increases, the inductive energy meter may not count electricity.

5.2.2.2 Electric feed pump

The steam turbine and blades of a thermal power plant are designed according to the rated speed and the guaranteed maximum shaft power. Lowering the rotation frequency will cause the loss of steam impacting the blade and increase the torque.

The change of frequency will bring great harm to the normal operation of the equipment of units, such as feed-water pump, circulating water pump, etc.

The relationship between the pump output and angular frequency can be expressed as

$$Q = \sqrt{(k_1 \omega^2 - H_{st}) / \Sigma R}$$

where ω represents the angular frequency; H_{st} is the static head to be overcome; k_1 is the coefficient determined by the structure and size of the unit. Q is the pump output. With the static pressure head, the pump can stop the water supply at a certain frequency before the frequency reaches zero. The critical frequency can be written as:

$$\omega_{cr} = \sqrt{H_{st}/k_1} \quad (5)$$

When the power supply frequency exceeds the rated value, the pressure head sent by the feed pump exceeds the required pressure head, which increases the power consumption of the entire plant.

In addition to water pumps, thermal power plants also have a large amount of ventilation torque machinery, such as primary blowers, secondary blowers and induced draft fans. In the absence of a static pressure head, the output of these machines is proportional to the first power of the frequency. The test proves that, as the frequency decreases, the output of the blower and induced draft fan decreases much faster than the frequency. When the frequency is increased, the pressure head generated by the blower and induced draft fan increases. The economy of the boiler is closely related to the content of carbon monoxide and carbon dioxide in the exhaust gas, and the excess amount of air in the combustion chamber. As the frequency of the power system decreases, chemical incomplete combustion increases. When the frequency is increased, the output of the blower is increased. The lowest loss in a boiler typically occurs at determined excess carbon dioxide content.

5.2.2.3 Induction motor

When the system frequency changes, the speed and loss of the induction motor will change differently, the temperature rise will change, and the efficiency may be affected.

1) Torque and speed

The relationship between the speed and frequency of the motor is:

$$n = \frac{60f}{p} \quad (6)$$

where n is speed; f is frequency; p is the number of pole-pairs.

The relationship between the torque and frequency of the motor is:

$$M = \frac{m_1 p U_1^2 \frac{r_2'}{s}}{2\pi f \left\{ \left(r_1 + C \frac{r_2'}{s} \right)^2 + \left(X_1 + C X_2' \right)^2 \right\}} \quad (7)$$

where U_1 is the stator terminal voltage; r_1 , X_1 is the stator resistance and reactance; r_2' , X_2' is the rotor resistance and reactance converted to the stator; m_1 is the content depending on structure; p is the number of pole pairs; s is the slip rate. When the motor running s is very small, the relationship can be simplified to:

$$M \approx \frac{m_1 p U_1^2}{2\pi f} \cdot \frac{s r_2'}{C r_2'^2} \propto \frac{U_1^2}{f} \quad (8)$$

When the motor is running normally, if the terminal voltage remains unchanged, the torque and frequency are close to being inversely proportional. For example, when a motor with a

nominal frequency of 60Hz is used for a power source with a nominal frequency of 50 Hz, the torque of the motor will increase to 1,25 times the original torque.

The maximum torque $M_{\max}$ is:

$$M_{\max} \approx \frac{m_1 p U_1^2}{4\pi C_1} \cdot \frac{1}{f(X_1 + CX_2')} \propto \frac{U_1^2}{f^2} \quad (9)$$

The absolute value of the maximum torque is inversely proportional to the square of frequency and close to the square of voltage.

2) Loss

The losses of induction motors include iron loss (hysteresis loss and eddy current loss), copper loss, mechanical loss (friction loss and wind loss), and stray loss. Mainly affected by frequency are iron loss and mechanical loss.

i) Iron loss

Iron loss contains hysteresis loss and eddy current loss. For iron loss, it refers to Formula (10). The iron consumption per 1 kg of steel sheet can be expressed by the following formula:

$$w_f = B^2 \left[\sigma_h \frac{f}{100} + \sigma_e d^2 \left(\frac{f}{100} \right)^2 \right] (W/kg) \quad (10)$$

where: w_f is the iron loss, B is the magnetic flux density, d is the thickness of the steel sheet, σ_h is the hysteresis loss coefficient, σ_e is the eddy current loss coefficient. It can be seen that the higher the frequency, the greater the iron loss.

ii) Mechanical loss

The mechanical loss comprises of the friction loss and wind loss of the bearing. General mechanical loss W_m can be approximated by Formula (11):

$$W_m = \frac{W_m\%}{100} \times (KVA)(KW) \quad (11)$$

where: $w_m\% = 0,0312(KVA)^{1/6} (rpm)^{1/3}$ if wind consumption is negligible; the mechanical loss is proportional to frequency.

5.2.2.4 Thyristor-based AC/DC converter

Thyristor-based AC/DC converter (rectifier and inverter) is also very sensitive to grid frequency. The deviation will cause an event of commutation error of thyristors and even damage thyristors if the converter operating in generation mode. Moreover, the fluctuation of DC voltage happens and may force converter to shut down.

5.3 The impact of voltage unbalance

5.3.1 General

Voltage unbalance can affect the operation performance of for example: the generator, electric motor, transformer, wind farm, reactive compensation equipment, Induction motor, and adjustable speed drive. As for the power system, this may result in abnormal relay movement, worsening transmission losses, and voltage deviation.

The Reference documents on impact of voltage unbalance are listed in Table 3.

Table 3 – reference documents on the impact of voltage unbalance

Equipment		Impact description	Reference
Electrical equipment	Generator and electric motor	• Cause additional negative-sequence currents • Temperature rise • Losses increase • Shorten winding life • Mechanical Vibration	Ref. [11] P89-90 Ref. [12] P12 Ref. [13] P905
	Transformer	• Hot-spot temperature rise • Losses increase • Shorten insulation life	Ref. [14] P503 Ref. [15] P2-3 Ref. [16] P324-325
	Wind farm	• Cause damage to equipment • Unbalance heat on wind turbines • Mechanical vibration of generator shafting	Ref. [17]P1074-1075 Ref. [18]P667
	Reactive compensation equipment	• The output instantaneous power appears the power fluctuation of twice frequency • Negative sequence and third harmonic currents appear in the inverter • Power Loses	Ref. [19] P239-241 Ref. [20]P3900-3901
	Induction motor	• Decrease in torque • Excessive heating due to more losses • Mechanical Vibration	Ref. [21] P263 Ref. [22] P3
	Adjustable speed drive (ASD)	• High input-current harmonic distortion • Overstressed DC-bus capacitors	Ref. [23] P733 Ref. [24] P4068
Power system	Relay protection	• Malfunction in distance protection and negative-sequence protection • Cause abnormal starts or even tripping of protection devices	Ref. [25] P689
	Transmission losses	• Cause additional losses of distribution lines and cable lines	Ref. [15] P2-3 Ref. [26] P365
	Voltage deviation	• The shift of neutral point of high voltage side of transformer • One phase voltage amplitude decreases and the other two phases voltage amplitudes increase • Damage to loads on line and increase in cost of power	Ref. [27] P4947-4948
Numbers in square brackets refer to the bibliography.			

5.3.2 Impact on electrical equipment

5.3.2.1 Generator and electric motor

1) Motor loss and temperature rise

When unbalanced phase voltages are applied to three-phase motors, this creates additional negative-sequence currents, increasing the heat losses primarily in the rotor. When single-phase power is used, the most severe condition occurs. Figure 2 illustrates the recommended derating for motors as a function of percent phase-voltage unbalance.

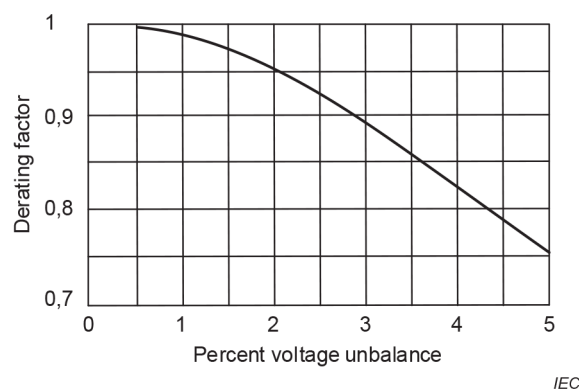


Figure 2 – Derating factor for motors operating with phase voltage unbalance

Quantitatively, negative sequence considerations result in the following:

Positive sequence impedance is predominately the effective rotor resistance R_r/S . With S normally 2 to 5 percent, this becomes 20 to 50 times R_r . Negative sequence slip because of the reversed rotation of the resulting flux is: $S_- = -2 + S_+ \doteq -2$. Because of this negative slip, the resulting high rotor frequencies of 115 to 120 Hz leads to skin effects that increase rotor resistance to these frequencies by up to five times its low-frequency value. The same phenomenon may also reduce rotor high-frequency inductance to 1/2. Thus the effective rotor resistance $R_r/(-2)$ is only 1/8 to 1/20 the effective full load (positive sequence) value. This leads to a motor negative sequence impedance of about 80 percent of its locked rotor impedance, and a small negative torque of 1/2 to 5 percent of the positive value.

Rotor losses increase more than stator losses. They may be approximately five times greater for a given negative sequence current than positive because of the higher negative sequence resistance.

The positive and negative sequence effects can be treated separately and then added together to obtain the motor's total response to a given set of input conditions. This independence is a result of the motor network's linear nature. It is slightly influenced by conductor saturation and changing resistance as a result of temperature rises. Thus, a 10 % negative sequence current would result in an increase of stator losses of $(0,10)^2$, or 1 %. However, if this current is in phase with the positive sequence current in a single-phase winding, the loss in this winding becomes $(1 + 0,10)^2 = 1,21$, or a 21 % increase.

Under unbalanced conditions, the temperature profile will differ significantly between stator and rotor, rotor parts, and stator phases than under balanced conditions causing the same total motor loss.

Table 4 summarizes a number of these effects for small unbalances. The data is a magnified version of the NEMA (National Electrical Manufacturers Association) illustration. As a composite of numerous motors, such a table cannot be precise. It is based on the following assumptions: motor starting inrush is five times the full load, negative sequence impedance is 80 % of locked rotor impedance, and negative sequence rotor resistance is five times the DC value. The losses in the maximum stator phase are determined by the fact that the negative sequence current is in phase with the positive sequence current during that phase.

Table 4 – Effect of voltage Unbalance on motors at full load

Voltage unbalance (percent)	0	2.0	3.5	5.0
Current, negative sequence (percent)	0	15	27	38
Current, stator (rms percent)	100	101	104	107.5
Increase in losses (percent)				
Stator average	0	2	8	15
Stator maximum 	0	33	63	93
Rotor	0	12	39	76
Total motor	0	8	25	50
Temperature rise (°C)				
Class A	60	65	75	90
Class B	80	86	100	120

2) Winding life

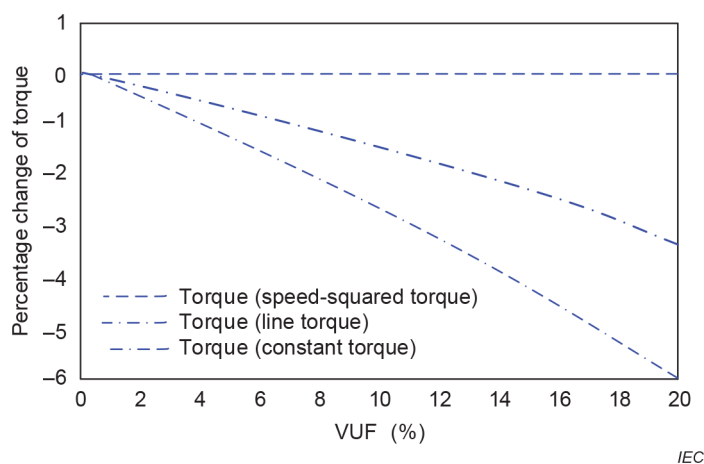
One potential issue that may arise from unbalanced voltage operation is higher temperatures, which dramatically stress the insulation system and shorten winding lives. A popular "rule of thumb" is that for every 10 degrees Celsius warmer a motor runs, its life is shortened by 50%. The life time is determined by Formula (12).

$$\text{Hours of Life} = A \times 0,5^{(T_m - T_{\text{ref}})/10} \quad (12)$$

3) Torque

For induction motors, the quality of supply voltages can significantly affect the overall performance of the motor. Undesired unbalanced voltages have negative effects on induction motors. The unbalanced voltage supplied to the induction motor may cause problems such as excessive heating due to more losses, over-voltages, mechanical oscillations, acoustic noise, decreased torque, and shortened induction motor life.

Figure 3 shows the percentage changes in torques of induction motor.

**Figure 3 – Percentage changes in torques of induction motor**

5.3.2.2 Transformer

1) Hot-spot temperature rise

According to the statement in Table E.1 of IEC 60076-7:2018 and the research in [10]¹, the hot-spot to top-oil (in tank) gradient for distribution transformers can be approximated by 23 °C, and $T_{\text{hot-spot}} = T_{\text{top-oil}} + T_{\text{rise hot-spot}}$. For distribution transformers, the top-oil temperature rise can be taken as uniform within the tank. According to IEC 60076-7:2018, Equation 5 and Table E.1, temperature rise can be approximated by:

$$T_{\text{rise hot-spot}} = 55 \left(\frac{1+5K^2}{1+5} \right)^{0,8} \quad (13)$$

Where $T_{\text{rise hot-spot}}$ represents the temperature rise of hot-spot temperature; K is the load factor for each phase (RMS phase current as a fraction of nominal current). If three phases are unbalanced, additional transformer losses occur especially when calculation is based on one-phase maximum current. This phenomenon exerts errors in calculating hot-spot temperature. The load factor K in (13) replaces $\sqrt{1 + \frac{\gamma_a^2 + \gamma_b^2 + \gamma_c^2}{3}} K_{\text{av}}$. Then, the $T_{\text{rise hot-spot}}$ under three-phase unbalanced meets:

$$T_{\text{rise hot-spot}} = 55 \left[\frac{1}{6} + \frac{5}{6} \left(1 + \frac{\gamma_a^2 + \gamma_b^2 + \gamma_c^2}{3} \right) K_{\text{av}}^2 \right]^{0,8} \quad (14)$$

where $K_{\text{av}} = I_{\text{av}} / I_R$; $\gamma_a, \gamma_b, \gamma_c$ are the phase current unbalance of phase a , b , and c .

According to Formulae (12), (13) and (14), it is clear that the transformer temperature is increased due to voltage unbalance, thus reducing the transformer's insulation life.

2) Insulation life

Transformer hot-spot temperature is the key to determining its life and load capacity. When three phases are unbalanced, the overload phase generates heat and the transformer's internal temperature is uneven during operation, causing insulation ages to decrease. Overall, the insulation aging is severely reduced at the hot-spot temperature location, which causes the transformer lifespan to decrease.

When $T_{\text{rise hot-spot}}$ increases due to the voltage unbalance, $T_{\text{hot-spot}}$ will also increase. The accelerated aging factor denotes a ratio between hot-spot temperature and base-spot temperature. The accelerating aging factor FAA can be obtained through:

$$F_{\text{AA}} = 2^{\frac{T_{\text{hot-spot}} - 98}{6}} \quad (15)$$

where F_{AA} represents the accelerated aging factor to calculate the transformer lifespan reduction; $T_{\text{hot-spot}}$ is the hot-spot temperature of the oil-immersed transformer.

5.3.2.3 Wind farm

In general, unbalanced grid voltage will cause unbalanced winding heating of the wind turbine. Wind turbine's electromagnetic torque also produces a frequency multiplier, causing mechanical vibration of generator shaft. In severe cases, grid voltage unbalance may cause wind turbine to shut down and cause damage to electrical equipment.

5.3.2.4 Reactive compensation equipment

The power network voltage imbalance will affect the output characteristics of the reactive power compensation device, and when the long-term over-voltage resulting from the voltage

¹ Numbers in square brackets refer to the Bibliography.

imbalance reaches 110 % of its rated voltage, the equipment may be out of operation. In the case of asymmetric power supply voltage, the intersection of positive and negative sequence components of current and voltage causes fluctuation with second harmonic in the instantaneous active power and instantaneous reactive power of STATCOM output, and an instantaneous active power fluctuation with second harmonic will also cause capacitor voltage fluctuation with the same frequency. Protection relay settings will also affect reactive compensation equipment performance. The smaller the set-value, the more sensitive the protection is. However, the likelihood of misoperation is higher. Thus, when designing the unbalance protection setting value, it is necessary to ensure sensitivity and protection will not be misoperating under these inherent unbalance conditions.

Simultaneously, the STATCOM inverter voltage output contains not only the positive sequence component, but also the fundamental wave negative sequence and the third harmonic component. Therefore, when the voltage is asymmetric due to the negative sequence component, the DC capacitance at both ends of the double-FM wave voltage is mapped to the inverter output via the switching function. The output voltage contains the fundamental frequency's 3-fold negative sequence and harmonic component, where the output current also contains the fundamental wave's negative sequence and third harmonic current. Moreover, due to the over-current of the third harmonic current, a large number of negative fundamental wave sequences can easily cause STATCOM device to quit operation.

5.3.2.5 Adjustable speed drive

Input-voltage unbalance can have serious effects on adjustable speed drives (ASDs), including abnormally low input line power factor, high input-current harmonic distortion, over-stressed DC-bus capacitors, high pulsating torque, and motor heating. Resulting in reduced power capabilities of the adjustable speed drive (ASD).

Most of the three-phase ASD systems are equipped with a three-phase diode rectifier as a front-end AC-DC conversion stage. During voltage unbalance events, three-phase diode rectifiers may enter single-phase operating mode (depending on the load level and unbalance level) which can generate low-order harmonic components in the DC-link voltage (second harmonic, fourth harmonic and fundamental). These low-order harmonics result in an undesirable impact on electrothermal stresses and thus the reliability of DC-link capacitors. Figure 4 shows the standard drive with DC-link LC filter under 5 % grid voltage amplitude unbalanced condition.

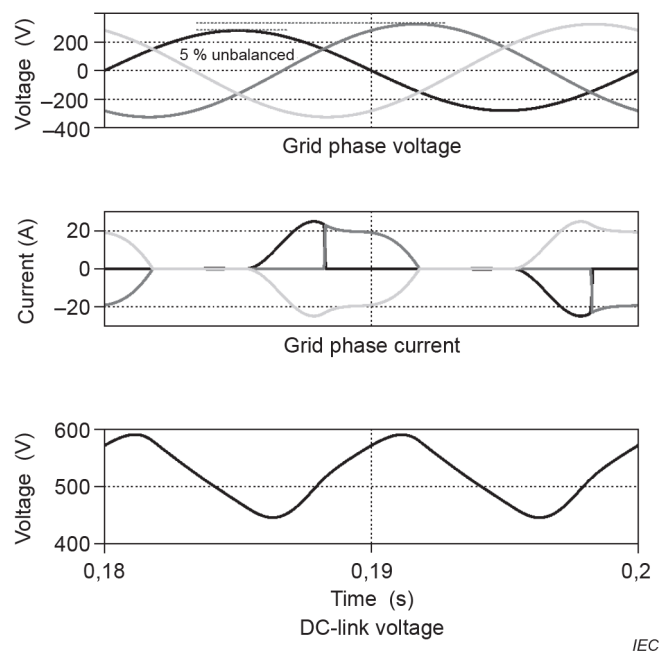


Figure 4 – Standard drive with DC-link LC filter under 5 % grid voltage amplitude unbalanced condition

5.3.3 Impact on power system

5.3.3.1 Relay protection

Power line distance protection or negative-sequence protection equipment often starts due to power unbalance characteristics. The operators choose to block the delay protection when the protection impedance element does not need to operate. During this period, if a fault occurs in the corresponding protection area, the protection device may refuse to operate, causing an override trip event and expanding the outage area. On the other hand, since the negative-sequence protection equipment starts, this event can cause the entire set of protective devices to malfunction, especially when system oscillation or other occasional factors, e.g. voltage collapse, occur.

In addition, the unbalance voltage may also cause devices of transformer negative over-current protection, generators negative over-current protection, bus-differential protection, high-frequency phase-differential protection, and distance protection, abnormal starts or even tripping. It might be noted that the negative sequence protection of generators or other electrical equipment could not be considered a malfunction under the influence of harmonics and negative-sequence.

5.3.3.2 Transmission losses

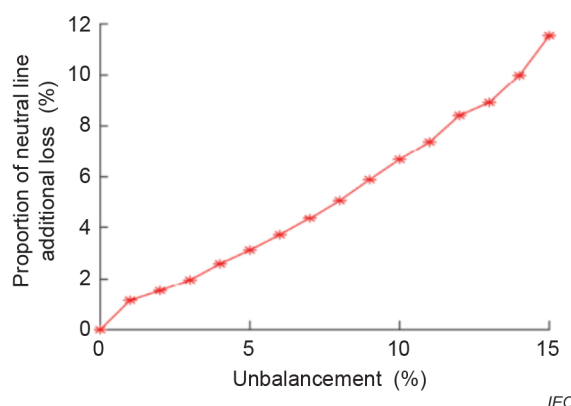
In the neutral point voltage imbalance, the neutral current through the neutral wire loop will result in additional losses due to the three-phase four-wire system.

The line loss will increase with the three-phase current unbalance. When the current three-phase unbalance reaches 15 %, the line loss increases by 4,8 %. Table 5 shows laboratory measurement results:

Table 5 – Line loss and additional loss increase under three-phase current unbalance

Unbalance / %	Line loss / W	Additional loss increment / %	Unbalance / %	Line loss / W	Additional loss increment / %
0	4 416	0	8	4 517	2,29
1	4 427	0,25	9	4 535	2,69
2	4 441	0,57	10	4 545	2,92
3	4 458	0,94	11	4 563	3,33
4	4 470	1,22	12	4 576	3,62
5	4 482	1,50	13	4 591	3,96
6	4 496	1,81	14	4 609	4,37
7	4 508	2,08	15	4 628	4,80

The proportion of additional neutral line loss is positively correlated with three-phase unbalance. When the unbalance increases to 15 %, the proportion of additional neutral loss reaches 11,54 %. Figure 5 shows a lab's measurement results curve:

**Figure 5 – Proportion of neutral line additional loss (%)**

5.3.3.3 Voltage deviation

The voltage unbalance may cause voltage deviation in a low-voltage supply network where transformer type Yyn0 is often introduced. When the three-phase load is balanced, the impedance of the whole system at each phase is balanced if the neutral point of the high voltage side is neither grounded nor connected to upstream power transformer neutral. The neutral point of the high voltage side of the Yyn0-type transformer locates at the central position N of vector triangle of phase voltage shown in Figure 6. When voltage unbalance occurs, the system's phase-impedance is unbalanced, leading to a neutral point shift. In particular, the position N1 denotes the unbalance degree of the three-phase load. This shift rises from the blocking of zero-sequence component and hence causes the cross-linked zero-sequence flux. Due to the magnetic circuit wye structure, this flux brings a neutral point shift. Neutral's shift direction indicates peak phase load, i.e. the smallest phase-impedance. This phase's voltage amplitude decreases, and the other two phases increase, see Annex B for demonstration by simulation. This phenomenon causes voltage deviation in the rural supply network. The Dyn11 type transformer can be applied to handle neutral point shift issues.