IEC TR 63282

Edition 2.0 2024-08

TECHNICAL REPORT

colour inside

LVDC systems – Assessment of standard voltages and power quality requirements

IEC TR 63282:2024-08(en)

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 29.020 ISBN 978-2-8322-9130-6

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LVDC SYSTEMS – ASSESSMENT OF STANDARD VOLTAGES AND POWER QUALITY REQUIREMENTS

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.
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IEC TR 63282 has been prepared by IEC technical committee 8: System aspects of electrical energy supply. It is a Technical Report.

This second edition cancels and replaces the first edition published in 2020. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) Optimized terms and definitions in Clause 3:

   Introduction of new terms and definitions and refining of existing ones.

b) Modified the definition of voltage bands:

   In Clause 5, the definition of voltage limits in voltage bands is added, from U_1 to U_6. The definition of voltage bands, from B4 to B7, is modified.

c) Distinguished the difference between oscillation and power quality phenomenon:

In Clause 3, the definition of oscillation is added based on IEV 103-05-04. In 6.3, relationship between oscillation and power quality is clarified. Annex B gives a LDC oscillation typical example which has really happened in a MV&LVDC system in China.

d) Modified the recommended voltage for distribution DC network:

The factors considered in voltage values definition is clarified. And the voltage is divided in two domains, distribution domain and installation domain. The voltage recommendation in LVDC is listed corresponding to voltage bands.

e) Modified the voltage immunity level assessment:

It is mentioned in 7.2 that the assessment of voltage immunity levels of mass LVDC power electronic devices need to be further discussed, ripple as an example is introduced.

f) Added DC power quality measurement methods:

In 7.3, DC power quality measurement methods is introduced based on AC methodologies. And some additional DC power quality indices are recommended to assess the DC system.

DC electric power and power quality measurement methods are introduced in 7.4, defining the electric value integration time and frequency ranges.

Typical electric power and power quality computation methods are modified in Annex D.

g) Added an annex on MVDC system:

A use case of a typical MV&LVDC distribution system is added in Annex F, to support developments of TS of 8A and 8B on DC microgrids.

h) Added an annex on Current OS voltage level:

The voltage level applied in Current OS is introduced in Annex L to give more information on the LVDC voltage level recommendation.

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

Draft	Report on voting
8/1695/DTR	8/1704/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.

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, or
- revised.

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INTRODUCTION

LVDC (low voltage direct current) distribution systems have recently been recognized by a number of stakeholders as an alternative approach to provide efficient power supply to the consumers. LVDC covers a wide range of power applications from USB-C up to megawatts for aluminium melting. LVDC is seen as a solution for greener and more sustainable energy systems in developed economies as well as an alternative option for electricity access in developing countries.

In industrial applications, LVDC is utilized where processing of resources results in the production, distribution and storage of physical goods, especially in a factory or special area of a factory.

The standardization of DC voltages is a key issue, and urgent work is needed. Existing LVAC systems have different standard voltages, depending on the geography and application. LVDC distribution voltages are optimized to provide a good context for industries that import and export equipment but also for general travellers. Appropriate international LVDC voltage ranges will provide a basis for design and testing of electrical equipment and systems and ease of transition for equipment from AC to DC supply.

LVDC voltages meet the range of use cases where LVDC systems can make a difference. The list of standard voltages is as short as possible and allow for cost-effective and safe operation.

The PQ (power quality) issues in DC power systems are not identical to those in AC systems, but there are some common issues. Power quality considerations are well studied and standardized on AC power systems, but many power quality phenomena and EMC have not yet been fully identified and evaluated for DC distribution systems.

Power electronic converters/inverters add further demands. Power quality phenomena in LVDC distributed systems can be related to the structure of the entire system, and the operating condition of sources and loads. At the same time, the DC output performance of a single converter and the coordination among several converters can also result in different power quality issues and grid stability.

Requirements for power quality and EMC in LVDC distribution are established in order to provide a solid basis for the planning and operation of LVDC distribution systems. In addition, the design and configuration of the protection system is addressed with the objective of enhancing the availability of the source, the reliability, and the lifetime of the system.

Generally, the standardization of voltage level and PQ phenomena of LVDC distribution greatly stimulate the wide adoption of LVDC.

This document provides information on the following topics: standard voltages, EMC requirements, power quality, and measurement methods.

LVDC SYSTEMS – ASSESSMENT OF STANDARD VOLTAGES AND POWER QUALITY REQUIREMENTS

1 Scope

The purpose of this document is to collect information and report experience for the standardization of voltage levels and related aspects (power quality, EMC, measurement, etc.) for LVDC systems (systems with nominal voltage up to and including 1 500 V DC).

Rationale for the proposed voltage values is given. Variation of parameters for the voltage (power quality) for their boundaries are defined. Nevertheless, some of the technical items are not exhaustively explained in this document and some gaps are identified for future work.

Attention is paid to the definition of DC voltage.

Systems in which a unipolar voltage is interrupted periodically for certain purposes, e.g. pulse voltage, are not considered.

Traction systems are excluded from this document.

This document gives technical inputs to TCs in charge of the standardization of different issues and coordinated by SyC LVDC.

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
nominal system voltage
suitable approximate value of voltage used to designate or identify a system

[SOURCE: IEC 60050-601:1985, 601-01-21, modified − The term has been changed from "nominal voltage of a system" to "nominal system voltage".]

3.2
DC supply voltage
line-to-line or line-to-mid-point voltage at the supply terminals

3.3
bipolar DC system
DC system comprising a positive and negative line, and a mid-point, distributed or not

3.4
unipolar DC system
DC system comprising a positive or a negative line, and a mid-point

3.5
DC system nominal voltage
U_n
value of the voltage by which the electrical installation or part of the electrical installation is designated and identified

Note 1 to entry: The DC system nominal voltage U_n is within the nominal band [U_2; U_3] but not always half-way between U_2 and U_3. In all cases

$$U_2 \leq U_n \leq U_3$$

Note 2 to entry: For a bipolar system, it is recommended to use a dual notation, for example, "$\pm U_{L-M}$" or "U_{L-M} / U_{L-L}".

3.6
DC voltage deviation
voltage deviation due to the slow change in power system operation state

Note 1 to entry: Voltage deviation is the difference between actual voltage and nominal system voltage when the change rate of the average DC voltage is in the appropriate speed in order to limit the deviation in an acceptable range.

3.7
voltage unbalance
condition in a bipolar system in which the line to mid-point voltages are not equal

3.8
ripple
set of unwanted periodic deviations with respect to the average value of the measured or supplied quantity, occurring at frequencies which can be related to that of the mains supply, or of some other definite source, such as a chopper or load changes

Note 1 to entry: Ripple is determined under specified conditions and is a part of PARD (Periodic and/or random deviation). It may be assessed by instantaneous value or RMS value.

Note 2 to entry: Sources of ripple may include, but are not limited to, voltage regulation instability of the DC power source, commutation/rectification within the DC power source, and load variations within utilization equipment.

Note 3 to entry: Ripple is determined as well in percentage to the DC component and in RMS value computed in line with CISPR for conducted disturbances. Ripple can be hundreds of kHz.

[SOURCE: IEC 60050-312:2001, 312-07-02, modified – "or load changes" has been added at the end of the definition, a sentence has been added to Note 1 to entry; Notes 2 and 3 to entry have been added.]

3.9
over-voltage
voltage the value of which exceeds a specified limiting value

[SOURCE: IEC 60050-151:2001,151-15-27]

3.10
under-voltage
voltage the value of which is lower than a specified limiting value

[SOURCE: IEC 60050-151:2001,151-15-29]

3.11
voltage swell
sudden increase of the voltage at a point in the electrical supply system followed by voltage recovery after a short period of time

Note 1 to entry: Application: for the purpose of this document, the swell start threshold is equal to the 110 % of the reference voltage (see CLC/TR 50422: 2013, Clause 3, for more information).

Note 2 to entry: For the purpose of this document, a voltage swell is a two-dimensional electromagnetic disturbance, the level of which is determined by both voltage and time (duration).

3.12
voltage dip
sudden decrease of the voltage at a point in the electrical supply system followed by voltage recovery after a short period of time

Note 1 to entry: The residual voltage can be expressed as a value in volts, or as a percentage or per unit value relative to the reference voltage.

[SOURCE: IEC 60050-614:2016, 614-01-08, modified – "Reduction" has been changed to "decrease", " electric power system" has been changed to "electrical supply system", "time interval" has been changed to "period of time", reference to sinusoidal voltage has been removed.]

3.13
voltage surge
transient voltage wave propagating along a line or a circuit and characterized by a rapid increase followed by a slower decrease of the voltage

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

3.14
voltage supply interruption
disappearance of the supply voltage for a time interval whose duration is between two specified limits

[SOURCE: IEC 60050-161:1990, 161-08-20, modified – In the term, "short interruption (of supply voltage)" has been changed to "voltage supply interruption", the note has been deleted.]

3.15
rapid voltage change
RVC
quick transition in voltage occurring between two steady-state conditions, and during which the voltage does not exceed the under-voltage/over-voltage thresholds

3.16
oscillation
physical phenomenon characterized by one or more alternately increasing and decreasing quantities

Note 1 to entry: Oscillation in LVDC system is characterized by an electromagnetic parameter (voltage current, power, etc.) in the system alternately increasing and decreasing. The phenomenon can be caused by interference, parameter mismatch or control stability issues.

[SOURCE: IEC 60050-103:2019,103-05-04, modified – Note 1 to entry has been completely changed.]

3.17
DNO
distribution network operator
party operating a distribution network

3.18
DSO
distribution system operator
party extending the function of a DNO to incorporate active management of some power resources

3.19
$\boldsymbol{U_+}$
positive voltage
voltage between the positive line and the mid-point

Note 1 to entry: Only defined for bipolar DC systems.

3.20
$\boldsymbol{U_-}$
negative voltage
voltage between the negative line and the mid-point

Note 1 to entry: Only defined for bipolar DC systems.

3.21
balanced voltage
$\boldsymbol{U_b}$
average of the positive and the negative voltage

Note 1 to entry: $U_b = (|U_-| + |U_+|)/2$.

Note 2 to entry: Only defined for bipolar DC systems.

3.22
unbalanced voltage
$\boldsymbol{U_u}$
average difference of the positive and the negative voltage

Note 1 to entry: $U_u = (U_+ - U_-)/2$.

Note 2 to entry: Only defined for bipolar DC systems.

3.23
mid-point
common point between two symmetrical circuit elements the opposite ends of which are electrically connected to different line conductors of the same circuit

Note 1 to entry: Only defined for bipolar DC systems.

[SOURCE: IEC 60050-195:2021, 195-02-04, modified – "of which the opposite ends" has been changed to "the opposite ends of which" and the note to entry has been added.]

3.24
under-voltage ride through
capability of equipment to stay connected and continue functioning during voltage dips

3.25
DC voltage
voltage equal to its average value during a defined time interval

3.26
over-voltage ride through
capability of equipment to stay connected and continue functioning during voltage swells

4 Structure of LVDC systems

4.1 General

The low-voltage DC systems described consist of loads, applications, electricity generation devices, and storage devices that are connected with each other with a direct current (DC) system/installation. Thus, as far as the recommended voltages and power qualities of certain LVDC systems are concerned, different analysis dimensions and elements are taken into consideration, including different architectures, operation modes, etc.

NOTE A LVDC system includes public and private LVDC systems. It is independent of the physical dimensions, electrotechnical properties and operating modes of the infrastructure. Installations can be very small or large in terms of power and geographical extent and use any voltages and number of voltage levels.

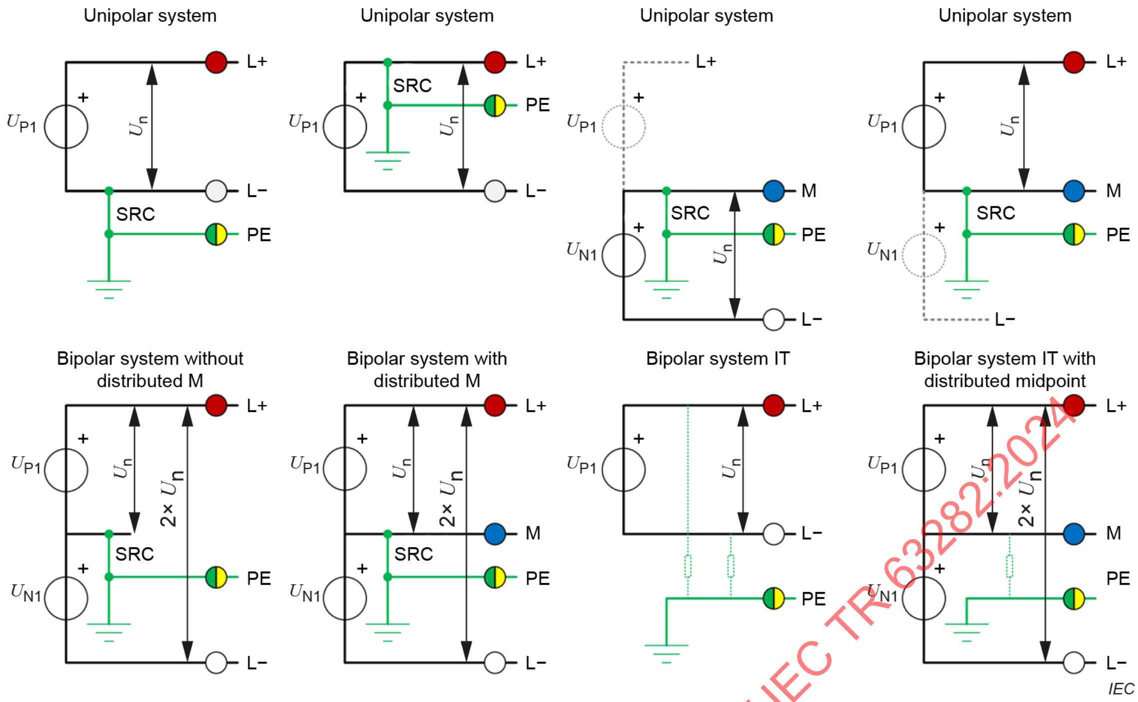
4.2 Architecture

Several use cases concerning existing technologies and projects have been introduced to support the analysis and classification of LVDC systems.

Details and examples can be found in Annex E, Annex F, Annex G and Annex H. Formal use cases are also under work in the frame of the SyC LVDC WG2.

Unipolar DC systems are designed with two output lines and bipolar DC systems with three output lines. Taking the earthing into account, they can be divided into TN-S system and IT system as shown in Figure 1.

In the TN-S system, the mid-point connection (M) is directly connected to the protective earth (PE). While in the IT system, the mid-point connection is not directly connected to the protective earth (PE), and there are intentional (by design) or unintentional impedances which are between conductors and earth.



Key

U_{P1} voltage source between the positive line and the mid-point

U_{N1} voltage source between the negative line and the mid-point

U_n DC system nominal voltage

NOTE All IT systems will have impedances between conductors and earth. These impedances can be parasitic and poorly defined or can be inserted by design.

Figure 1 – Unipolar, balanced and bipolar DC systems

4.3 Operation modes

4.3.1 Passive DC systems

In passive DC systems, most of the integrated sources, which need control objectives as an input from outside, can be either voltage source or current source. The control strategy of passive sources is frequently based on master-slave control and the energy balance margin of the system mostly relies on the capability of the voltage source. Normally, the voltage source is designed to support the power supply of the system.

NOTE A passive device/load or source (other than a protective device) has not been programmed to be capable of reacting to changes in system variables (voltage, power); for example, a directly connected battery is a passive source.

In a passive DC system, passive sources and devices, possibly combined with active sources and devices, determine the behaviour of the installation.

4.3.2 Active DC systems

In active DC systems, nearly all the sources and loads are connected to the DC bus by self-controllable electronic devices. The control strategies of active sources are based on droop control and the energy balance of the system is realized automatically by tracing the U-I curves configured in the devices. The normal operation voltage band can be adjusted by different configurations of control parameters in devices.

NOTE An active device/load or source (other than a protective device) can measure and control independently and is programmed to be capable of reacting to changes in system variables (voltage, power), serving to maintain system integrity.

In an active DC system, the active devices determine the behaviour of the installation. It has no passive sources. Passive loads do not dominate the behaviour of the system.

5 LVDC voltage division

5.1 General

The voltages are divided into different levels for temporary and continuous operation.

Between zero and maximum, the voltages are divided into 6 different stages: U_1 ... U_6.

To cover steady state and transient voltage levels, a matrix with all the voltages, voltage bands, operating states and areas is made. The matrix is presented in Figure 2. See Annex J for the detail of voltage with respect to earth.

5.2 Voltage bands

The range between two voltages is called a voltage band. Voltage bands are useful for describing voltage limits without going into the level of detail of time limits. U_i corresponds to the upper limit of band B_i (i = 1, 2, 3, 4, 5, 6).

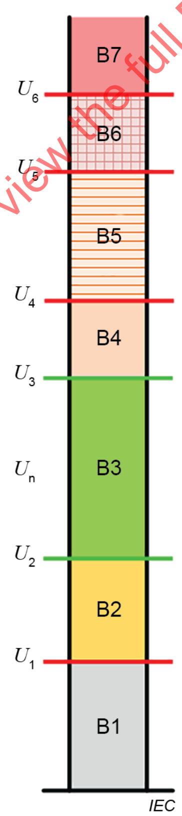


Figure 2 – Voltage bands in DC systems

– U_1: Undervoltage disconnecting voltage

Minimal voltage level where critical devices (e.g. controller, communication gateways) can operate.

– U_2: Minimum voltage for continuous operation with full functionality

Minimal voltage level where devices can operate. For sources, this value is considered without cable losses. For loads, a lower value can be considered due to cable losses.

NOTE 1 The voltage can be lower for the load because of the cable losses.

– U_3: Maximum continuous operating voltage

The maximum voltage level below which devices can operate in steady-state conditions. Sources limit their output to keep the voltage below U_3

– U_4: Maximum temporary operating voltage

The maximum temporary voltage level below which devices can operate.

NOTE 2 Such higher voltage can be caused by converters going to unloaded conditions and the fully charged state of capacitors (in AC systems it is called a swell.) This value is important for protection devices like RCD, etc. This defines the maximal level that can be in a system.

Source unidirectional converters which are unable to discharge their respective capacitor when transitioning from the loaded to unloaded condition could temporarily operate at higher voltage.

– U_5: Overvoltage disconnecting voltage

Minimum voltage at which overvoltage surge protective devices start to conduct.

NOTE 3 This is sometimes called breakdown voltage.

Overvoltage protective devices do not react between U_4 and U_5 (on transients due to charging of capacitors for example).

– U_6: Maximum voltage that equipment overvoltage protection devices clamp

This voltage is defined to specify and coordinate amongst transient voltage suppressors in sensitive equipment, such as equipment with semiconductor devices, against overvoltage.

NOTE 4 The overvoltage protection is normally in conformity with the overvoltage category and ensures that U6 is not exceed.

– B1: Blackout band (0 ... U_1)

Longer events will cause a shutdown of the whole system. This band is temporarily passed during the start-up of the system, e.g., for pre-charging.

– B2: Critical band (U_1 ... U_2)

This is the band to which the voltage can drop below the normal operation band due to high overload.

NOTE 5 Critical devices can operate in this voltage band.

– B3: Nominal band (U_2 … U_3)

This is the normal operation band.

– B4: Switching, commutation and protection devices operation band (U_3 … U_4)

In this band, the voltage can overshoot or rise due to a sudden change of current.

– B5: Overvoltage protection devices non-operating band (U_4 … U_5)

Surge protection devices don’t clamp the voltage in this band.

NOTE 6 The voltage can reach this band due to the operation of switching or protection devices. This can lead to capacitor charges even if they should be mastered.

– B6: Overvoltage protection devices operation band (U_5 … U_6)

Surge protection devices clamp the voltage in this band.

– B7: Prohibited band (U_6 … ∞)

In this band, permanent equipment damage is very likely.

5.3 Operation ranges with respect to DC voltage and time

To achieve continuity of operation, 4 ranges are defined, of which 3 ranges (R1 to R3) are transient ranges and 1 range (R4) is the steady range. These ranges can occur routinely or in exceptional situations. In each range, the allowed overvoltage and dynamics are different. Voltage bands are divided in these 4 ranges. See Figure 3.

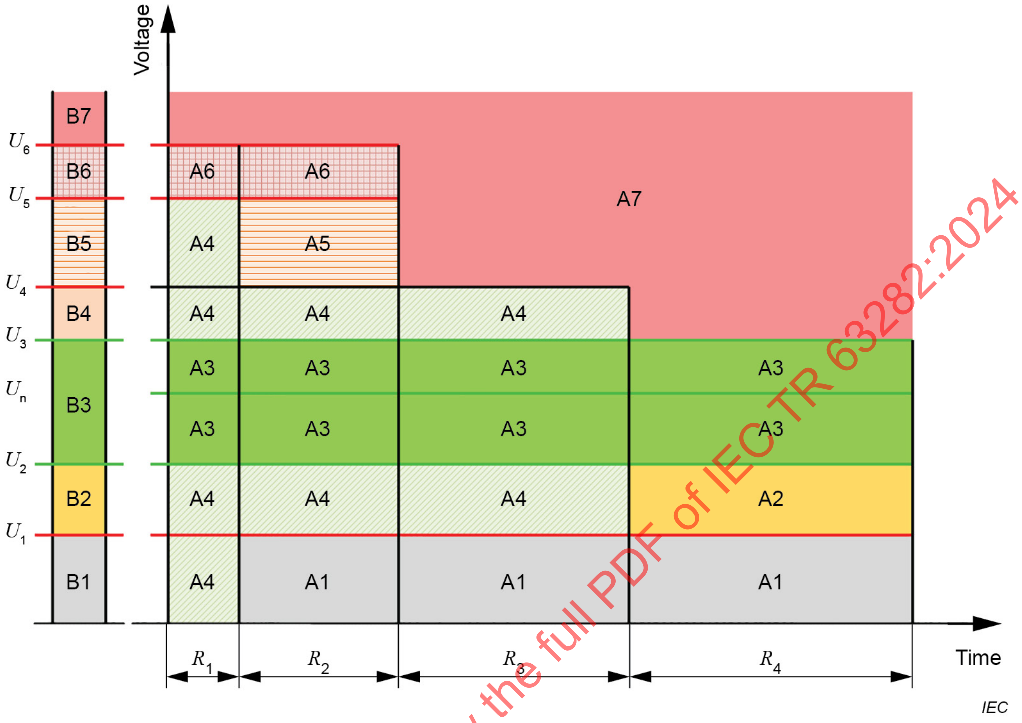


Figure 3 – DC Voltage areas for safe interoperability

To account for time-limited capabilities of the system components, the following time-limited states are defined in the graphic.

NOTE In Figure 3, the duration of the states only indicates that:

R1 < R2 < R3 < Continuous operation (R4)

States R1 through R3 are transient states and can have different durations.

– R1: Transient range

  The transient state is limited to a very short time. After being in the transient state, the system will return to a steady state.

– R2: System fault range

  The state involves, or is the result of, failure of a system circuit or item of system plant or equipment or apparatus. In this state, the system normally requires the immediate disconnection of the faulty circuit, plant or equipment or apparatus from the power system by the tripping of the appropriate circuit-breakers.

– R3: Voltage control range

  In this state, action is required by the system to address system balance issues.

– R4: Continuous operating range

  The system can remain in this state indefinitely.

5.4 States

The area between these voltages and states is defined as follows:

- A1: Blackout state

  Supply in this area is insufficient for operation to be maintained.

- A2: Emergency state

  The voltage in this area indicates that the supply is under stress. Loads are still able to operate correctly, but perhaps not meet all performance requirements. Action can be taken to reduce the stress on the system, for example through load-shedding or the introduction of additional power sources.

- A3: Normal state

  For the normal operation of a DC system, the voltage difference between the power terminals is maintained between U_2 and U_3 under all conditions. All equipment performance requirements are met within this band.

  Operation between these limits includes all normal operating states of the system, and normal droop control ranges. The voltage delivered to a load is within this band including the $I \times R$ voltage drop in the cabling. Annex C gives the example of the supply radius in DC distribution systems.

- A4: Abnormal state

  In exceptional circumstances, voltage can stray into this area for an extended period. Installation and equipment are designed to withstand this, and continue to operate normally, but possibly with reduced performance. Actions are taken to modify power input to rebalance the system.

- A5: Overvoltage state without clamping

  In this area, the voltage can increase due to operation of switching or protection devices. Overvoltage protection devices do not clamp these voltage overshoots.

- A6: Overvoltage state with clamping

  In this area, the voltage can overshoot due to operation of switching or protection devices. Overvoltage protection devices clamp these voltage overshoots.

- A7: Prohibited state

  In this area, permanent equipment damage is very likely. If technically possible, all power sources are switched off.

6 Power quality phenomena relevant to LVDC networks

6.1 General

Voltage quality is important for ensuring that systems function as intended. Voltage quality is specified in order to provide a system designer with a reference to design the supply, load and distribution system. Voltage quality requirements can be different for different use cases and system layouts. It is the designer's responsibility to ensure that regardless of the system layout and network topology, the voltage variation, transients and other voltage disturbances do not exceed the application and use-case specific limits of the operating ranges, nor the values tolerated by the devices used in the installations.

Ideally, a perfect voltage source is considered, with a stable voltage within a normal voltage band. Voltage quality is defined in terms of limits to deviations outside this band caused by different disturbances. These deviations outside this band or disturbances can be continuous or discontinuous.

Use case, application and electromagnetic environment specific compatibility levels are defined for temporary voltage variation, voltage dips and swells, and the maximum duration and magnitudes of DC voltage fluctuations. Annex A gives the examples of PQ waveforms collected from a certain LVDC project.

The characteristics of good power quality are:

– voltage is maintained within agreed limits in normal operation (6.2 to 6.9);
– ripple and high frequency voltages/current disturbances are below permissible limits (6.5).

6.2 Relationships between voltage band and power quality in LVDC systems

For the normal operation of a DC system, the voltage at a specific/any node is maintained at the target operating value for each operating point within limited variations under all conditions. A constant DC voltage indicates a balance of the power injected into or exported from the DC system.

DC system control is designed to ensure that at any transmission power level and in any operating mode, the line-to-earth DC voltage in TN systems and the line-to-line or line-to-mid-point DC voltage in IT systems remain within the normal operating range of the DC voltage.

There are some events that can cause the DC voltage to deviate transiently or temporarily from the normal operating band or to fluctuate. The irregular operation or trip of a system component can result in a steep voltage dip, a high voltage rise or voltage fluctuations showing up as DC power quality problems. The frequency and magnitude of the events leading to these DC voltage excursions or fluctuations need to be limited.

As an example of a time-domain voltage acceptability curve for the DC voltage, Figure 4 shows voltage band and power quality that are to be considered in DC systems. Annex K gives the example of voltage profiles in CIGRE.

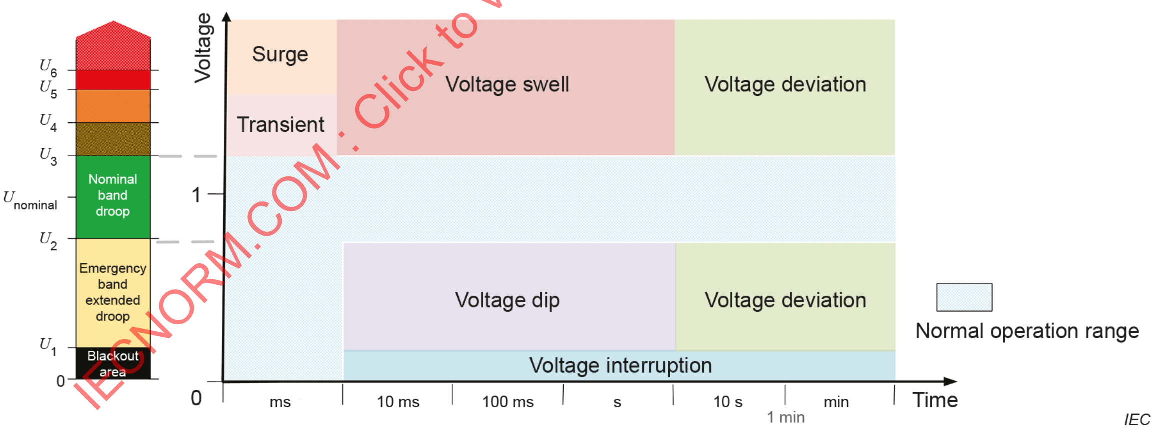


Figure 4 – Relationships between voltage band and power quality in LVDC systems

6.3 Relationship between oscillation and power quality in LVDC systems

When a disturbance is applied to a system with a specific structure (impedance parameters) and control parameters, an oscillation phenomenon can occur due to the mismatch between control and impedance parameters. Oscillation as such is not a PQ phenomenon but it will influence the PQ. Two common causes of oscillation are the measurement system impacted by a specific frequency interference and the mismatch of control parameters between multiple devices.

Figure 5 gives an example of voltage oscillation in a real system.

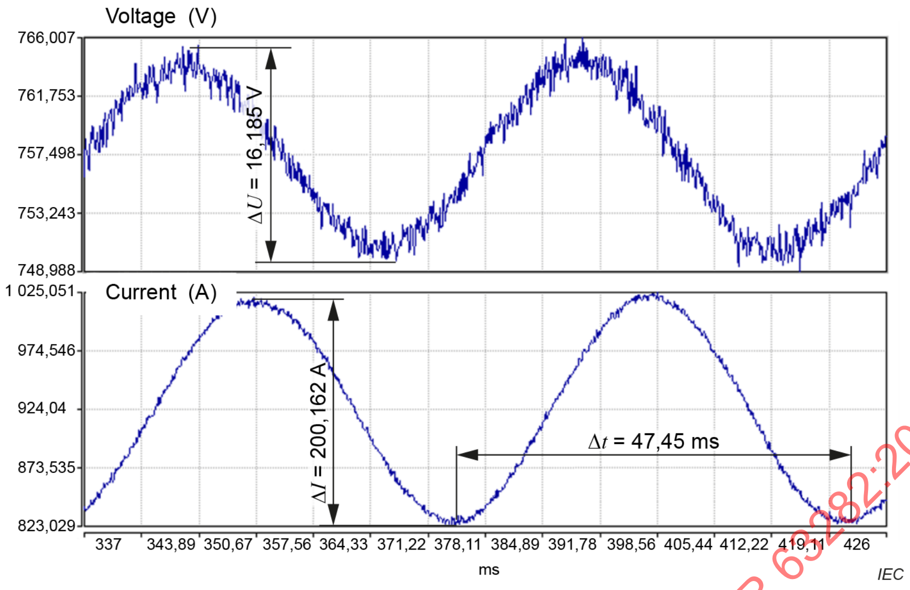


Figure 5 – Oscillation example

Figure 5 shows that an oscillation with frequency of about 21 Hz occurs in the system. The voltage oscillation amplitude is about 16 V, and the current oscillation amplitude is about 200 A. The system protection acts and stops the oscillation.

See Annex B for details on the oscillation characteristics.

The oscillation phenomenon is closely related to the load.

The system oscillation can be controlled by adjusting the modes that cause the system oscillation. For example, by strengthening the shielding of the measuring system or modifying the control parameters, system oscillation can be suppressed.

The oscillation can cause variation of some power quality indices such as fast voltage fluctuation, flicker and DC ripple (equivalent to harmonics and inter harmonics, such as the recordings in Figure 5) depending on oscillation frequencies.

6.4 Supply voltage deviation

The DC voltage in the system can be controlled by converter controls within specified limits for all power flows, including overload rating. If a central DC voltage controller is used, its response time is adequate to meet the specified performance.

The above considerations apply to undisturbed operation. Possible deviations can be caused to the following:

– If the operating DC voltage is outside the steady-state DC voltage band, then the system and system elements can disconnect and shut down when a safe operation is not guaranteed.
– If the operating DC voltage is outside the normal operating band, then the system and system elements will not meet all performance criteria.

Large voltage deviations from the nominal values will shorten the life of electrical equipment, possibly threaten system stability and increase the cost of network operation. Equipment operating under this condition in a repetitive manner or for long periods of time can malfunction, breakdown or become irreversibly damaged.

The equipment can withstand voltage excursions as defined in Figure 4 without damage. Active elements operate safely and contribute to a damping of these excursions and fluctuations. Protective devices operate only at higher voltages than defined in Figure 4 as they can result in even more severe excursions and fluctuations. However, equipment can disconnect in case of unsafe operation or potential equipment damage.

Particular attention is paid to under-voltage ride through capabilities and over-voltage ride through capabilities of active elements as this will be very important for the stability of the system during temporary fault situations.

In steady state operation of a DC system, there is a balance between the power injected into the DC system and the power withdrawn from the DC system, including losses. The main objective of the primary control is to limit the DC voltage deviation to an acceptable range and to find a new balanced operating point for the power flow in the DC system.

6.5 Ripple and high frequency interference

In a LVDC system, there is no fundamental frequency, and the concept of harmonic distortion does not apply. Previous definitions of power quality typically involving harmonic distortion limits in AC systems are not applicable. A comparison of average DC and AC RMS values could be the basis for setting power quality indices for LVDC systems.

Since a power converter connected to a DC distribution bus averages DC current and some other frequency components, which are a function of the converter internal switching frequency and power topology, the impact of the power converter on the DC power bus is evaluated. Any AC component of load current that flows in the LVDC bus will result in a ripple voltage appearing at all points along the bus. The ripple currents flow between connected loads and the DC power source. The fast switching of converters and associated rapid change of potentials will generate common mode (CM) voltage level shifts, which can interfere with communication or control systems. Perturbations in both differential mode (DM) and common mode voltage cannot be ignored.

If a pulse width modulated (PWM) converter is used to produce the DC voltage, a high-frequency waveform caused by the pulse width modulation switching is superimposed on the DC and AC side and shows up as interference. The interference also can come from converter-based loads connected to the DC bus.

Periodic and random variations are given for the following three bands, the interference frequency bands can be defined as < 9 kHz, 9 kHz to 150 kHz and > 150 kHz in line with generic EMC standards:

a) low-frequency interference:

   source frequency and its harmonics only (AC sources only), the interference frequency bands can be defined as < 9 kHz, 9 kHz to 150 kHz and > 150 kHz in line with generic EMC standards;

b) switching interference:

   power converters switching frequency and its harmonics;

c) total, including spikes (the bandwidth of the measuring equipment is stated).

Some organizations have mentioned ripple as DC harmonics and presented several methods for calculation.

The main adverse effect of ripple, beside additional losses, can be interference with the operation of system components and interfering the operation of neighbouring systems (power and communication) through radiated and conducted interference.

LVDC converters generate characteristic and non-characteristic ripple voltages on the DC system. Ripple voltages drive ripple currents through the DC system. The characteristic ripple voltages depend on the DC voltage, current, DC circuit reactance, converter topology, converter switching frequency and converter control strategies whereas non characteristic ripple voltages are caused by measurement and control errors. Resonance conditions within the DC system can result in potential amplifications.

As it can be expected that more than one equipment can affect the ripple levels at a specific DC node, sufficient headroom is specified between maximum acceptable ripple levels and the DC system equipment. All users are appropriately designed to make their individual contribution within the allowed individual share. Resonance effects are taken into account. The DC system operator provides information to evaluate potential ripple resonances.

The connection of any component does not result in levels of distortion or fluctuation of the existing DC system voltage and current at the connection point, exceeding those agreed on.

Studies to characterize distortion of voltage/current waveforms at the point of the connection are performed. These take into consideration the impedance of a DC circuit at the ripple frequency and background ripple of the existing DC system. Ripple generation of new connections can be subject to verification of compliance at commissioning.

There are also harmonic distortion requirements for the connection to the AC system for power generation and use.

6.6 Voltage swell

Voltage swell phenomena can frequently occur, but it is unpredictable and random. Depending on the magnitude and duration, voltage swell can affect different types of loads differently for the same voltage swell event. Recommended limitations of voltage swells A4 and A5 in Figure 3 are still under consideration.

Where assessment is performed or statistics are collected to be provided to network users or authorities, for measurements of voltage swell and dip in DC systems, it is suggested that the number of equipment affected by each event is detected and stored.

All connections are able to safely operate without tripping during and following over-voltage events to support regulation of the DC System voltage back to pre-disturbance levels. The new connection is able to withstand the maximum sustained over-voltage limit and will have an over-voltage protection consistent with the existing system.

The size and response characteristics of DC energy dissipation devices are also consistent with the operation of the existing DC system.

An example of voltage swell can be seen in Figure 6. Normally, swell threshold and time duration are used to identify a voltage swell event.

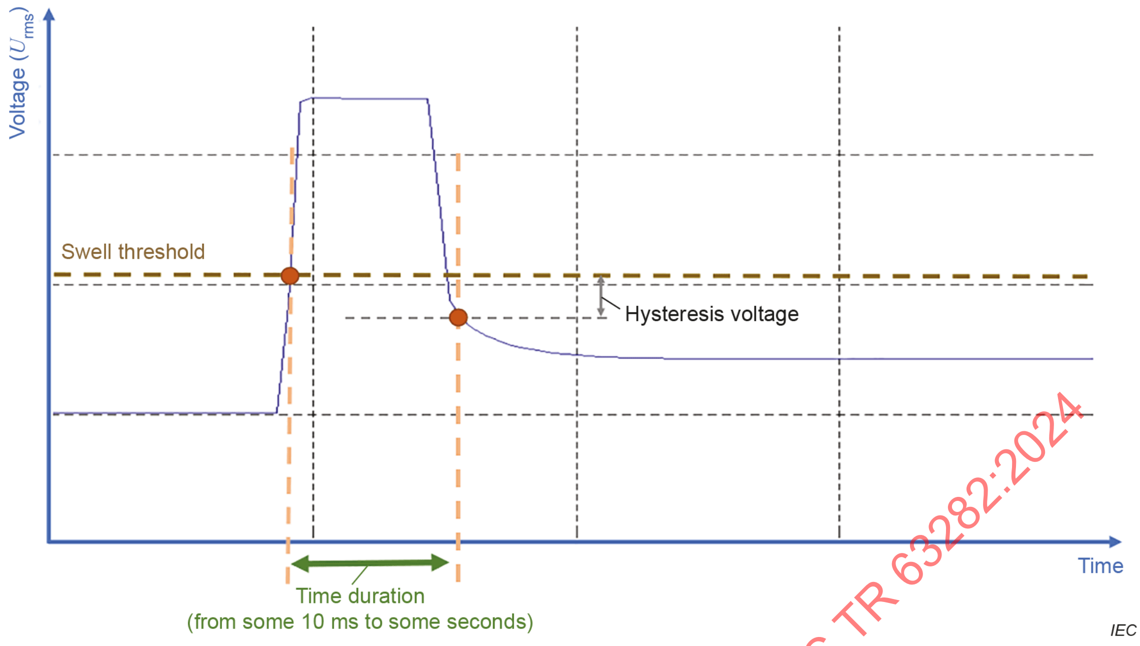


Figure 6 – Voltage swell example

6.7 Voltage dip

Voltage dips typically originate from system faults, load faults (protection, lightning, short-circuits, disconnection, etc.) in the public network or in network users' installations and appliances, or from direct connection of capacitive loads. The annual frequency depends on the reliability of the electrical installation and its supply system. Moreover, the distribution over the year can be very irregular.

The power quality characteristics of individual events are defined for each equipment, by residual voltage and duration, irrespective of the specific shape of the voltage variation.

For DC measurements, the number of equipment affected in each event can be detected and stored for more information.

Generally, according to the network user connection, or the concrete situation, line-to-line, line-to-earth and line-to-mid-point voltages are considered.

All connections are able to safely operate without tripping during and following under-voltage events to support regulation of the system DC voltage back to pre-disturbance levels. Fault-tolerant transient under-voltage characteristics in terms of retained voltage levels depending on duration of the event for the DC system are also defined. Following fault clearance, the connection returns to normal operating conditions subject to normal DC voltage and power control, within a defined time period. The under-voltage ride through requirements is defined to ensure the desired behaviour.

DC voltage excursions can be experienced in the whole DC system. Power exports from or imports to the DC system stay within the limits that can be permanently balanced by converter station controls. Thus, any power unbalance will have direct impact on the DC voltage. The trip of a converter station can result in a steep voltage dip or high voltage rise depending on its function as power import or export.

An example of voltage dip can be seen in Figure 7. Normally, dip up threshold, dip down threshold and time duration are used to identify a voltage dip event.

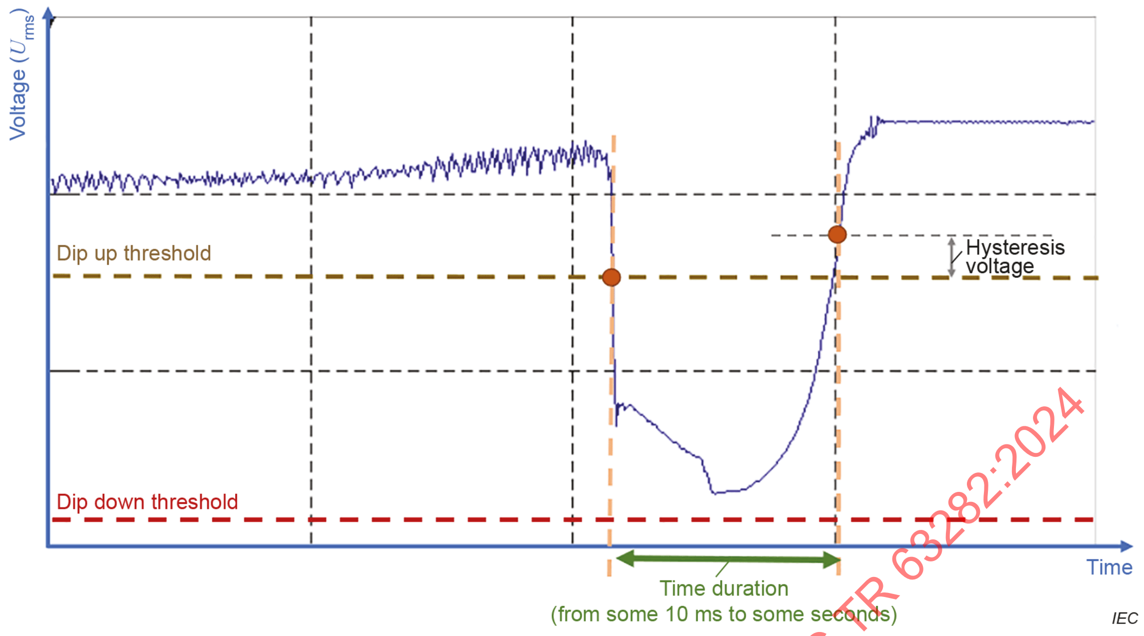


Figure 7 – Voltage dip example

Similar to AC systems, voltage dips in DC systems are likely to cause equipment and devices to malfunction, loss of data and general nuisance for the users.

It is also noteworthy that LVDC systems are less susceptible to voltage dips and swells occurring in the AC system when the interconnecting converter actively controls the DC voltage. In data centers, today the overall reliability of power distribution is based on the use of UPS systems. A similar result could be ensured by active DC systems with the appropriate requirements. Some loads, such as computers and emergency lighting, cannot be used in systems affected by disturbances in the AC utility system. Both the software and the hardware of important computer systems can be damaged due to voltage transients or power outages, and lighting used to illuminate emergency exits or important processes cannot be shut off.

6.8 Voltage supply interruption

On unipolar systems, a voltage interruption begins when the voltage falls below the interruption threshold.

On bipolar systems, a voltage interruption occurs when the line-to-mid-point voltage drops below an interruption threshold.

The interruption threshold is generally 5 % or 10 % of the nominal voltage.

6.9 Rapid voltage change (RVC)

Under normal operating conditions (excluding events), rapid voltage changes do not exceed indicative values.

Rapid voltage change indicative values are in the range of 3 % to 5 % of the nominal voltage.

These values specifically refer to relative steady-state voltage changes aggregated over very-short time intervals e.g. 200 ms time intervals (all variations during these intervals are aggregated in the so-called steady-state voltage). They are based on the usual design criteria for high power supply or load starting, for example.

An example of RVC event can be seen in Figure 8. Normally, the threshold of RVC in voltage amplitude is between the swell threshold and the dip up threshold.

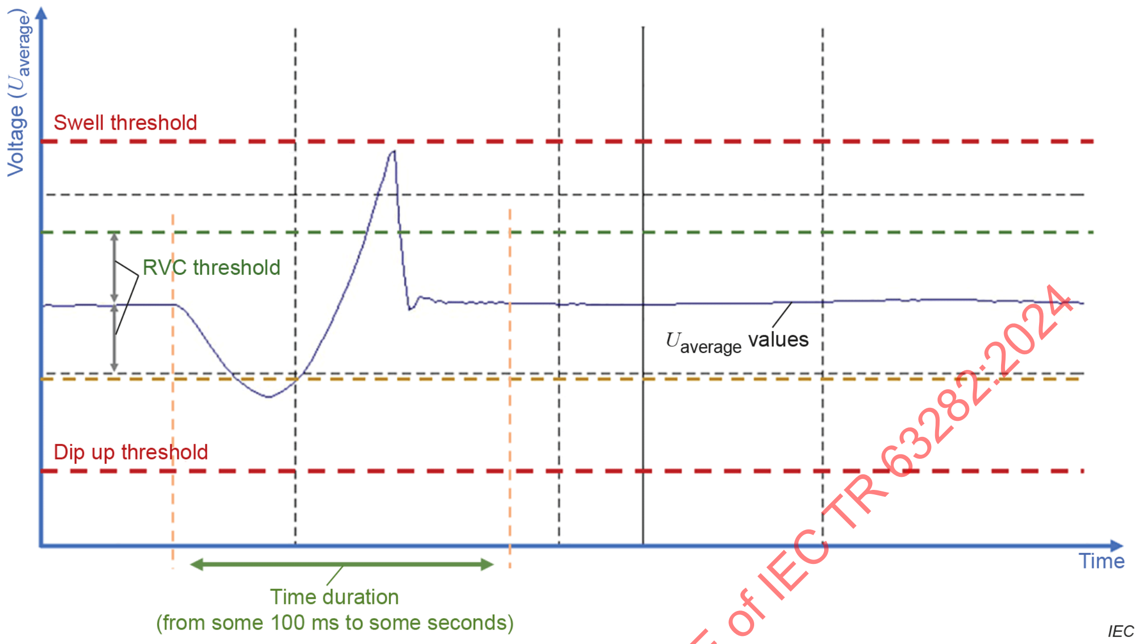


Figure 8 – RVC event: example of a change in average voltage that results in an RVC event

Rapid changes to DC voltage can originate from events in the DC system or from the external AC system.

6.10 Voltage surges

Voltage surges are transient overvoltages with durations of several microseconds. A transient overvoltage due to lightning, switching, or other causes can exceed the insulation rating of the electrical equipment causing degradation of insulation and damage to the equipment.

Figure 9 gives an example of voltage surge in a real system.

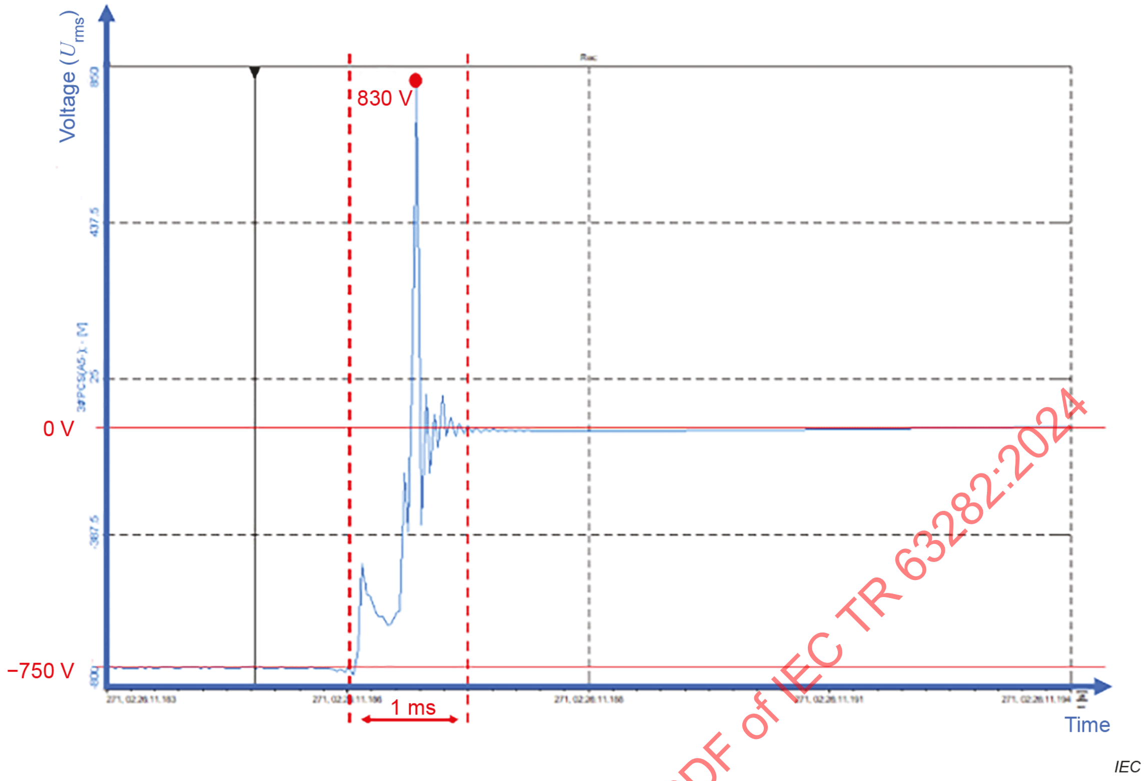


Figure 9 – Example of voltage surge

When a circuit is struck by atmospheric effect or an inductive load or a large load is switched on/off, it often produces a high switching overvoltage. The switching action can cause a high transient voltage or current surge. For example, when the relay coil of a 6 V DC relay is disconnected, the voltage surge of 300 V to 600 V can appear, depending on the coil type. When a large capacitor bank is connected to the DC system, a current surge will occur, unless the connection is controlled, which will transiently decrease the system voltage. Voltage surge phenomenon is increasingly endangering the safety of the automation equipment. Eliminating surge interference and preventing surge damage have always been the core issues related to the safe and reliable operation of automation equipment. In most cases, voltage surge can damage electronic device circuit and its components. The degree of damage is closely related to the voltage withstanding strength of components and the convertible energy in the circuit.

IEC 61204 series defines EMC, performance, and safety requirements for LV DC supplies. Similar limits are considered for LVDC systems.

6.11 Voltage unbalance

In case the currents through the positive and the negative lines are not perfectly matched because of unequal load distribution, the positive and negative voltages can become unequal. The condition in which the positive and negative voltages differ is referred to as voltage unbalance. The amount of voltage unbalance can vary continuously as the loads and generators in the system are randomly turned on or off by the customers.

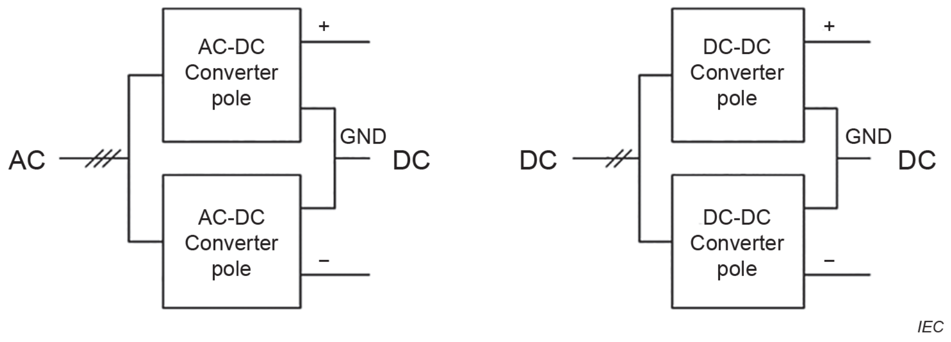


Figure 10 – A schematic of a bipolar system (the CIGRE B4 DC test system)

The bipolar LVDC system can be regarded as two series connected unipolar LVDC systems, namely a positive and a negative part (see Figure 10). The positive and negative voltages are in that case separately controlled by means of separate power converters. Nevertheless, single power converters exist with three output terminals for connecting to a bipolar LVDC system such as neutral-point clamped converters and three-level DC-DC converters. Instead of controlling the positive and the negative line-to-mid-point voltage, three-terminal converters control the balanced and unbalanced voltage, as defined in 3.7.

7 Guidance for voltages and power quality in LVDC system

7.1 Considerations for voltages in distribution DC networks

7.1.1 General

TC 8 is in charge of specifying the recommended voltages for LVDC distribution as one of the system aspects. These recommendations are expected to be the result of a factual state of the art. Hereafter are the proposals for implementation in IEC 60038.

NOTE Information on preferred voltage values in different countries are provided in Annex I.

7.1.2 Factors considered to define voltage values

Different factors have been considered to define these values, such as:

- application domain,
- network topology and architecture (radial or meshed system, distributed sources, etc.),
- multiplication by two factors for converters,
- compatibility with AC voltage levels for easy conversion with some existing types of converters (depending on the converter design, the compatibility is easy to fulfil),
- existing DC applications or available products,
- DC voltages in existing standards (IEC 60664-1 coordination standard, etc.),
- safety/electric shock in case of fault protection (keep U_4 as the DC limit used in IEC 60364-4-41:2005/AMD1:2017, Table 41.1 to allow safety to be ensured),
- safety/fire risk, corrosion (batteries, arcing, PV, etc.),
- supply radius/transmission capacity (voltage drop, thermal capacity of cables),
- system efficiency (losses in converters, in cables and all the other components),
- sustainability (life cycle of different components, raw materials, etc.),
- insulation (coordination),
- clear identification (between AC and DC).

Finally, two different tables of DC voltages are proposed:

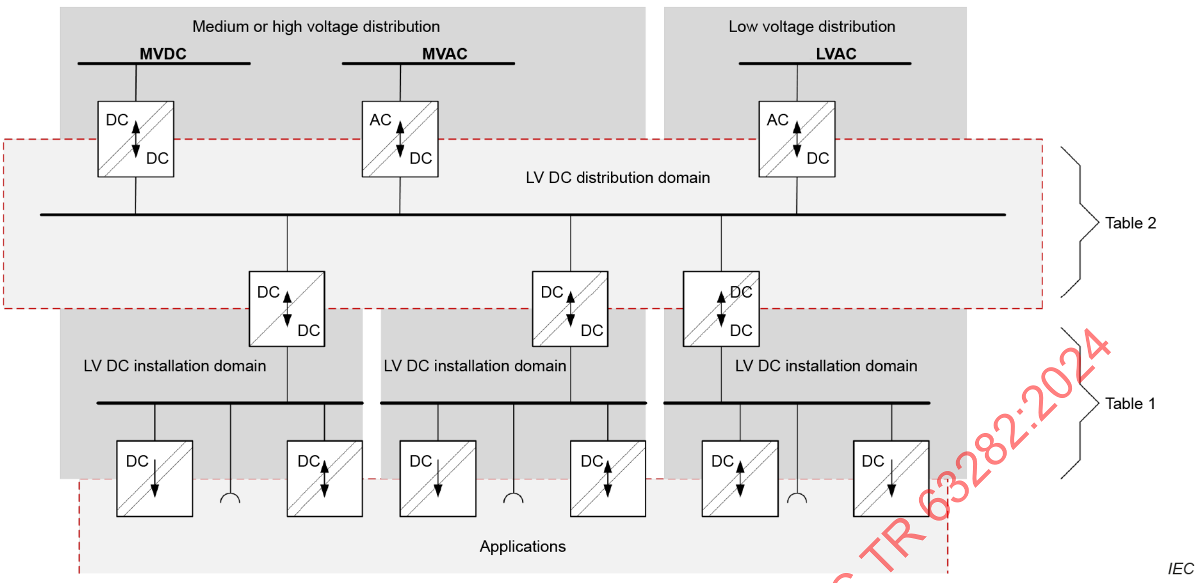


Figure 11 – LVDC distribution domain and installation domain

– one for distribution domain:

installations for high power, long distances pure distribution purposes, excluding final circuits,

– one for installation domain:

installations, for example, final circuits, for the purpose of supplying voltage to end-user or production appliances.

Figure 11 shows the typical structure of the two LVDC system domains.

Different commonly used voltages have been listed in use cases, which have been included in Table 1 and Table 2.

Table 1 – Voltage between lines (unipolar systems) or line and mid-point (bipolar systems) for installation domain

Nominal U (system) Rated U (equipment) V	U_1 V	U_2 V	U_3 V	U_4 V	U_5 V	U_6 V
±175 350	250	320 (source) * 310 (load)	380	400	420	540
±350 700	500	640 (source) * 620 (load)	760	800	840	1 080
±700 1 400	1 000	1 280 (source) * 1 240 (load)	1 520	1 600	1 680	2 160
* Source and load are both related to equipment, but the source defines the system.						

Table 2 – Voltage between lines (unipolar systems) or line and mid-point (bipolar systems) for distribution domain

Nominal U (system) Rated U (equipment) V	U_1 V	U_2 V	U_3 V	U_4 V	U_5 V	U_6 V
750	530	675 (source) * 640 (load)	795	825	870	2 800
±750 1 500	1 060	1 350 (source) * 1 280 (load)	1 590	1 650	1 700	4 600
* Source and load are both related to equipment, but the source defines the system.						

The proposed voltage values take into account the compatibility of the installations belonging to these two domains.

An industrial site can contain installations falling into either or both of the above domains. The use of the installation determines the domain.

The voltages are close to each other, but not the same, because of the requirements arising from the different use and operating environment:

– Equipment tolerating higher operating voltages (robustness) is required in the distribution domain compared to the installation domain.
– Voltage bands are optimised for both domains:
  - Distribution domain values are optimised for high transmission capacity, particularly for longer transmission distances, and the need to provide resilient and secure supply in all operating conditions, including during faults, to supplied equipment belonging to the installation domain.
  - Installation domain values are optimised for supplying high density of various, usually fairly low-power, different appliances and equipment in more confined spaces, where the equipment is likely to be operated by laypersons.

Different (rated) voltage labels can be used to identify the installations and equipment (e.g, switches, breakers, sockets, cables, etc.) intended for the different domains (similar to identification of the application areas of LV breakers based on standards IEC 60898 and IEC 60947). Clear identification/labelling of equipment is necessary to get correct robustness according to the application. Annex I, Annex L and Annex M give other preferred voltages in different countries and organizations.

7.1.3 DC voltages

ELVDC (extra low voltage DC) voltages, such as 12 V, 24 V, 48 V, etc. have not been listed as an example of recommended voltages in the above tables but they could be included as LVDC voltages for some distribution purposes.

Voltage levels having historical background, and which are actively used in specific applications, such as in industrial and traction DC systems, remain in use in accordance with existing definitions (see, e.g., IEC 60038:2009/AMD1:2021, Table 2 and IEC 60038:2009, Table 6). These could not be mixed with the DC voltages proposed in Table 1 and Table 2.

7.2 EMC, compatibility and testing of equipment

Electromagnetic compatibility (EMC) is the ability of different electronic devices and components to work correctly even in the presence of other devices that emit electromagnetic interference. This means that each piece of equipment emitting electromagnetic disturbance have it limited to a certain level and that each individual equipment has adequate immunity to electromagnetic disturbance in the environment it is meant to operate in.

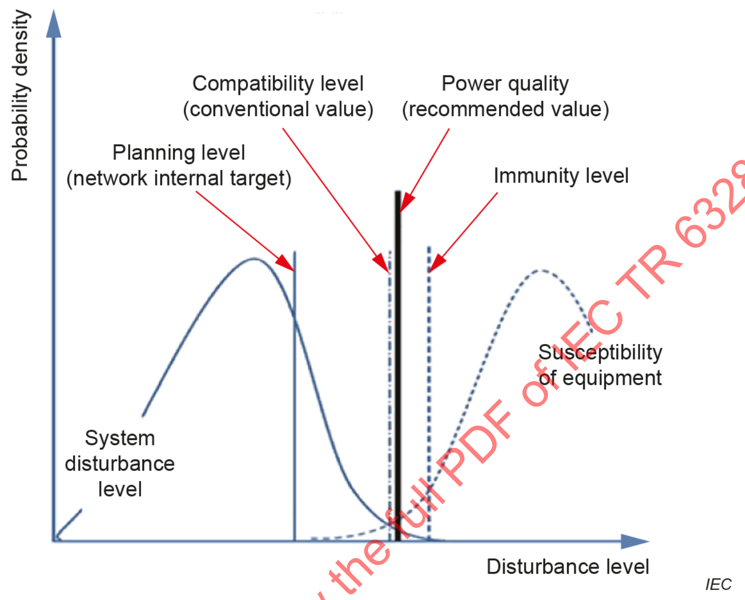


Figure 12 – Relation between disturbance levels (schematic significance only)

Power quality requirements are consistent with EMC conceptions. As described in EN 50160 and IEC TS 62749 for AC, they are usually identical or close to compatibility levels for the related phenomena (see Figure 12).

Existing standards dealing with EMC emission and EMC immunity levels can be adapted in the context of LVDC distribution (refer to IEC 61000-2-2:2002, IEC 61000-2-12:2003, IEC 61000-2-4:2002, IEC 61000-4-13:2002, IEC 61000-4-19:2014, IEC 61000-4-17:2009, IEC 61000-4-29:2000, CISPR 16-2-1:2014, CISPR 16-2-1:2014/AMD1:2017 and CISPR 16-3:2020).

NOTE IEC 61000-6-1 and 61000-6-2 (generic immunity standards) cover high frequency phenomena for DC input output power ports.

For LVDC application, joint work is expected to be carried out in order to review whether environments defined for AC (e.g. public, residential, commercial and light industry/industrial environments) are relevant for establishing DC compatibility levels. Then compatibility levels will be specified for each LVDC phenomenon as reference benchmark for defining EMC and power quality requirements (coordination of emission and immunity levels, see Table 3, Table 4 and Table 5 for some existing levels).

Example for steady state phenomena < 2 kHz: Figure 13 illustrates the existing LVAC voltage compatibility and immunity levels (for class 2 of IEC 61000-4-13):

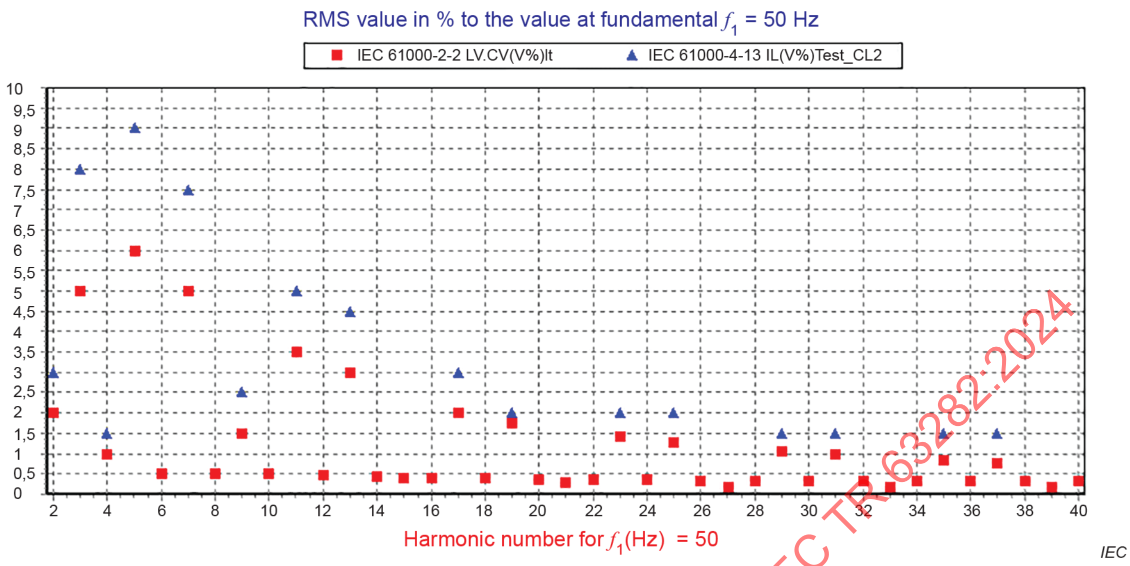


Figure 13 – LVAC voltage compatibility and immunity levels

Concerning the phenomena 2 kHz to 150 kHz in LVAC systems, relevant compatibility levels are illustrated in Annex D (Figure D.7). Therefore, the definition of relevant emission and immunity levels in this band is in progress according to application domains.

Table 3 – Immunity test requirements for DC input and output power ports of devices meant to be used in residential, commercial and light industrial environment

Environmental phenomenon	Test item	Test specification	Unit	Basic standard for test method
Fast transients	Peak line-to-ground voltage	0,5	kV	IEC 61000-4-4
	T_r/T_h	5/50	ns	
	Repetition frequency	100	kHz	
Surges	T_r/T_h	1.2/50 (8/20)	µs	IEC 61000-4-5
	Peak line-to-ground voltage	0,5	kV	
	Peak line-to-line voltage	0,5	kV	
Radio-frequency continuous conducted	Frequency	0,15 to 80	MHz	IEC 61000-4-6
	Amplitude	3	V	
	AM (1 kHz)	80	%	

Table 4 – Immunity test requirements for DC input and output power ports of devices meant to be used in industrial environment

Environmental phenomenon	Test item	Test specification	Unit	Basic standard for test method
Fast transients	Peak line-to-ground voltage T_r/T_h Repetition frequency	±2 5/50 100	kV ns kHz	IEC 61000-4-4
Surges	T_r/T_h Peak line-to-ground voltage Peak line-to-line voltage	1,2/50 (8/20) ±0,5 ±0,5	µs kV kV	IEC 61000-4-5
Radio-frequency continuous conducted	Frequency Amplitude AM (1 kHz)	0,15 to 80 10 80	MHz V %	IEC 61000-4-6

Table 5 – Ripple on DC input power port immunity test

Environmental phenomenon	Test item	Level	Percentage of the nominal DC voltage	Basic standard
Steady state DC disturbance	Testing and Measurement Techniques – Ripple on DC input power port immunity test	1 2 3 4 x	2 5 10 15 x	IEC 61000-4-17

IEC 61000-4-17:1999 gives the immunity test method of DC ripple in peak-peak values, but the test procedure mentioned does not apply to equipment connected to battery charger systems incorporating switch mode converters. In the new DC distribution system, almost all converters are controlled in switch mode. This document needs to be completed or replaced.

Therefore, one of the missing blocks in the standardization context is the assessment of EMC immunity and allowed emission levels of mass LVDC power electronic devices. This step is done in coordination with future definition of DC compatibility levels.

7.3 Considerations for DC power quality

The recommendations of some DC power quality measurement methods and indices are mainly derived from existing AC power quality methodologies. The main reasons are to:

– start DC power quality assessment with acquired know-how on AC power quality such as frequency bands and measurement window lengths,

– try to convert existing PQ monitoring technologies,

– adapt simulation tools for DC grid PQ assessment.

This is just first step and with arising development of DC applications, evolution of DC PQ assessment method will continue. The following DC power quality indices are proposed for future DC system:

– Peak-peak ripple: under a given sampling frequency, it is the maximum difference between max RMS value and min RMS value during a given measurement duration (T_w = 20 ms for example) divided by DC component. The RMS values are computed during integration duration (T_i = 200 ms, 1 min, or 10 min for example).
– Distortion in a DC system: DC distortion is defined as total RMS value of all alternating voltage components on the DC voltage during T_w.
– DC RMS ripple or distortion factor. DC distortion factor is the ratio of the DC distortion to the mean DC voltage during T_w.
– Ripple spectrum or distortion spectrum. The distortion spectrum quantifies AC components in terms of the amplitude and phase of each frequency component. The distortion spectrum includes the components resulting from amplitude and frequency modulation as well as AC components of the waveform, i.e., everything except the DC component.
– RMS ripple (or integral value, or spectral energy) is measured in each frequency band of interest with adequate time and frequency resolutions. According to frequency ranges, measurement methods can be different (refer to IEC 61000-4-30:2015, IEC 61000-4-15:2010, IEC 61000-4-7:2002, CISPR 16-2-1:2014, CISPR 16-2-1:2014/AMD1:2017 and CISPR 16-3:2020).

Joint work could be done in IEC technology committees and subcommittees in order to define DC power quality assessment methods, compatibility level, immunity level and emission level.

– To finalize DC ripple indicator (DC distortion, ripple distortion and ripple spectrum), particular attention is paid on choosing aggregation time interval and sampling frequency.
– To determine whether to use the RMS or averaging operator for assessing voltage dips and swells in LVDC systems, along with specifying the appropriate aggregation time interval. Current aggregation time intervals for AC systems can be inadequate to detect power quality deviations. The adequate averaging operator can be used.

As for AC, power quality requirements in LVDC systems require coordination with the compatibility level (conventional value) and immunity level (protection) of equipment.

Some existing standards which have already given some recommended values for the PQ indexes in LVDC distribution or equipment could be taken into account in the context of LVDC systems:

– IEC 60092-101,
– IEC 61000-4-29,
– IEC 61204-3.

7.4 Measurement methods

7.4.1 General

Most of the voltages stated in the document are DC values with AC components during a given time. DC RMS value is computed by the same formulas as in an AC system (see Annex D for detailed explanations).

7.4.2 DC system electric value integration time

The integration time or measurement window length of DC system RMS values and power quality indices are defined according to the power quality domain; it can be for example the following:

– 200 ms and 10 min values can be used for continuous phenomena such as DC ripple, unbalance;

– fast RMS value integrated during T_i (as half cycle RMS in AC system) can be used for transient values such as voltage dip/surge, in line with most existing UVRT (under voltage ride through) curves.

7.4.3 Frequency ranges of ripple spectral analysis

At present stage for total DC distortion assessment and DC ripple spectral analysis, two frequency ranges can be for example:

– The 0 kHz to 9 kHz range, referred to low frequency conducted disturbances of AC system, quantified with IEC methods (refer to IEC 61000-4-30:2015, IEC 61000-4-15:2010).

– The > 9 kHz range, referred to conducted disturbances of AC system, quantified with quasi peak detector according to the specific testing environment requirements.

7.4.4 DC power quality measurement methods

For DC power supply systems, it is referred to IEC 61000-4-30. Further work is necessary to fill in the gap of DC power quality measurement methods in this and other relevant documents such as 61000-4-7 and 61000-4-15.

7.4.5 DC system electric power measurements

As analysis in Clause D.5 shows, in a DC system with ripples, three types of powers components can co-exist: active power, reactive power and distortion power. Apparent power is the key parameter to quantify supply capacity and active power is for metering system.

Total active electric power P_{total} at a metering point includes AC and DC power components:

$$P_{total} = P_{DC} + P_{AC}$$

7.5 DC power quality standardization framework

DC power quality standardization contains:

– DC power quality terms. The specific terms in LVDC power quality need to be further optimized and defined.

– Measurement. The specific measurement in LVDC power quality is surveyed in a separate project.

– Index and recommendation. The power quality indices and recommendations in LVDC are different from AC systems. This needs to be surveyed in a separate project. It is the key in the LVDC power quality standardization.

– DC power quality assessment. Based on the power quality index and recommendation in LVDC, assessment is the application of power quality data. The standardization in assessment will guide the LVDC power quality management and fieldwork.

Annex A
(informative)

PQ waveforms collected from a certain LVDC project

Suitable PQ waveforms could be obtained from the operating projects. As supplementary information, Figure A.1 to Figure A.3 are parts of the waveforms corresponding to some PQ phenomena captured from an existing ±750 V/±375 V LVDC system in Tongli, China.

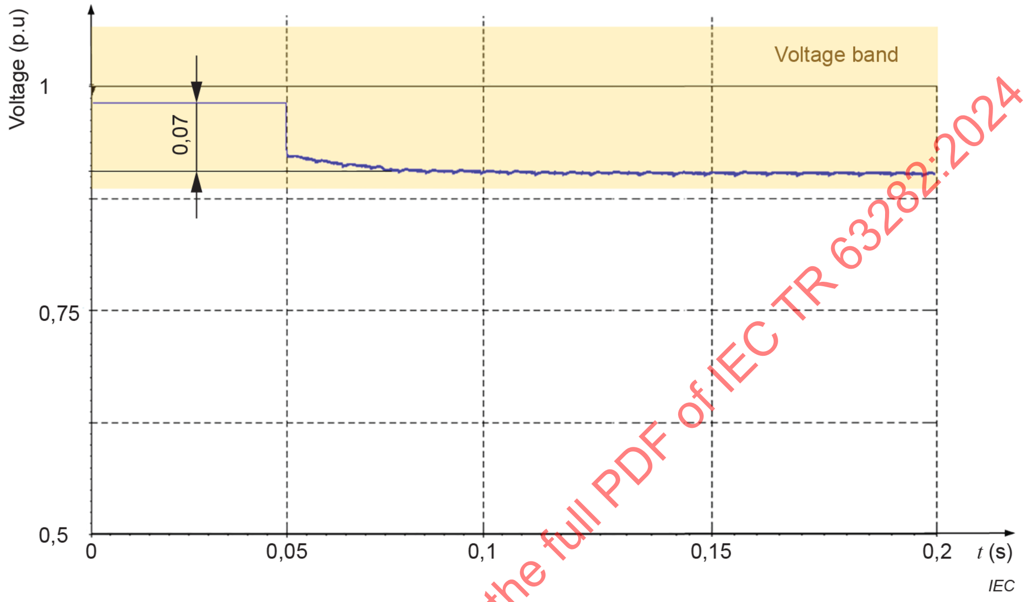


Figure A.1 – Voltage deviation caused by load switching

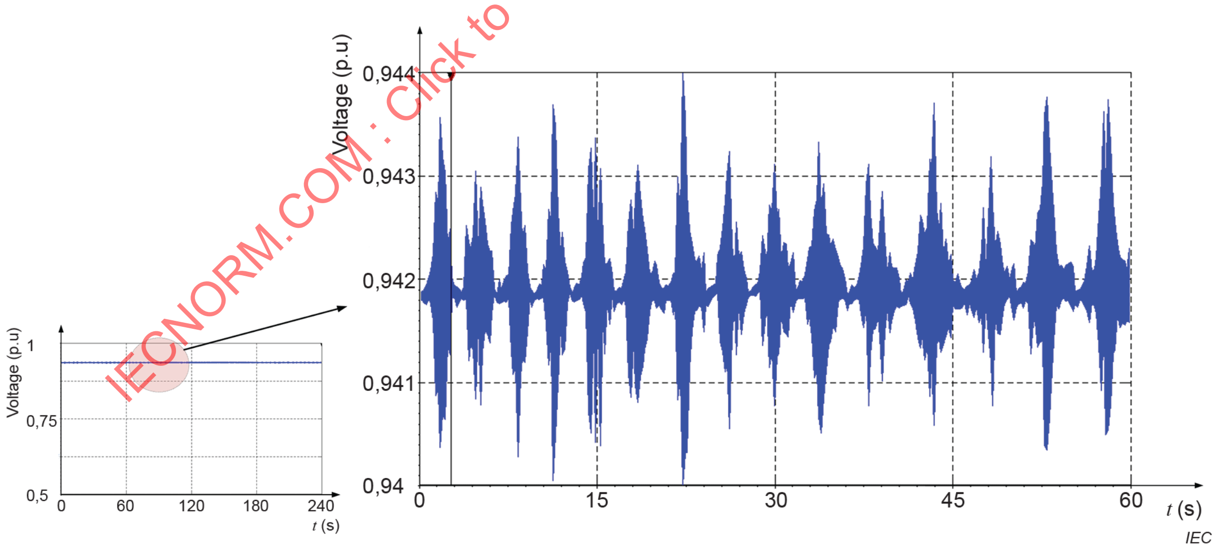


Figure A.2 – Voltage ripple in steady state

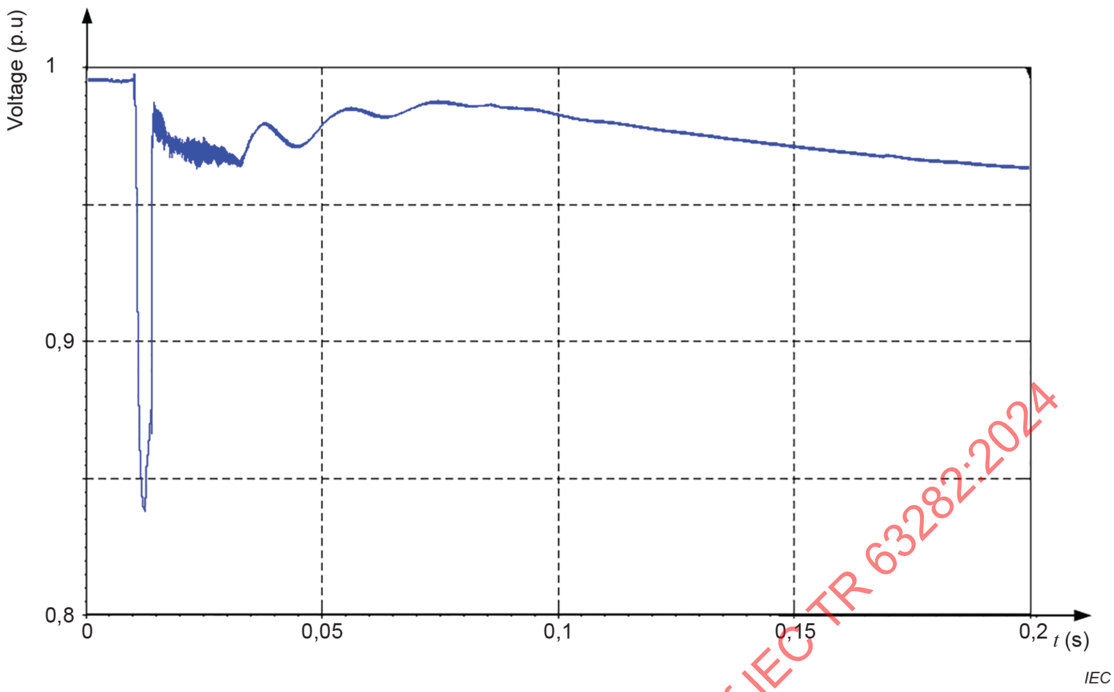


Figure A.3 – Voltage dip caused by the start-up of motor load

Annex B
(informative)

A LVDC oscillation typical example

As an example of a LVDC oscillation, the scenario happened in an MV&LVDC system in China. During the commission process of the substation, the oscillation happened on a ±375 V DC bus. Figure B.1 shows the equivalent topology of the whole system.

DC transformer (DCT) I controls the power transmission, and the rated capacity is 2 MW. DC transformer II controls the DC voltage of ±375 V and the rated capacity is 700 kW. The power flows between DCT I and DCT II.

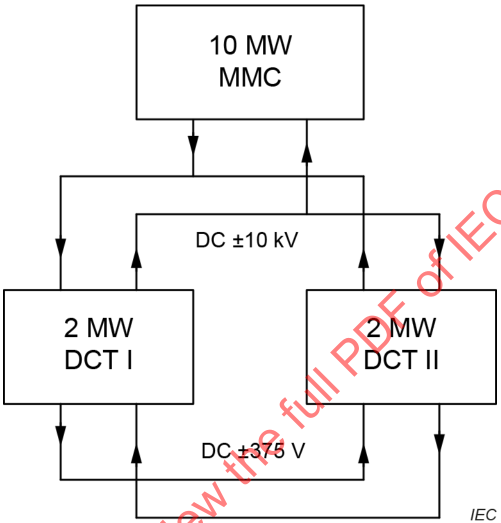


Figure B.1 – Equivalent topology of the substation

Figure B.2 shows the oscillation waveform. The oscillation occurs at 21 Hz when the transmitted power increased from 500 kW to 700 kW. Voltage on the ±375 V bus is changed around 748 V ~ 766 V. Current is changed around 823 A ~ 1 025 A. Power is changed around 80,55 kW ~ 622,08 kW. The oscillation continues for 2,23 s and then overvoltage protection of the system acts and stops the oscillation.

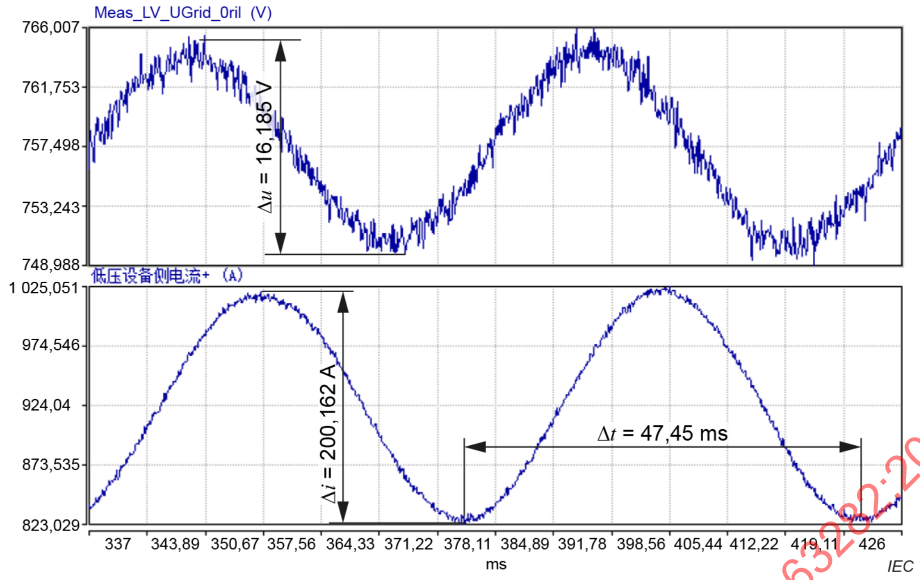


Figure B.2 – The voltage and current oscillation waveform on ±375 V bus

The oscillation is caused by the effect of negative input impedance. The oscillation could be avoided by optimizing the control parameter of the two DCTs to improve the system stability.

Annex C
(informative)

Supply radius in DC distribution systems

Supply radius means the distance of the line from the power source to the furthest load it supplies. Supply radius calculation in DC distribution systems considers voltage level, conductor nominal section, maximum long-term operating temperature and other factors. The supply radius calculation of the DC distribution system is based on the content of voltage deviation in different voltage levels in Clause 7. Considering that the conductor temperature and the DC resistance of overhead lines increasing with the growing transmission current, the supply radius of all typical nominal sections at operating temperature of 70 °C in a DC distribution system is calculated based on the unit DC resistance of the overhead line conductor at 20 °C. The results of the load distance in different voltage levels are shown in Table C.1, Table C.2 (based on the preferred DC voltages in China).

Table C.1 – 1,5 (±0,75) kV typical supply radius of overhead DC lines

Unit: kW·km

Voltage level kV	**1,5 (±0,75)**	**1,5 (±0,75)**
Nominal section mm^2	Voltage deviation 10 %	Voltage deviation 15 %
120	390	585
150	477	715
185	589	883
240	769	1 153
NOTE The supply radius values of 1,5 (±0,75) kV overhead lines are based on an aluminium strand conductor.		

Table C.2 – 750 (±375) V, 220 (±110) V typical section supply radius of overhead DC lines

Unit: kW·km

Voltage level V	**750 (±375)**	**220 (±110)**	**750 (±375)**	**220 (±110)**
Nominal section mm^2	Voltage deviation 10 %		Voltage deviation 20 %	
95	77	7	154	13
120	98	8	195	17
150	119	10	238	21
185	147	13	294	25
NOTE The supply radius values of 750 (±375) V and 220 (±110) V overhead lines are based on an aluminium strand conductor.				

Annex D
(informative)

Electric power and power quality computation in DC system

D.1 DC mean and RMS values of voltage or current

The mean value is usually used in DC electric systems to quantify voltage, current or power during a given period T, i.e., a measurement window's length:

$$V_{\text{mean}} = \frac{1}{T}\int_0^T V(T)\text{d}t \tag{D.1}$$

More generally, the DC root mean square value (RMS) value is used to quantify all DC and AC components. It is the total RMS value of the DC component (or mean value) and RMS value of all AC components in a given measurement window's length T, i.e.:

In the time domain, computation of the RMS value is identical in both DC and AC systems during the given measurement window:

$$V_{\text{RMS}} = \sqrt{\frac{1}{T}\int_0^T V^2(t)\text{d}t} \tag{D.2}$$

In the frequency domain with FFT or DFT transforms, the DC RMS value is computed with the same formula as for AC systems during the given measurement window:

$$V_{\text{RMS}} = \sqrt{\sum_{k=0}^{n} V_k^2} \tag{D.3}$$

where

T is the measurement window's length;

n is half of the sampling points during the given window FFT or DFT;

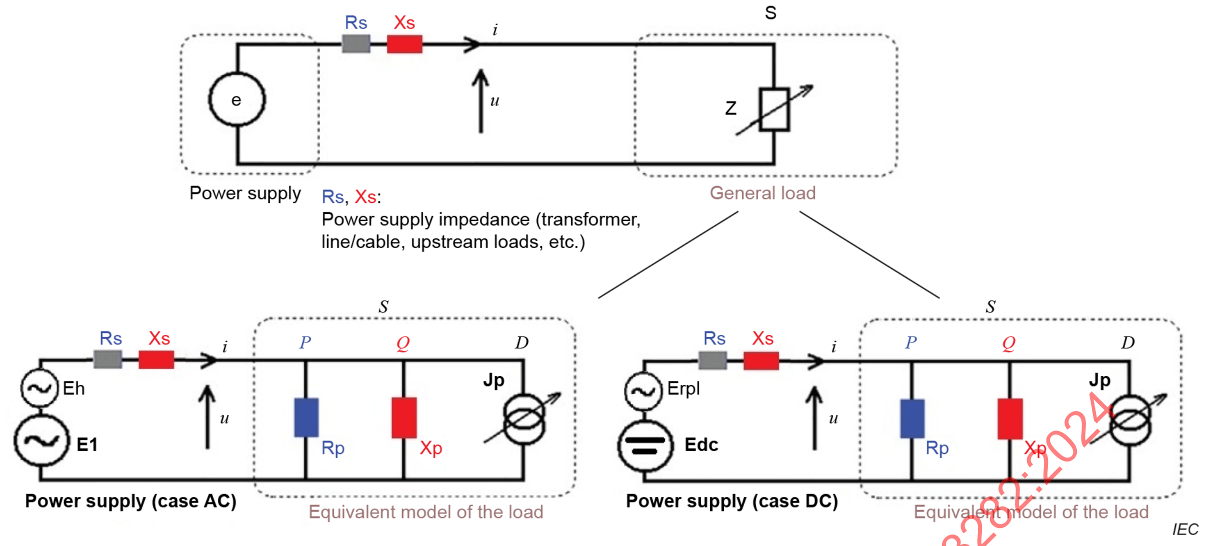
V_k is the RMS value at index k, i.e. at frequency $k \times f_\text{w}$;

f_w is the window frequency referred to the width of the Fourier transform window;

k = 0 is the DC component.

D.2 General electric power system: decomposition of a general electric load

In an electric power system, an electric load can call different types of currents from power grid: DC current, sinusoidal current with different phase angles, and non-sinusoidal currents. In a general case, load consumption can be represented by linear and nonlinear components referred to different electric powers (see Figure D.1). From these decomposed equivalent circuits, it is observed that there is no important methodological difference in dealing with AC or DC power quality issues.



Key

E1	fundamental voltage source of AC case
Rs, Xs and Eh	upstream grid equivalent model with frequency-dependent resistance, reactance and background disturbance voltages
Edc, Erpl	DC voltage source and ripple component of DC case
Rp, Xp and Jp	frequency-dependent resistance, reactance and disturbance current injection
S	apparent power
P	active power
Q	reactive power
D	distortion power resulted from deformation of voltage and current

Figure D.1 – Equivalent model of a general electric load

D.3 Computation of electric powers and PQ indices

D.3.1 Computation of electric values in time domain

The instantaneous active power is defined by the multiplication of voltage and current in sampled values:

$$p(t) = u(t) \times i(t) \tag{D.4}$$

The mean value of active power P is computed by integration of the instantaneous power p during the pre-defined analysis period T:

$$P = \frac{1}{T}\int_0^T p(t)\mathrm{d}t = \frac{1}{T}\int_0^T u(t) \times i(t)\mathrm{d}t \tag{D.5}$$

In the above formula, DC components are included.

In simplified computation system, DC power can be measured with mean values of voltage and current:

$$P = V_{\text{mean}} \times I_{\text{mean}} \tag{D.6}$$

In the above simplified formula, influence of AC components is neglected. If AC components are not negligible, Formula (D.5) is used to compute true active power.

RMS values of voltage U and current I:

$$U = \sqrt{\frac{1}{T}\int_0^T u(t)^2 \mathrm{d}t} \text{ and } I = \sqrt{\frac{1}{T}\int_0^T i(t)^2 \mathrm{d}t} \tag{D.7}$$

If waveforms U and I are sinusoidal: $P = I \times U \times \cos(\phi)$

D.3.2 Computation of electric values in frequency domain

Generally, in electric power system monitoring, electrical values such as voltage and current are sampled in the analogical time domain, by means of a Fourier transform within a defined window length; they are decomposed into frequency domain values as DC components and AC components (magnitude and phase):

$$u = U_0 + \sqrt{2}\left[U_1 \times \sin(\omega t + \phi_1) + U_2 \times \sin(2\omega t + \phi_2) + U_3 \times \sin(3\omega t + \phi_3) + \ldots + U_n \times \sin(n\omega t + \phi_n)\right] \tag{D.8}$$

$$i = I_0 + \sqrt{2}\left[I_1 \times \sin(\omega t + \phi_1) + I_2 \times \sin(2\omega t + \phi_2) + I_3 \times \sin(3\omega t + \phi_3) + \ldots + I_n \times \sin(n\omega t + \phi_n)\right] \tag{D.9}$$

where

n is the maximal harmonic referred to measurement window frequency f_1;

f_1 is the measurement window frequency, $\omega = 2\pi f_1$;

U_0, I_0 are the DC components;

U_k, I_k are the AC components (k > 0) in RMS values.

Relevant electrical values can be computed with frequency domain components:

Root mean square values or RMS values:

$$U = \sqrt{U_0^2 + U_1^2 + U_2^2 + U_3^2 + U_4^2 + \ldots + U_n^2} = \sqrt{\sum_{k=0}^{n} U_k^2} \tag{D.10}$$

$$I = \sqrt{I_0^2 + I_1^2 + I_2^2 + I_3^2 + I_4^2 + \ldots + I_n^2} = \sqrt{\sum_{k=0}^{n} I_k^2} \tag{D.11}$$

Electric powers of single-phase system:

$$S = U \times I \tag{D.12}$$

$$P = \sum_{k=0}^{n} \left[U_k \times I_k \times \cos(\phi_k) \right] \tag{D.13}$$

$$Q = \sum_{k=0}^{n} \left[U_k \times I_k \times \sin(\phi_k) \right] \tag{D.14}$$

$$D = \sqrt{S^2 - P^2 - Q^2} \tag{D.15}$$

where

ϕ_k is the phase angle difference between voltage and current at frequency $f = k\,f_1$ (k>0)

ϕ_0 is either 0 or π.

The above active power formula gives exact power values even if AC components exist. In a simplified or economical way, it is possible to measure only DC power by mean values of voltage and current:

$$P_{DC} = U_{DC} \times I_{DC} \tag{D.16}$$

D.3.3 Total harmonic distortion T_{hd} used in AC system

Based on the frequency domain decomposition, the total harmonic distortion can be computed:

Total voltage harmonic distortion:

$$T_{dh\_U} = \frac{1}{U_1} \sqrt{U_2^2 + U_3^2 + U_4^2 + \ldots + U_n^2} \times 100\,\% \tag{D.17}$$

Total current harmonic distortion:

$$T_{dh\_I} = \frac{1}{I_1} \sqrt{I_2^2 + I_3^2 + I_4^2 + \ldots + I_n^2} \times 100\,\% \tag{D.18}$$

In a pure sine wave system or in a pure DC system: T_{dh} = 0.

According to IEC definitions, the total harmonic distortion for AC systems is computed up to harmonic number 40 or 50 (2 000 Hz or 2 500 Hz) depending on the countries. In Europe, harmonic frequency ends at 2 kHz.

If the frequency range of the above formulas exceeds 2 kHz, it can be called as total distortion T_d instead of T_{hd}, so $T_d \geq T_{hd}$.

Computation of other power quality indices: see IEC 61000-4-30 for AC systems.

In a DC system, T_{dh} can be represented by the RMS ripple value, i.e. I_1 or U_1 are replaced by a mean DC component value during the measurement period. In fact, harmonic in DC system is not a correct term as the fundamental frequency does not exist, see Clause D.6 for ripple computations.

D.3.4 The relation of different electric powers

$$S = \sqrt{P^2 + Q^2 + D^2} \quad \text{(D.19)}$$

$$Q' = \sqrt{Q^2 + D^2} \quad \text{(D.20)}$$

Power factor is generally computed as:

$$P_F = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2 + D^2}} \quad \text{(D.21)}$$

In a pure sinusoidal system (D = 0), λ becomes:

$$P_F = \frac{P}{\sqrt{P^2 + Q^2}} = \cos(\phi) \text{ and } \tan(\phi) = Q / P \quad \text{(D.22)}$$

where

ϕ is the phase angle difference between voltage and current at fundamental frequency.

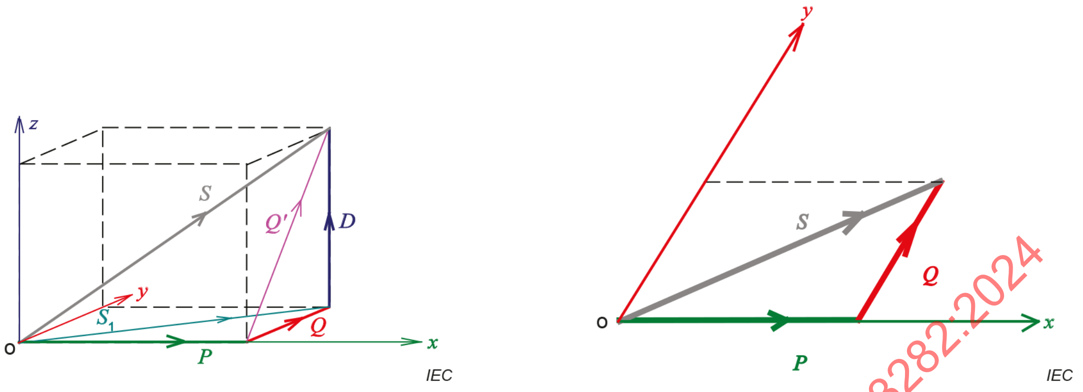
The values of cos (ϕ) and tan (ϕ) are computed only by phase angle between voltage and current at fundamental frequency.

In a non-sinusoidal system, the power factor λ takes into account both reactive power Q and distortion power D, but the terms cos (ϕ) and tan (ϕ) take into account only the reactive power at fundamental frequency.

In DC systems, cos (ϕ) and tan (ϕ) cannot be significant because reactive power is near zero. Furthermore, S, P, D, P_f remain useful and are physically significant. D quantifies the existence of distortion power and P_f indicates the performance of a load, i.e., if P_f is near to 1, the load is grid-friendly in both AC and DC systems.

D.4 Representation of electric powers in AC system

These different powers can be represented by an equivalent 3D vector diagram. See Figure D.2.



a) **General case (non-sinusoidal)**

b) **Particular case (sinusoidal)**

Figure D.2 – Representation of electric powers in AC system

D.5 Representation of electric powers in DC system

In a DC system with the presence of AC components (or disturbances in voltages and currents), the different electric parameters can be also represented by 3D vector diagram (see Figure D.3):

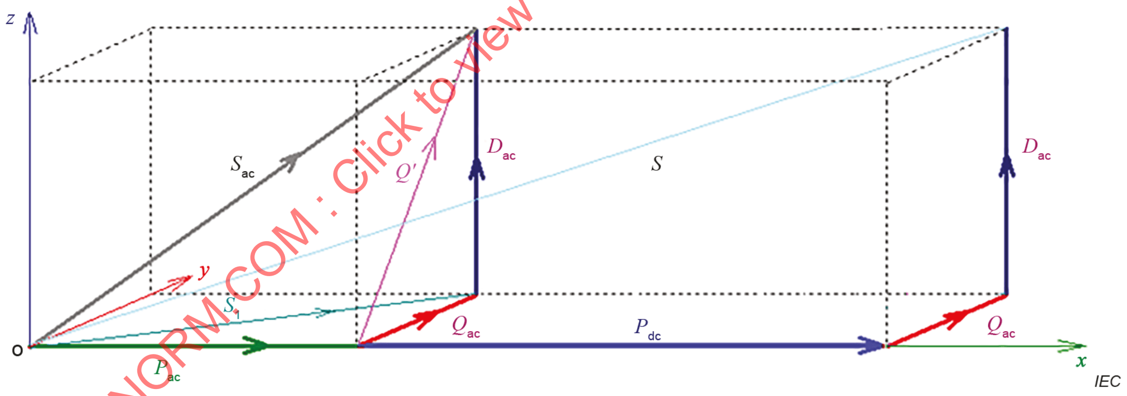


Figure D.3 – Representation of electric powers in DC system

The powers Q, D are only computed with AC components. Active power P_{AC} is resulted from the AC voltages and currents, and P_{DC} is resulted from of DC components.

In a pure AC system, $P_{DC} = 0$.

In a pure DC system, $D = 0$, $Q = 0$, $P_{AC} = 0$.

In a DC system with ripples, total electric power at a metering point $P_{total} = P_{DC} + P_{AC}$. This could be considered in future DC metering systems.

Remark:

A DC system with the presence of AC components represents theoretically the general electric power system, that is to say, in a DC system, some power quality issues can exist as well as in AC system. In so-called today's world-widely used AC power system, the DC components are very small and just considered as negligible.

– General case of electric power system: presence of DC + AC components;
– AC power system is a particular case: DC component is considered as negligible.

D.6 Power quality indices in DC system

D.6.1 General

The DC value can include ripples (or AC components) (see Figure D.4):

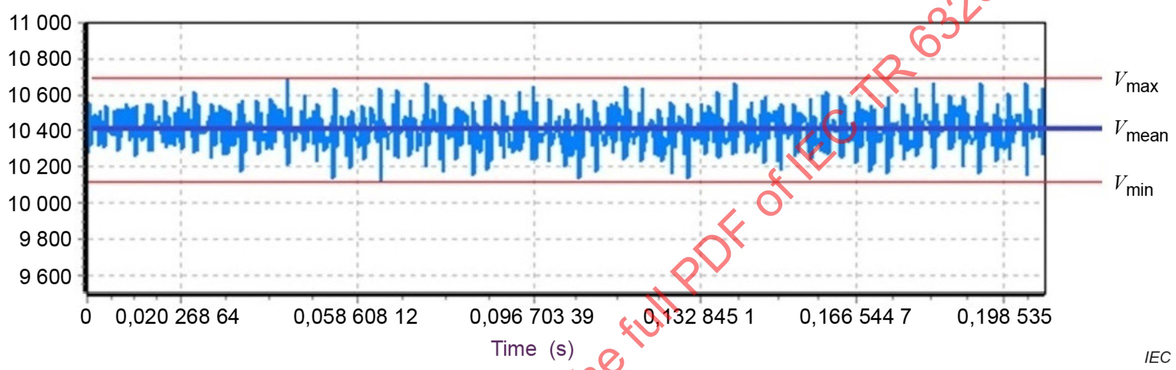


Figure D.4 – Ripples of output DC voltage of positive of a PWM AC/DC converter

D.6.2 DC peak-peak ripples

For general DC power supply, the following formula is used to quantify DC ripple peak-peak value of each measurement period. Peak-peak ripple is the maximum difference between max RMS value and min RMS value during T_w divided by DC component.

$$\text{Peak-peak ripple}\ldots(\%) = \text{abs}\left(\frac{V_{max} - V_{min}}{V_{mean}}\right) \times 100\ \% \qquad \text{(D.23)}$$

D.6.3 Ripple spectra

Figure D.5 illustrates DC voltage and current waveforms measured at the input of a new LVDC load (electronic dimmer) and their FFT analysis. The spectra show that the load current contains a large range of spectra covering mainly from 100 Hz to 150 kHz. The potential impacts of these spectra of DC voltage are surely different in each range of frequencies because the impedances of DC power supply and distribution links are function of frequency as well. In this case, computed DC PQ indices are: RMS ripple is 2,33 % for DC voltage and 215 % for DC current in the range of frequency < 9 kHz. For information, the observed disturbance voltage level 9 kHz to 150 kHz is about 86 dBµV which is lower than the existing AC voltage compatibility level. Furthermore, the definition of EMC emission limits is documented in CISPR 11 (Industrial, scientific and medical equipment) and CISPR 15 (electrical lighting and similar equipment).

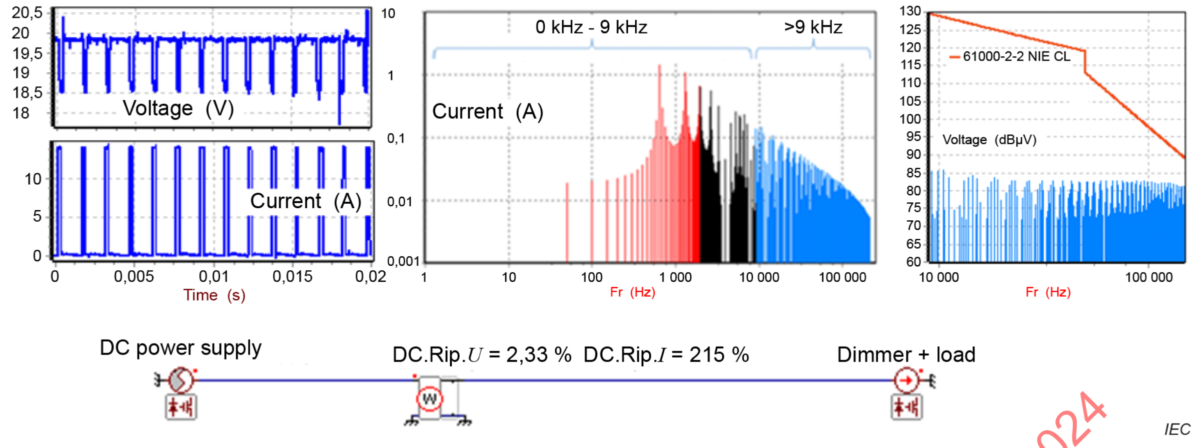


Figure D.5 – Spectral analysis of DC voltage and current measured at the input of an electronic load

D.6.4 DC RMS ripple or ripple distortion

Time domain computation with sampled values:

RMS values:

$$U = \sqrt{\frac{1}{n_s} \cdot \sum_{t=t_0}^{t_n} u^2(t)} \text{ and } I = \sqrt{\frac{1}{n_s} \cdot \sum_{t=t_0}^{t_n} i^2(t)} \quad \text{(D.24)}$$

DC values (or mean values):

$$U_0 = \frac{1}{n_s} \cdot \sum_{t=t_0}^{t_n} u(t) \text{ and } I_0 = \frac{1}{n_s} \cdot \sum_{t=t_0}^{t_n} i(t) \quad \text{(D.25)}$$

where n_s is the sampled number during the observed period.

DC ripple in RMS values:

$$U_{rpl} = \sqrt{U^2 - U_0^2} \text{ and } I_{rpl} = \sqrt{I^2 - I_0^2} \quad \text{(D.26)}$$

DC ripple rates in %:

$$u_{rpl} = \frac{\sqrt{U^2 - U_0^2}}{U_0} \times 100\% \text{ and } i_{rpl} = \frac{\sqrt{I^2 - I_0^2}}{I_0} \times 100\% \quad \text{(D.27)}$$

Frequency domain computation of DC power quality values with sampled values:

Based on DFT or FFT analysis of DC signal (voltage or current) during specified period, DC electric parameters and power quality indices are computed:

RMS

$$U = \sqrt{U_0^2 + U_1^2 + U_2^2 + U_3^2 + U_4^2 + \ldots + U_m^2} \tag{D.28}$$

$$I = \sqrt{I_0^2 + I_1^2 + I_2^2 + I_3^2 + I_4^2 + \ldots + I_m^2} \tag{D.29}$$

Ripple in RMS

$$U_{\text{rpl}} = \sqrt{U_0^2 + U_1^2 + U_2^2 + U_3^2 + U_4^2 + \ldots + U_m^2} \tag{D.30}$$

$$I_{\text{rpl}} = \sqrt{I_0^2 + I_1^2 + I_2^2 + I_3^2 + I_4^2 + \ldots + I_m^2} \tag{D.31}$$

Ripple distortion in %

$$u_{\text{rpl}} = \frac{U_{\text{rpl}}}{U_0} \times 100\,\% = \frac{\sqrt{U^2 - U_0^2}}{U_0} \times 100\,\% \tag{D.32}$$

$$i_{\text{rpl}} = \frac{I_{\text{rpl}}}{I_0} \times 100\,\% = \frac{\sqrt{I^2 - I_0^2}}{I_0} \times 100\,\% \tag{D.33}$$

Where m is the maximal harmonic referred to windows' frequency f_1.

The maximum measurement frequency f_{m} is defined in accordance with studied frequency domains. In compliance with on-going IEC EMC standards, f_{m} can be set as:

– f_{m} > 2 kHz for harmonic frequency range defined by IEC;

– f_{m} >150 kHz for disturbances 2 kHz to 150 kHz.

D.7 Illustration example of distortion power in DC system

Computation of DC powers based on sampled values of U_{DC} and I_{DC} (512 points) during a window of 20 ms (see Figure D.6, e.g. a repeatable load control). Even if the DC voltage is almost perfect, distortion power exists:

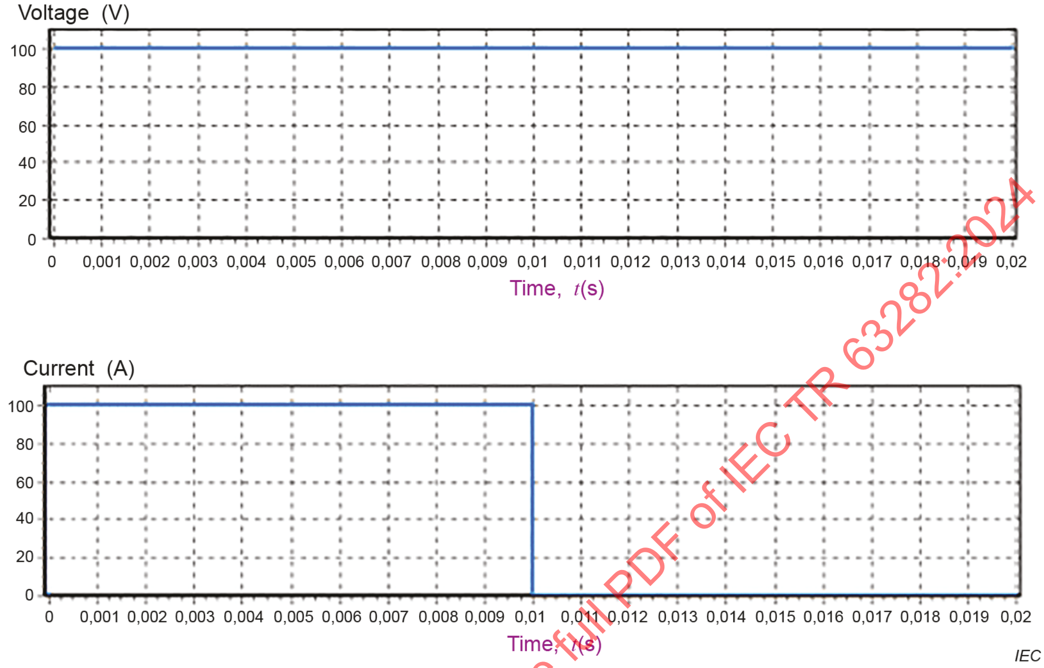


Figure D.6 – DC powers caused by intermittent DC current

With these voltage and current, different powers can be computed during 20 ms for a repeatable load variation (just as an example, see computed electric values of this example in Table D.1):

Table D.1 – Different powers

DC electric parameters	Values
U (V)	99,999 78
I (A)	70,650 26
S (VA)	7 065,01
P (W)	4 997,337
Q (Var)	−0,005 851
D (Var)	4 994,096
P_F (*)	0,707 336 1

D.8 Main conclusions on electric value computation in DC system

– Active power is smaller than apparent power in a DC system if nonlinear load is connected.

– Reactive power can be very small in a DC system if the ripple of DC supply voltage is negligible.

– Distortion power can be important in a DC system if a nonlinear load is connected. It is taken into account in overall system design.

– Power factor P_F is taken into account in the DC load profile assessment.

– DC system power quality mitigation: the key figure is to reduce as much as possible the distortion power (or increase P_F to 1) in order to increase the efficiency of DC power supply.

D.9 Need of characteristics of DC voltage

One of the key steps in assessing of DC power quality is to define characteristics of DC power supply voltage in public networks. Characteristics of DC voltage supply can be defined similar as follows:

– For disturbance frequencies less than 2 kHz: IEC TS 62749 (EN 50160 as well) can be adapted to the relevant DC voltage ripple values.

– Conducted disturbances levels 2 kHz to 150 kHz in LVAC network are defined based on the compatibility voltage levels of IEC 61000-2-2. They can be adapted in DC systems (Figure D.7 below illustrates LVAC compatibility voltage levels measured in differential mode values). For LVDC, the extension of power quality phenomena to the frequency range < 150 kHz is necessary because DC power sources and loads are almost all equipped with power electronic interfaces.

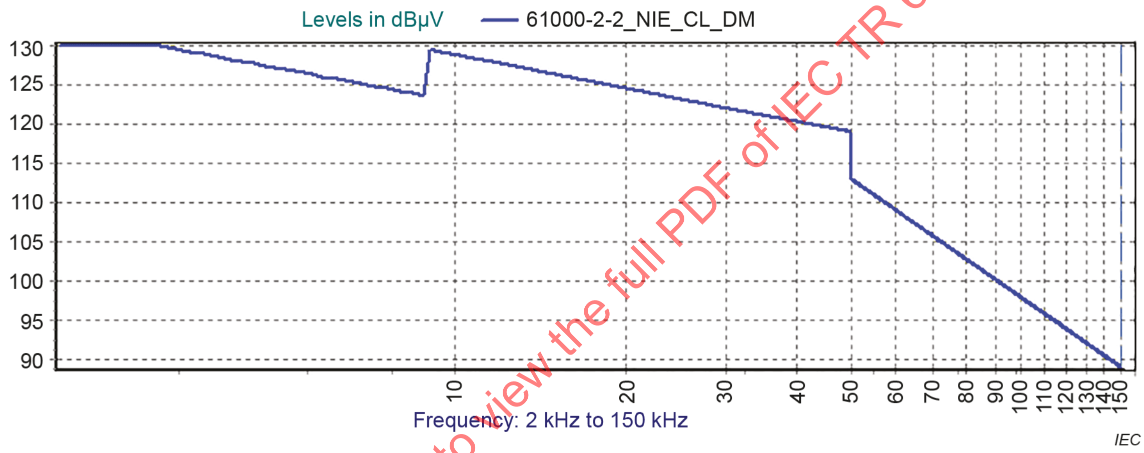


Figure D.7 – LVAC compatibility level measured in differential mode values

Annex E
(informative)

District LVDC system demonstration project in Tongli, China

E.1 Project overview

District LVDC system demonstration project in Tongli, China is composed of four different microgrids: ±750 V LVDC, ±375 V LVDC, 220 V LVDC and 380 V LVAC. It is sponsored by 2017 National key research and development project of China. This project aims to distribute the use of green energy in high-penetration districts, explore the power supply mode of different applications, develop high-efficiency DC distribution equipment and introduce the construction mode of a low-energy DC building.

As Figure E.1 shows, the above four microgrids are connected through power electronic transformers (PET), powered by a 10 kV AC line and can realize flexible power control and the interconnection and complementation of multiple energy sources.

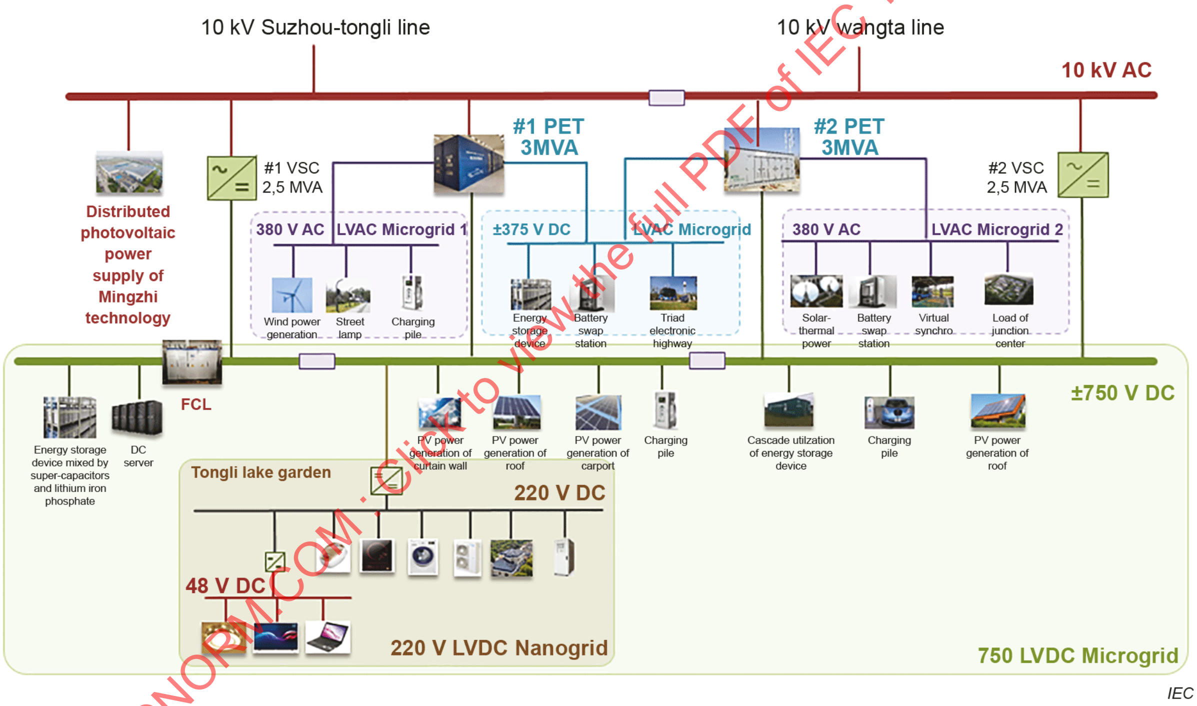


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Figure E.1 – Architecture of the district LVDC system in Tongli

E.2 Voltage level selection principle

Various types of sources and loads are connected to different voltage levels of the Tongli system. The selection principles are given as follows:

Due to the adaptability of MPPT strategy range of PV string, the relatively long transmission distance and the large transmission capacity, the ±750 V DC microgrid is connected to a 2,9 MW PV power and energy storage.

Similarly, the voltage between the poles of the ±375 V LVDC grid is 750 V, which is connected to the energy storage equipment, battery swap station and electronic highway.

Furthermore, there is a 220 V DC nanogrid connected to the bus of ±750 V DC through a DC/DC converter, which provides the DC power for some home appliances in a residential community such as air conditioner, washing machine and some kitchen appliances. The reason for choosing 220 V DC as the voltage level is that there is a relatively complete supply chain foundation in the existing DC system of substation and data center. However, it could be noted that as in the tests and operations shown, the DC modified appliances can withstand higher voltage and have a correspondingly higher efficiency.

As for the small household appliances whose power capacity is below 500 W, such as electric fans, air purifiers, etc., considering the safety and power supply radius, they are all powered by a 48 V DC bus which is connected to the 220 V nanogrid by a DC/DC converter.

E.3 System operation

The LVDC system in Tongli can operate in various modes according to the external power grid conditions. When the light intensity or/and energy storage capacity is sufficient, it can act as an active system and achieve self-sufficiency. The surplus power can be fed back to the external grid. When the PV power and energy storage is insufficient, the system can realize the optimal configuration by the control of PET. Besides, the system can be controlled in APF or STATCOM modes in different occasions to improve the power quality of AC power grid. Since its first operation in October, 2018, the Tongli LVDC system has been running stably for 18 months and provides valuable platform and data for the project team to study related technical problems of LVDC system.

Annex F
(informative)

A typical MV&LVDC distribution system in Wujiang, China

F.1 Project overview

A typical MV&LVDC project shown in Figure F.1 has been put into operation since June, 2021, which is located in Wujiang, China, in the developed Yangtze river delta with high load density. The capacity of this project is 20 MW, including 6,21 MW integrated PV generator. There are three stage of voltage levels in this system: ±10 kV DC, ±375 V DC and ±48 V DC. The whole system supplies power to 10,54 MW of various kinds of loads, including resident load, data center, commercial load, industry load and charging station and provides electric energy for 150 households. The project adopts the ring topology structure and develops a series of key MV&LVDC system components such as the DC transformer, the MVDC circuit breaker and the DC adapter. The whole system contains two 10 MW/±10 kV AC/DC converters, 4 DC circuit breakers, 82 DC load-break switches, 19 DC transformers and 150 adapters (see Figure F.2).

Besides, the project has proposed and applied typical design schemes for DC access in various scenarios such as industrial frequency conversion load, data center, household electric appliances and the integration of PV, energy storage and charging station. The following describes each scenario in detail:

– Industry load: The project adopts DC power supply for the injection molding machine in Hongsheng factory with the capacity of 3,3 MW, which can omit the primary rectification link, and make full use of the feedback kinetic energy of frequent startup and shutdown of the rotor to improve the energy utilization rate.
– Data center: The project provides DC power supply to Jiuli data center with the capacity of 1 MW, omitting multi-level AC/DC conversion within the power supply of the data center, and the measured power efficiency is improved by 1,5 %.
– Resident load: The project provides DC power to 150 households, develops 15 types of DC appliances, omits the rectification link and power factor correction (PFC) link in traditional appliances, breaks through the arc free breaking technology, and improves the comprehensive energy efficiency by 2 % through the third-party detection.
– PV access: The project is connected to the roof photovoltaic of Baotong, Hongyi, Mingzhi and other industrial parks, with a total of 6,21 MW. When DC absorption is adopted for photovoltaic, the AC/DC link in the converter can be omitted and the operation energy efficiency can be improved.

Furthermore, the project adopts floating grounding mode at the LV side, which can realize continuous operation under single pole grounding fault. At the same time, it is equipped with a leakage current protector and an insulation monitoring device, which can find the single pole fault point in time and ensure the safety of the system. The true bipolar connection is adopted, which can provide multiple voltage levels for the load side and improve the power supply reliability of the system. Besides, power quality monitoring system is deployed at both MV side and LV side to monitor the ripple, dip, oscillation and other power quality problems of DC system in real time, which can provide the basis for power quality control of the DC system.

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Figure F.1 – Location map of the typical MV&LVDC system

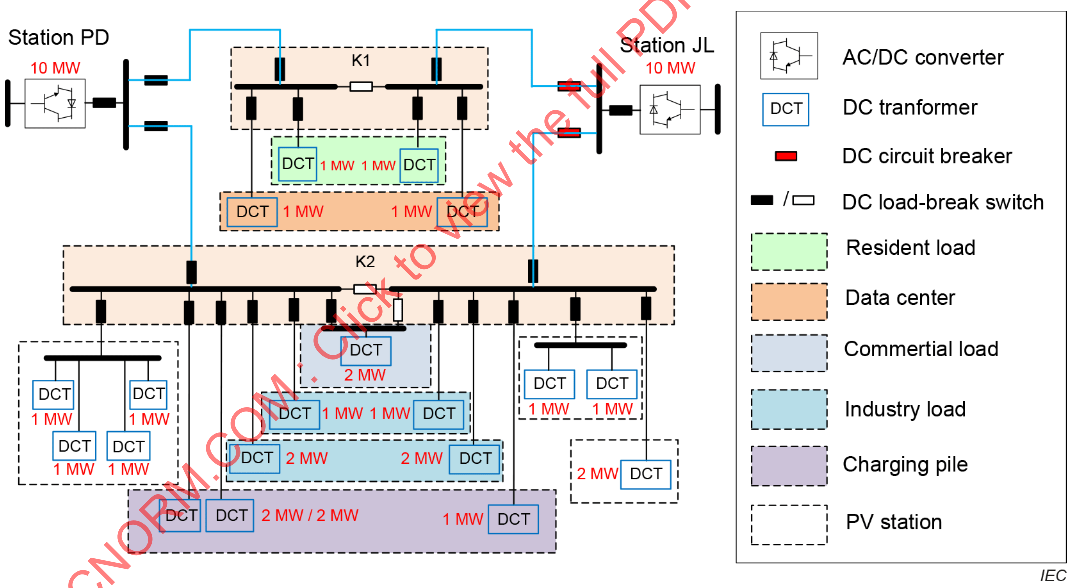

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Figure F.2 – The structure of the MV&LVDC system in China

F.2 Voltage selection

The typical medium AC voltage levels in China are 110 kV, 35 kV, 10 kV. The typical medium DC voltage level in China is ±35 kV, ±10 kV, ±3 kV, 3 (±1,5) kV.

The MV&LVDC distribution system in Wujiang is connected to a 10 kV AC grid. There are three stages of voltage levels in this system: ±10 kV DC, ±375 V DC and ±48 V DC.

– System capacity

The current-carrying capacity of a DC cable is 1,03 to 1,04 times of the AC cable. The typical current-carrying capacity of cables is listed in Table F.1. The transmission capacity of AC and DC cable can also be calculated. With the same transmission capacity, the DC distribution voltage level corresponding to the AC system is listed in Table F.2.

Table F.1 – The current carrying capacity of medium voltage AC and DC cables

Voltage level / kV		Laying method	Cable section / mm^2				
			185	**240**	**300**	**400**	**500**
AC	10	Air	570 A	680 A	780 A	910 A	-
		In ducts	420 A	500 A	570 A	670 A	-
		Direct burial	485 A	565 A	640 A	735 A	-
DC	35	Air	582 A	685 A	783 A	917 A	1 061 A
		In ducts	453 A	505 A	577 A	659 A	757 A
		Direct burial	500 A	582 A	654 A	752 A	855 A
	10	Air	587 A	700 A	803 A	937 A	-
		In ducts	433 A	515 A	587 A	690 A	-
		Direct burial	500 A	582 A	659 A	757 A	-

Table F.2 – The voltage level corresponding relationship between AC and DC with the same transmission capacity

	Voltage level / kV			
AC	110	35	10	0,4
DC	±92,4	±29,4	±8,4	0,64

The transmission capacity of the ±10 kV DC system is larger than that of the 10 kV AC system. The load capacity of the whole project is 10,61 MW, with 6,2 MW PV and 2 MWh storage. In order to satisfy the power supply requirements, the medium DC voltage level ±10 kV is suitable for the for the MV&LVDC distribution system.

– Transmission distance

The voltage drop on the cable is an important factor to consider in the voltage level selection. In this system, all the power electric equipment has the ability of ±10 % voltage adjustments. A ±10 kV DC cable has a longer transmission distance than a 10 kV AC cable.

– Converter adjustments

For a converter, the modulation ratio is defined as the ratio of the peak value of AC phase voltage to the single pole output DC voltage. In the application, the modulation ratio is set as 0,7 to 0,95, for better voltage utilization and power quality.

The modulation ratio M is

$$M = \frac{2\sqrt{2}U_{ac}}{\sqrt{3}U_{dc}} \tag{F.1}$$

where

U_{ac} is the RMS of AC system voltage;

U_{dc} is the converter DC voltage.

The voltage between two poles of the converter ΔU_{dc} is calculated in Table F.3 with a modulation ratio of 0,7 and 0,95.

Table F.3 – DC voltage range with modulation ratio limit

AC system voltage / kV	110	35	10	0.38
$\Delta U_{dc}(M = 0{,}7)$ / kV	256,6	81,7	23,3	0,9
$\Delta U_{dc}(M = 0{,}95)$ / kV	189,1	60,2	17,2	0,7

The voltage between two poles is suggested to range within the interval in the table. The medium DC voltage in this system is ±10 kV, allowing full use to be made of the 10 kV AC voltage, with improved power quality.

Annex G
(informative)

An office building with general building utilities and office workplaces

G.1 Sustainable circular building

The ABN AMRO Pavilion at the Zuidas in Amsterdam aims to be the most sustainable circular building, and DC takes this one step further. It has a 3 000 m^2 of meeting venues with LED lighting and PV panels connected to a complete DC grid on 350 V DC. See Figure G.1.

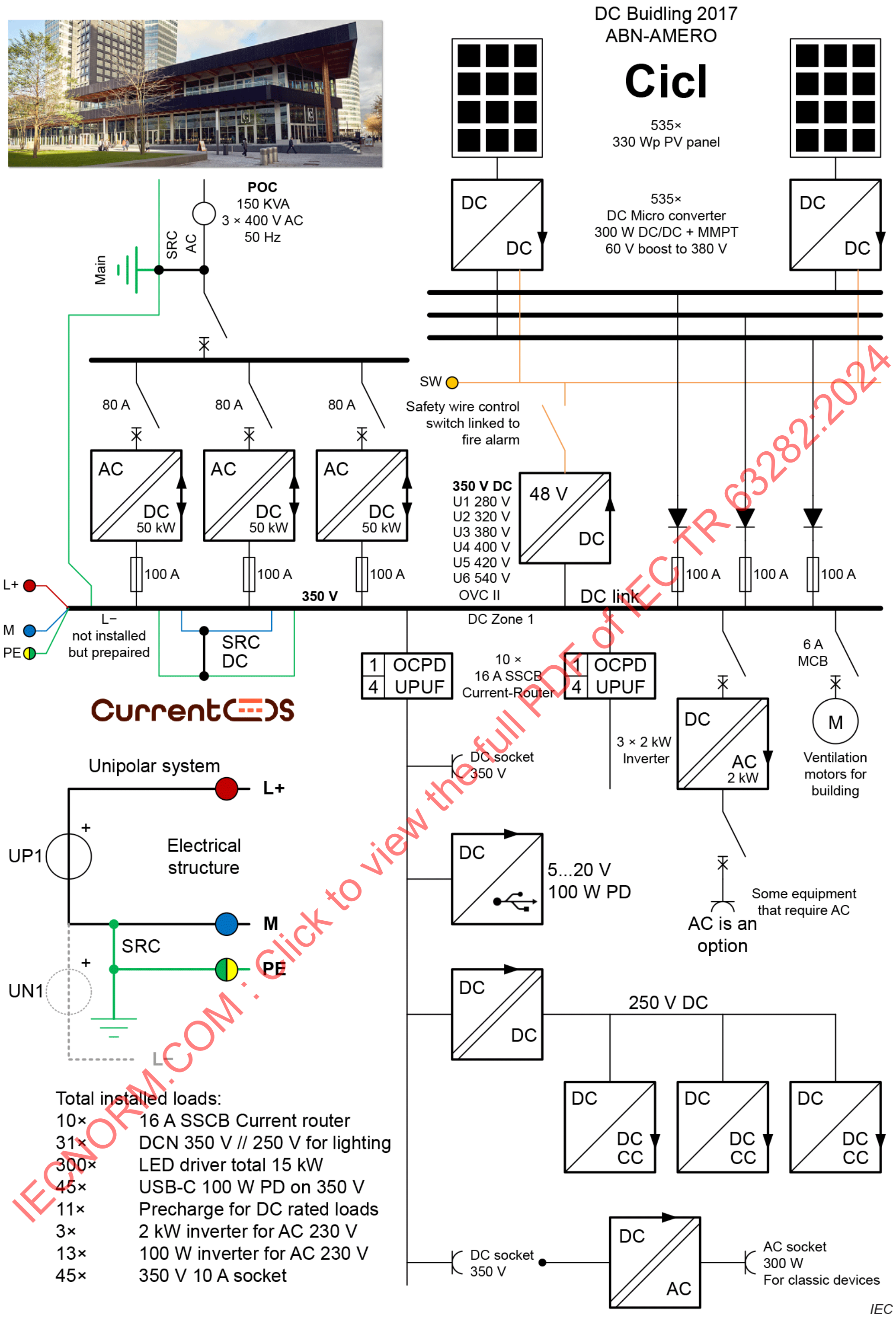

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Figure G.1 – Office building with general building utilities and office work places

This use case shows an office building with general building utilities and office workplaces where mainly information equipment is connected.

The office is designed to operate CO_2 neutral, through generation of renewable energy with solar power and energy storage by means of batteries.

The main operating voltage between L+ and M is in the voltage band 320 V DC to 380 V DC.

There is an AC/DC converter that serves as a reference for the voltage and exchange of excess energy and energy source in case of energy shortage in the system.

On the side of the users there is also a storage unit and there is the building lighting by means of LED’s and power outlets by means of USB-C (5/12/20 V up to 100 W). Users that require more power than 100 W can be connected to the 350 V level. On this level the user can plug-in his/her equipment for use.

All the equipment, converters, switches, chargers are semiconductor based and bidirectional operating for current/power.

For the proper functioning and protection of the equipment in the installation, zones are defined. These zones are marked with a yellow triangle. See overview for DC zones.

DC zones are separated by protection devices. The protection is an electronic switch that can be controlled by the operating system manager that manages the energy supply and the demand in the installation.

Active DC installation consists of:

a) 3 active front end (3 × 50 kW);
b) Solid state protection devices
   – 16 A,
   – RCD included;
c) PV installation 150 kW
   – Every PV has his own optimizer (one defective panel will not infect the whole system);
d) Storage (batteries)
   – Peak shaving,
   – UPS,
   – Island mode;
e) USB-C (100 W)
   – Flexible output voltage (5 V to 20 V output range),
   – Power and data combined in one connector/cable;
f) 350 V DC wall socket (protected by solid state circuit breaker);
g) DC/AC converter (230 VAC 2 kW),
   – For normal AC devices;
h) Mobile DC/AC converters (For users to charge laptop without USB-C).

Advantages:

– additional functions;
– integrated UPS;
– less conversion losses;
– island mode enabled;
– congestion management is easier with droop curves implementation;
– connected to the fire alarm.

Risk classification of DC installations:

Depending on the design, a certain risk can be assigned to a DC installation. Based on the energy stored in batteries and the power that can be delivered by the installation at a certain point, a classification into hazardous and less hazardous installation components can be made. Five different risk categories have been defined for DC installations, ranging from DC zone 0 (highest risk) to DC zone 4 (lowest risk). These DC zones are described here.

Depending on the DC zone in question, different requirements could be set on the knowledge, expertise and skills of the designer, fitter, installer and the operators.

G.2 Zone system

DC zones are part of the Dutch NEN NPR9090:2018 and part of Current OS. In Current OS, the DC zones are more precisely described.

Electrical hazards associated with all electrical installation include

– electric shock and burns from contact with live parts,
– injury from exposure to arcing, fire from faulty electrical equipment or installations.

To ease design and operation of DC installations, circuits or group of circuits are classified in 5 zones numbered from zone 0 to zone 4. Different installation rules apply in the different zones.

Most of existing DC installations are in zone 0, 1 and 2. These are already covered in the IEC 60364 series.

Zones 3 and 4 are protected by new semiconductor power distribution components, namely current source converter and semiconductor circuit breakers. Fault energies and consequent risks are lower in these zones.

Different zones are connected by means of devices able to limit the flow of the fault energy from one zone to the other.

Zone 0 – Unprotected source:

In this zone there are high-power voltage sources or sources with similar behaviour during the fault, such as batteries (multiple linked batteries or batteries with large energy content), the public electricity grid, capacitor and supercapacitor banks, including the connection circuits to the protective device.

Circuits downstream of power converters with large capacitors are also classified in zone 0. The rationale for this and criteria for classification are under consideration.

Characteristics of zone 0 are:

– multiple power sources not possible,
– bi-directional power flow possible,
– very high fault current and energy,
– high arc-flash incident energy.

As arc-flash risk can be very high, zone 0 circuits have limited extension and are housed in an enclosure, e.g., in a battery rack or in a panel, only accessible to highly skilled people wearing appropriate personal protection equipment (PPE). NFPA-70E:2024 standard for arc flash could be considered.

In the system shown in Figure G.2, the batteries connected in a string can yield a very high fault energy and are therefore classified as zone 0.

Zone 1 – Protected circuits with high short-circuit energy:

Power distribution circuits, typically busbars, powered from sources in zone 0 and protected from zone 0 by electromechanical circuit breaker or fuses are classified as zone 1.

The main characteristics in zone 1 are:

– high overcurrent possible,
– multiple sources possible, but all connected to the main distribution board, so that the circuit is fed from one end only,
– bi-directional power flow,
– high Arc-flash risk.

These are typical characteristic values (for information only) of zone 1:

– if J/cm^2 is below that of zone 0, then the system is in zone 1,
– typical incident energies are in the range of 1 J/cm^2 to 5 J/cm^2,
– typical time constants are in the range of 1 ms to 5 ms,
– typical I^2t ratings are in the range of kA^{2}s.

Circuits in zone 1 are distributed only at short distances, for example inside a container, from the battery compartment to the electronics compartment, or in a dedicated room.

In Figure G.2, a cabinet used in a system is shown. Different zones are present within the same cabinet. The circuit protected by the fuse is classified in zone 1. The overcurrent protection device (OCPD), such as a fuse or a circuit breaker, connected after the battery string, can limit the fault energy according to its I^2t rating, and consequently limits the electric risk downstream. However, with a fuse or electromechanical circuit breaker, the residual fault energy and risk are still relatively high; this circuit is classified as zone 1. After the OCPD, a DC/DC converter is used to control the current to and from the batteries. The large DC-link capacitors downstream this converter can supply very large short-circuit current, before this is limited by the converter itself. So, this part of the cabinet is classified again as zone 0.

Figure G.2 – Example of zone 0 and zone 1

Zone 2 – Current-limited protected source:

Circuits fed by current-limited power sources, for example PV string optimizers or DC/DC converters with smaller capacitors are classified in zone 2. But also, hybrid breakers with strong current limiting behaviour.

More actionable criteria for distinguishing zone 1 and 2 (alternative to the capacitors size) are under consideration.

NOTE 1 Fault currents are too small to actuate conventional OCPD.

The main characteristics in zone 2 are:

– multiple sources possible,
– bi-directional power flow,
– limited arc-flash incident energy,
– low fault current makes protection challenging.

Characteristic values (for information only) below are under consideration:

– typical time constants are in the range of xxx μs,
– typical I^2t ratings are in the range of a few kA^2s,
– needs voltage-based protection (detecting undervoltage).

The example shown in Figure G.3 is very similar to the one in Figure G.2, but the DC-link capacitor of the converter is much smaller and so is the fault energy. Therefore, the circuit is classified as zone 2.

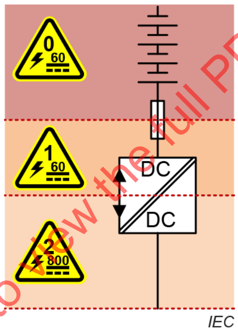

Figure G.3 – Example of zone 0, 1 and 2

An example of a purely zone 2 system is shown in Figure G.4, in which only current-limited sources are included. As both the PV panels and the DC/DC converter have limited short-circuit current, the full system is zone 2.

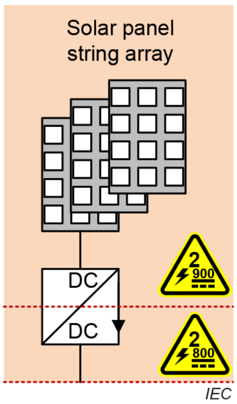

Figure G.4 – Example of zone 2 system

Zones 3 – Multiple-sources circuits with electronic protection:

Circuits fed by multiple sources are in zone 3 when very low fault currents are ensured by proper design rules (below) and use of fast semiconductor-based circuit breakers.

NOTE 2 As zone 3 circuits are fed by multiple sources or bidirectional “prosumers” (e.g. battery systems), either from a central location or distributed, the power flow does not have a predetermined direction.

An example of zone 3 system is shown in Figure G.5. All the sources are connected to the bus via a fast protection device, for example an SCCB.

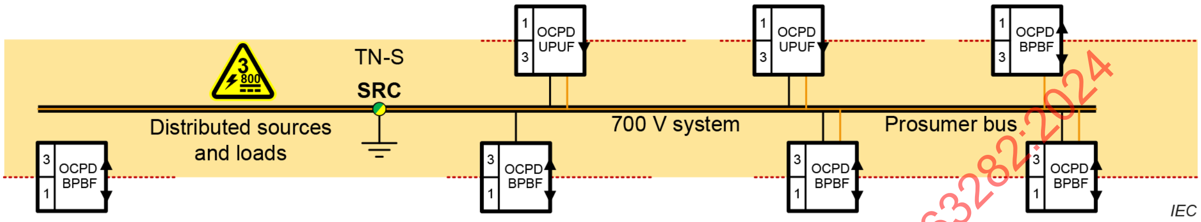

Figure G.5 – Purely zone 3 system with the protection devices of distributed sources

Zone 4 – Single-source circuits with electronic protection:

Circuits fed by a single source are in zone 4 when very low fault currents are ensured by proper design rules (below) and use of fast semiconductor-based circuit breakers.

NOTE 3 Different to zone 3, the power flow in zone 4 circuits has a predetermined direction (upstream to downstream) as circuits are fed by a single source.

An example of zone 4 system is shown in Figure G.6.

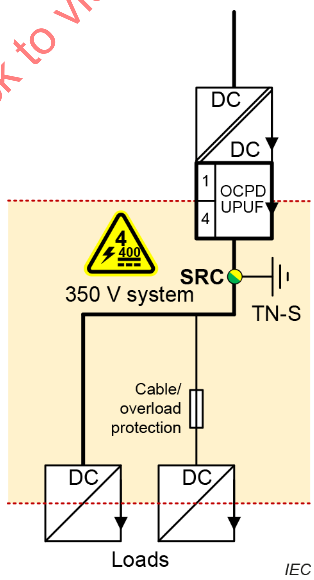

Figure G.6 – Example of a zone 4 system with a single source

An overview of a whole system as an example of four zones is shown in Figure G.7.

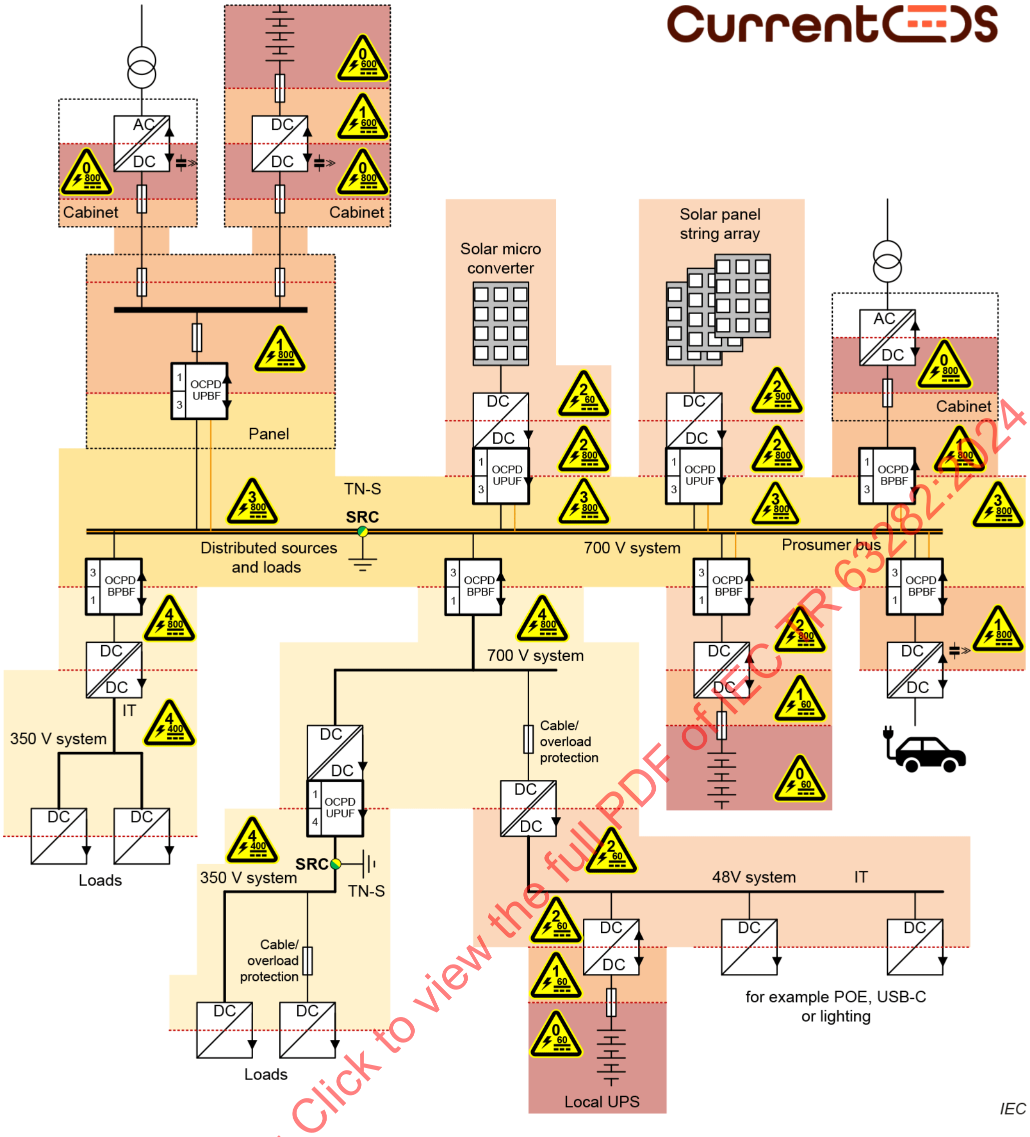

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Figure G.7 – Current OS system overview and safety zones

Zone labelling:

Distribution cabinets and busbars are marked with the label in Figure G.8, where:

Z: Zone level (0 … 4) [mandatory]

V: Maximum zone pole to earth voltage U_4 [optional]

Figure G.8 – DC zones label

Skilled installers and maintenance personnel will immediately recognize the risk of the installation and can take proper measures.

NOTE 4 indication of the voltage can be drawn in the label.

Examples of labels are shown in Figure G.9.

Figure G.9 – Examples of DC zones labels

Cabinets containing circuits in different zones are marked with the label of the lowest level. For instance, in a panel including zone 0 and zone 1 circuits, the label is for zone 0.

A coding system for cables is under consideration (see Table G.1).

Table G.1 – Safety zones and labels

Zone 0 - Unprotected source	
Zone 1 - Protected circuits with high short-circuit energy	
Zone 2 - Current-limited protected source	
Zone 3 - Multiple-sources circuits with electronic protection	
Zone 4 - Single-source circuits with electronic protection	

G.3 Aspects regarding the DC zone classification in DC installation

Table G.2 – Functions for different DC zone classification

Zone	Limit zone 0-1	DC zone 1	DC zone 2	DC zone 2	DC zone 3	DC zone 3	DC zone 4
Location in diagram	A	B	C	D	E	F	G
Aspect							
Residual current protective device	Optional	Optional	Optional	Optional	*	*	*
Overcurrent protection (NEN 1010:2015 H 43)	Mandatory	Mandatory	*	*	*	*	*
Arc protection (NEN 1010:2015 421.7)	Recom-mended	Recom-mended	Recom-mended	Recom-mended			
Isolation during maintenance (NEN 1010:2015 H 536)	Mandatory	Mandatory	Mandatory	Mandatory	Manda-tory**	Mandatory**	Manda-tory**
Plug with an early-break contact	Optional	Optional	Optional	Optional	Optional	Optional	Optional
Physical shielding of equipment + zone marking (NEN 1010:2015 H 132 .5)	Mandatory (IP2x)	Mandatory (IP2x)	Mandatory (IP2x)	Mandatory (IP2x)	Mandatory (IP2x)	Mandatory (IP2x)	Mandatory (IP2x)
Corrosion prevention (NEN 1010:2015 C 542)	Mandatory	Mandatory	Mandatory	Mandatory	Mandatory	Mandatory	Mandatory
Temperature alarm	Optional	Optional	Optional	Optional	Optional	Optional	Optional
* These combinations are mandatory as soon as the necessary protection components are available. Mandatory**: An alternative to isolation during maintenance is shorting and earthing. Advice: Ensure 1 m of cable between the fuse and the electronics to prevent the electronics being damaged by the heat of the fuses.							

DC zones 2 and 3 are not always required to be present. For example, they are not required if the installation does not contain any sources that are characteristic of these DC zones. DC zone 0 always leads to DC zone 1, but it also is possible to go directly to DC zone 4 from DC zone 1.

Designers, fitters and installers take the limited short-circuit current into account in DC zones 2 and 3. This applies specifically when applying DC circuit breakers, DC fuses or DC devices with fuses. The minimum short-circuit currents of the DC sources are included in the installation documents.

This also applies to the minimum currents needed to trip the circuit breakers or fuses applied, also those in permanently installed devices (see Table G.2 for more details).

Annex H
(informative)

An example of configurations for active DC systems

H.1 General

An active system operating system is an operating system that enables congestion management in systems and is based on voltage levels without the need of real time communication, which makes DC systems independent and autonomous.

H.2 Structure

The active system is a method of controlling the power balance in the last mile of a grid system. The active grid of the last mile can be connected to a passive AC or DC system and can contain other (local) sources like renewable energy sources and storage means prosumers. The power that can be distributed can be limited when the renewables are not available. Therefore, the operating system controls the available energy. A principle diagram for the active grid in the last mile is shown in Figure H.1.

Devices used in DC systems are mainly active electronic devices. Electronic (switching) devices like converters and switches have limited overvoltage and overcurrent capabilities and therefore the voltage and current can be controlled.

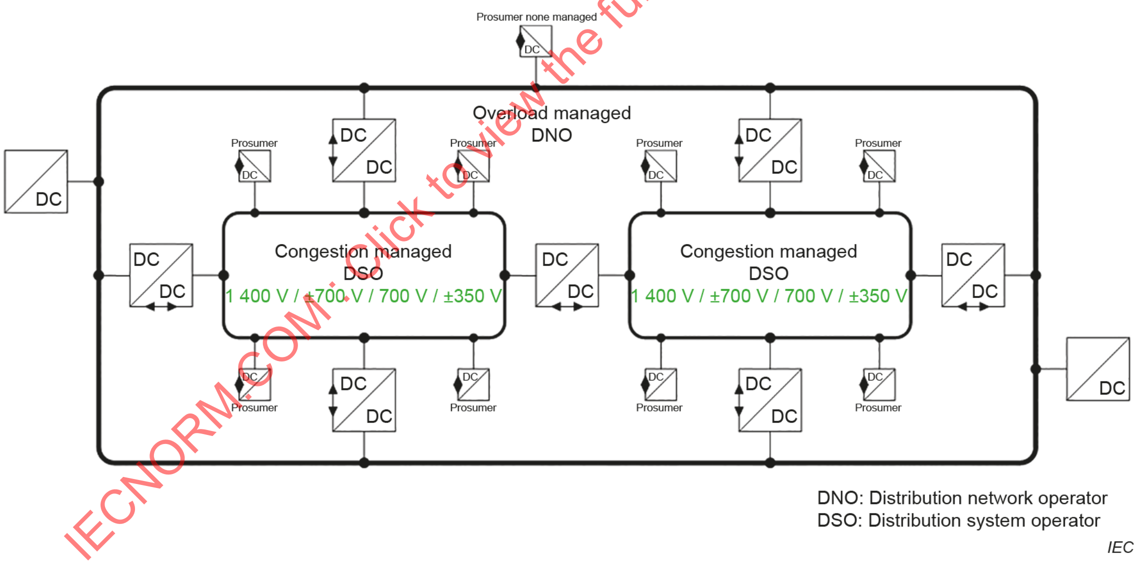

Figure H.1 – Active DC distribution system

DNO and DSO don't have the same roles in the active DC distribution system. By separating the roles of DNO and DSO, higher stability and availability are enabled by making agreements between consumer or prosumer and network provider. This can result in highly improved system organization.

H.3 State of grid (SOG)

Grid can be nominally loaded (0 %), maximally loaded (100 %) and minimally loaded (−100 %). The state of the grid has nothing to do with the power in the system but is purely an indication of the state of the system, seen through a voltage level.

Nominal state of grid is within the −droop to +droop range in the nominal voltage band.

The SOG becomes negative when the voltage is below the nominal bus voltage.

The SOG becomes positive when the voltage is above the nominal bus voltage.

The SOG becomes > 100 % when the voltage is more than the maximum value of the nominal voltage band.

The formula to calculate the SOG is as follows:

$$\text{SOG} = \frac{U_{\text{bus}}(\text{actual}) - U_{\text{bus}}(\text{nominal})}{U_{\text{busMax}}(\text{nominal}) - U_{\text{busMin}}(\text{nominal})} \quad \text{(H.1)}$$

Table H.1 – Examples in case of 350/700 V DC systems

U_{bus}(actual) in 350 V DC	U_{bus}(actual) in 700 V DC	SOG
250	500	−333 %
300	600	−167 %
320 [b]	640 [b]	−100 %
330	660	−67 %
350 [a]	700 [a]	0 %
370	740	67 %
380 [b]	760 [b]	100 %
400	800	167 %

[a] nominal bus voltage ($U_{\text{bus(nominal)}}$).

[b] min/max bus voltage ($U_{\text{bus,min/max(nominal)}}$) for bipolar systems, and line to line stays below the 1 500 V DC limit.

The value of the maximum tolerated losses in active DC systems is as low as possible, as shown in Table H.1.

There are several reasons why low allowed voltage drop on the cable is a good choice:

a) Theoretically, in DC, losses up to 20 %, even 30 %, are possible. However, such a high voltage drop is not recommended if we want to achieve an efficient and strong system.

b) Going further and assuming 10 % is not a good choice either because such voltage drop would adversely influence the earthing point's design, because many diodes would be required to compensate circulations.

c) Third point are the droop curves. In case of for example ±10 % droop and 10 % cable losses, the end user will highly be influenced because of the high voltage difference and already implemented droop curves. To avoid discrimination between users, a smaller voltage drop is desired. If low cable loss and deviation is taken, then droop curves are not directly influenced.

d) The cable sizes. If a higher voltage drop is allowed, it will directly impact dissipations and thermal characteristics of the cable, which will result in bigger investment in enabling bigger spacing for such an installation.

The strong compromise between thermal losses, efficiency of the system, length of the cable, protection schemes, earthing points and other aspects of importance is achieved, as shown in Table H.2.

Table H.2 – Allowed cable voltage drop

Nominal voltages V	Allowed cable voltage drop ΔU, ΔU %=1,4 % V
350	±5
700	±10
1 400	±20

a) Droop mode

There is one dominant voltage source that acts as a reference directing the state of the grid of the system. The dominant source establishes the state of the grid. However, the sum of the rated power levels of the non-dominant power sources cannot be higher than the rated power of the dominant power source and the rated power of an electrical installation.

The dominant source can represent the connection between an AC/DC distribution grid and an active DC system. It serves as the voltage reference and it balances the power flow in the grid, as shown in Figure H.2.

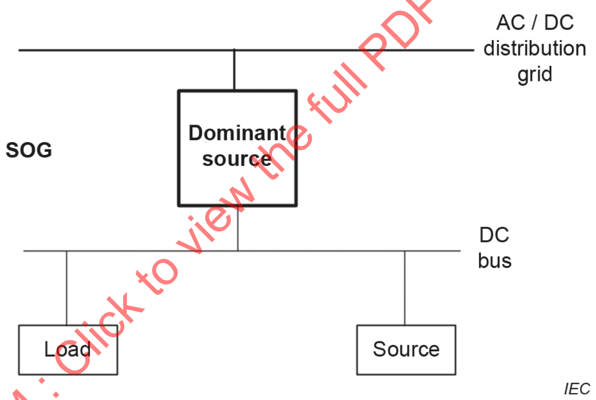

Figure H.2 – DC distribution system with one load and one source

If there is electricity production from the sources, for example PV, in the active grid, the voltage level in the voltage band generally increases. This enables devices to be connected to the grid, and currently connected dynamic loads, like electric vehicles, are enabled to increase their own consumption. This voltage increase occurs up to a maximum voltage level (U_{max}), as shown in Figure H.3.

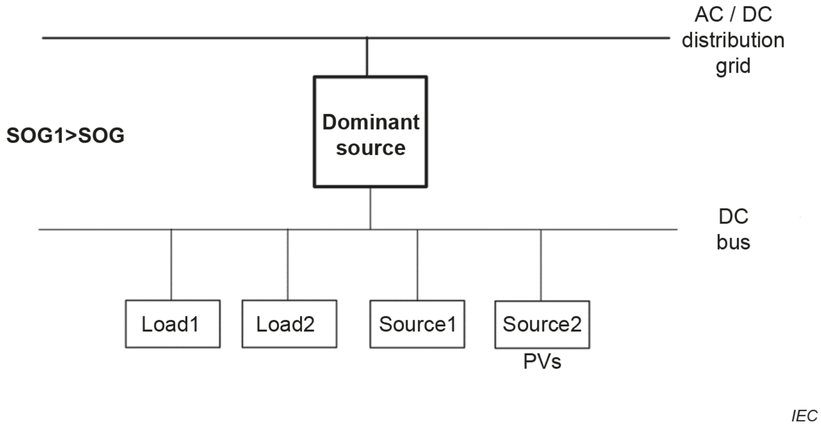

Figure H.3 – DC distribution system with more than one load and a source and increasing source power

When the voltage reaches U_{max} and excess power is getting higher than a maximum power of all loads combined, dump loads, if available, can be activated, as shown in Figure H.4. This is done in order to prevent the bus voltage from further rising and causing possible over-voltages. In this case, active sources also get activated, limiting the power, if the voltage keeps increasing. However, if none of this is enough to limit the rise of the bus voltage, then the system enters the protection state.

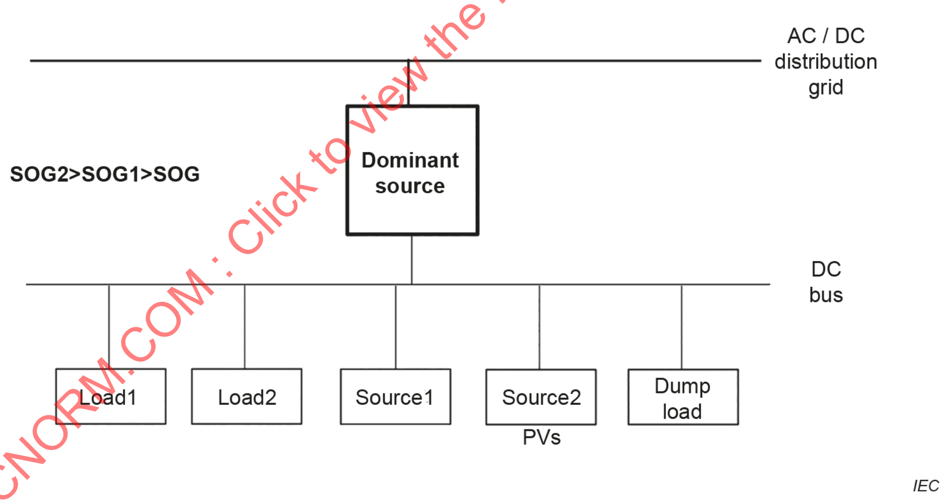

Figure H.4 – Distribution system with more than one load and a source and dump load active

On the other hand, as the voltage level of the grid decreases, due to the higher power consumption and low production, only higher priority devices can still operate, as shown in Figure H.5. When the voltage further decreases below its minimum level (U_{min}) and enters the emergency area, the current that can be withdrawn is limited. If additional power is still required from devices, the voltage is scaled down until it reaches its lowest value and the grid is then in the down state.

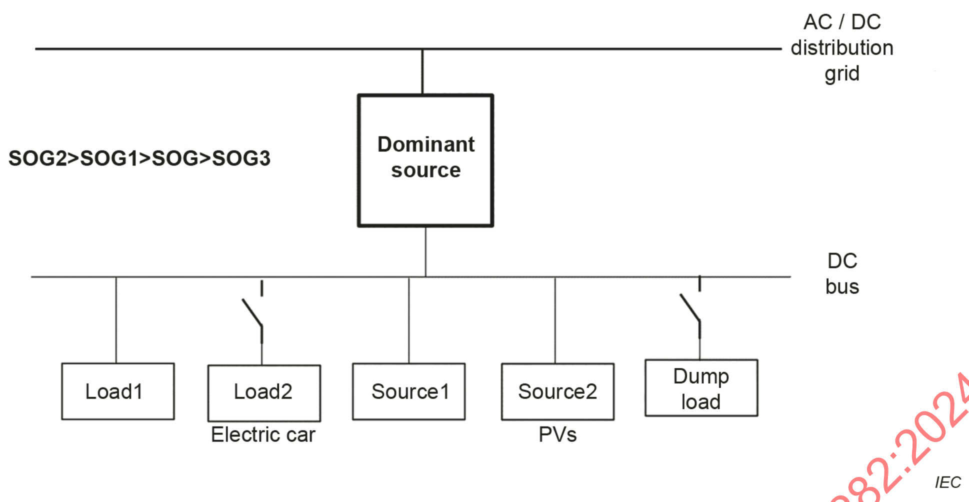

Figure H.5 – Distribution system with more than one load and source in overloaded mode

NOTE The dominant source is not the necessary component, but where the dominant source is not available, the system can be configured and designed differently, particularly with regard to the protection scheme.

b) Control

Each active device connected to the DC system complies with the droop curves of the system. The droop curve is a set of parameters that are stated on each device when started up for the first time. The values of the droop curve related to a specific device can be modified during operation. These values (parameters) will determine under which operating voltages the consumer device can operate and how much power it can consume. In the case of sources, it will state under which operating conditions the source device will operate acting as a current source.

The parameters are set in the device (converter) itself with the possibility of changing them in the future. Thus, external communication is not needed for the device to regulate. Once they are set, the device is expected to regulate its power on its own following the state of grid. The speed of regulation depends on the type of converter or device. Nevertheless, this is expected to be fast (order of ms, us).

Parameterizing is not time critical and is not used as a means of fast control.

Additionally, knowing that the load converters (converter + load) will follow and regulate looking at the state of grid, a source converter (source + converter) can also influence the system by changing its behaviour. For this, the source can also behave as a voltage source, providing a steady voltage with variable current. In this case, the state of grid can be influenced to increase/decrease load consumption.

c) Inertia

It depends on the source type. It is possible for some devices to deliver inertia, like AFE’s or battery systems. Inertia in the system is important for stabilization and fast response of the system.

Annex I
(informative)

Preferred voltage in different countries

I.1 Preferred voltage in China

The recommendation in China specifies standard voltage values which are intended to serve

– as preferential values for the nominal voltage of electrical supply systems, and this is not an absolute rule, it depends on the concrete situation;
– as reference values for equipment and system design.

DC nominal voltage between 110 V and 1 500 V is preferred, to be chosen from Table I.1. DC nominal voltage for ELVDC equipment below 110 V is selected from the values given in Table I.2.

Table I.1 – Nominal voltage in LVDC distribution system

unit: Volt (V)

Preferred	Supplementary
1 500 (±750)	
750 (±375)	
	1 000
	600
	440
	400
	336
	240 (250)
220 (±110)	
	110 (125)

NOTE 1 The unmarked voltage values correspond to unipolar DC lines, and the voltage values with plus-minus sign correspond to bipolar DC lines.

NOTE 2 For technical and economic reasons, additional voltages can be required for certain specific fields of application.

NOTE 3 The preferred value is expected to be a priority for new systems to be constructed in the future.

a) Preferred value 1 500 V:
   – Recommended by IEC 60038 and IEC 60850, 1 500 V is one of the preferred DC traction voltages, which is also the traction voltage of Metro in some areas of China.
   – In some industrial parks, the DC voltage of the industrial loads is 750 V.
b) Preferred value 750 V:
   – Recommended by IEC 60038, the preferred voltage for equipment is 750 V, which is convenient to connect into three-phase AC 220 V/380 V.
c) Preferred value 220 V:
   – Recommended by IEC 60038, it is compatible with the internal DC voltage of converter air conditioners, converter washing machines and converter refrigerators, etc.

d) Supplementary value 440 V:
   – Recommended by IEC 60038.
e) Supplementary value 400 V:
   – Recommended by ITU-TL.1200, the preferred voltage is 400 V.
f) Supplementary value 336 V:
   – DC supply voltage of data center is 336 V in some areas of China.
   – 336 V is close to the input voltage of an electric vehicle.
g) Supplementary value 240 V (250 V), 110 V:
   – DC supply voltage of data center is 240 V in some areas of China.
   – 250 V is recommended by IEC 60038.
   – 110 V is recommended by IEC 60038.

Table I.2 – Nominal voltage in ELVDC equipment

unit: Volt (V)

Preferred	Supplementary
96	
	80
72	
60	
48	
	40
36	
	30
24	
	15
12	
	9
	7,5
6	
	5
	4,5
	4
	3
	2,4

The nominal voltage of equipment below 120 V DC references IEC 60038 directly.

a) The preferred DC voltage level for the following load is 48 V:
   – communication equipment;
   – household type photovoltaic, wind power, battery storage system and fuel cell.
b) Because the voltage of the primary and secondary cells is below 2,4 V, and the choice of the type of cell to be used in various applications will be based on properties other than the voltage, these values are not included in the table. The relevant IEC technical committees can specify types of cells and related voltages for specific applications.
c) It is recognized that for technical and economic reasons, additional voltages can be required for certain specific fields of application.

I.2 Preferred voltage in the Netherlands

The choice of a nominal voltage of an electrical installation has a bearing on the length of the cables and the measures to protect against electric shock.

The Netherlands standards propose a nominal voltage of 350 V DC relative to earth (or +350 V DC and −350 V DC with an earthed central conductor). The main arguments for this are the following:

a) A voltage level of 350 V DC relative to earth (of +350 V DC and −350 V DC with an earthed central conductor) can still offer protection comparable to that offered with 230 V AC systems. If a higher voltage is selected, this level of protection will no longer be possible due to the voltage variations that can be expected.

b) 350 V DC and 700 V DC offer the possibility of an equivalent and fully-fledged system comparable to single-phase 230 V AC and respectively three-phase 400 V AC. See also Table I.3.

c) If existing cabling for three-phase 400 V AC is used, at least the same power can be transferred.

d) Due to voltage doubling (700 V DC, 1 400 V DC), 350 V DC offers the possibility of using virtually the entire voltage range up to 1 500 V DC as defined in IEC 60364 (all parts), HD 60364 (all parts) and NEN 1010:2015.

e) 350 V is not used in AC systems. This prevents confusion and enhances safety.

Table I.3 – Comparison between DC and AC system voltages

U_n DC	U_n AC	P_{max} at 16 A_{RMS}
350 V DC	230 V AC single-phase	5,6 kW (DC) / 3,7 kW (AC)
700 V DC or ±350 V DC	400 V AC three-phase	11,2 kW (DC) / 11,1 kW (AC)
1 400 V DC or ±700 V DC	690 V AC three-phase	22,4 kW (DC) / 19,1 kW (AC)

Voltage tolerances:

Where permanently installed secondary batteries are applied as a back-up power supply for the DC installation, the voltage level as supplied by these batteries can vary, depending on their charge levels. This particularly applies if no voltage regulator is applied after the battery.

The occurrence of considerable voltage variations is taken into account in passive DC installations. If the voltage variations cannot be calculated, or if the battery details are missing, the following tolerances are assumed:

– maximum voltage: 1,2 U_n;

– minimum voltage: 0,8 U_n.

In active DC installations where the voltages and currents that occur are monitored, agreements are made as to the maximum permissible voltage variations. The voltage variations that occur in active DC installations can give information about the operation of the installation in accordance with the network code of conduct.

I.3 Preferred voltage in Germany

Recommended voltages for distribution systems are given in Table I.4. There are four voltage classes (VC1-VC4) defined, that are used for controlled and for uncontrolled systems and for unipolar and bipolar systems. All the equipment used in these distribution systems is designed to fit to the voltage class selected and the class is indicated on the device.

A DSO can choose a suitable voltage out of the voltage class and can operate in the full area (U_2-U_3) or in a subset of it. Bipolar systems use a VC between line and mid-point and VC+1 between line and line.

NOTE 1 For example, one DSO is able to choose 380 V ± 20 % for a VC1 distribution. Another DSO can choose a distribution voltage of 350 V ± 10 %. They both use the same equipment which fits to U_2 and U_3 as defined in Table I.4.

NOTE 2 A bipolar system with 380/760 V uses VC1 devices between line and mid-point and VC2 devices between line and line. The same devices can also be used in 350/700 V systems.

Table I.4 – Overview of the DC voltage classes (VC) and the corresponding U_2 and U_3 values

Voltage class (VC)	Use case	U_2 V	U_3 V
1	Distribution to/in residential and commercial buildings	320	440 [b]
2a	Distribution to/in industrial applications	440	800
2b	Distribution to/in HPDC charging parks	440	1 000 [a]
3a	Industry applications with active infeed converters	620	750
3b	Industry applications with uncontrolled rectifiers as connection to the AC grid	485	750
4	Long distance and high-power distribution	1 280	1 500

[a] IEC 61851-23 specifies DC charging up to 1 000 V DC. A distribution up to this level is thus possible.

[b] Useful upper limit for using cheap 650 silicon power electronic devices. As for example used in today's SMPS.

Annex J
(informative)

Voltage with respect to earth

All the content in this document relates to the differential mode, but a common mode description will be needed. There are lot of aspects to this topic, but it fully depends on the earthing structure, and has nothing to do with the differential aspects.

Clause 5 and Clause 7 relate exclusively to the voltage potential difference generated across the power terminals of the supply, or from which the load can draw current. There are also maximum limits for the voltage between either power terminal and earth. Generally, these maximum voltage limits will be absolute values – polarity is not important.

These limits are important for considerations of safety, insulation breakdown, lighting protection and transmission of, or immunity to, radio interference, but they are not relevant to the powering of the equipment itself – so there are no minimum voltage limits to earth.

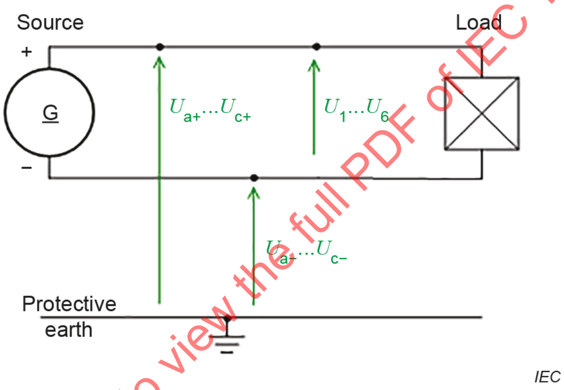

Figure J.1 – DC voltage definitions

Six additional voltage limits are defined: U_a+, U_b+, U_c+, U_a-, U_b-, U_c- (see Figure J.1). These maximum limits become of critical importance when there are protection devices between power terminals and earth.

Unipolar systems will have significant differences between the potentials to earth of the power terminals. They can therefore have different limits for U_a … U_c. For example, in a negative-earth system, U_a-, U_b- and U_c- can only be a volt or so (see Figure J.2 and Figure J.3).

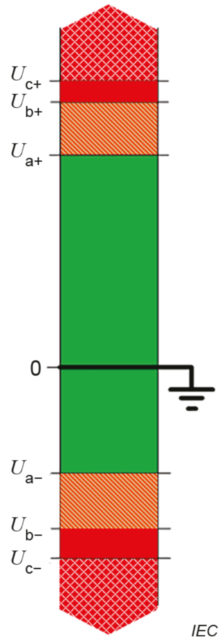

Figure J.2 – DC voltage bands relative to earth

– Below U_a: Normal operation

Under all normal circumstances, voltages to earth will be in this region.

– U_a – U_b: Overvoltage protection band

Transient voltages can only remain in this band for very short periods. Non-linear surge protection devices with limited energy absorption capabilities can activate.

– U_b – U_c: Safety margin for electrical installation

In this region, dielectric breakdown within components and consequently permanent equipment damage are likely. Insulation will not break down. Devices that can break down in this region will not expose users to risk of electric shock.

– Above U_c: Insulation breakdown

In this region, permanent equipment damage is very likely. Users can be exposed to risk of electric shock.