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Edition 1.0 2020-11

TECHNICAL REPORT

colour inside

LVDC systems – Assessment of standard voltages and power quality requirements

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INTERNATIONAL
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COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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LVDC SYSTEMS – ASSESSMENT OF STANDARD VOLTAGES AND POWER QUALITY REQUIREMENTS

FOREWORD

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

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

Draft TR	Report on voting
8/1549/DTR	8/1556/RVDTR

Full information on the voting for the approval of this Technical Report can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

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

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- withdrawn,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

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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 now seen not only as a solution for electricity access in developing economies but also as a solution for greener and more sustainable energy in developed economies.

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

The power quality phenomena for the distribution of DC power are not identical to AC phenomena while 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 evaluated for DC distribution systems.

Power electronic converters/inverters add further demands. Power quality phenomena in LVDC distributed systems can be related to the topology 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 should be 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 to be addressed with the objective to enhance 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 should greatly stimulate the wide adoption of LVDC.

Besides the main contents concerning voltage level and power quality, the following topics are also presented:

Clause 4 discusses architectures and topologies for LVDC networks.

Clause 7 recommends permissible limits for voltage bands and PQ phenomena.

LVDC SYSTEMS – ASSESSMENT OF STANDARD VOLTAGES AND POWER QUALITY REQUIREMENTS

1 Scope

The purpose of this document is to collect information and report experience in order to make recommendations for the standardization of voltage levels and related aspects (power quality, EMC, measurement …) for LVDC systems (systems with voltage level lower than 1 500 V d.c.).

Rationale for the proposed voltage values are given. Variation of parameters for the voltage (power quality) and recommendation 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.

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 terminological databases for use in standardization at the following addresses:

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

3.1
nominal system voltage
suitable approximate value of voltage used to designate or identify a system

[SOURCE: IEC 60050-601:1985, 601-01-21]

3.2
DC supply voltage
line-to-line or line-to-midpoint voltage at the supply terminals

3.3
bipolar DC system
DC system comprising positive, midpoint and negative lines

3.4
unipolar DC system
DC system comprising of two lines

3.5
DC system nominal voltage
U_n
suitable approximate value of voltage used to designate or identify a DC system

Note 1 to entry: A bipolar DC system is preferred 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

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 DC component and in RMS value computed in frequency range < 150 kHz (in line with SC77A and CISPR for conducted disturbances).

[SOURCE: IEC 60050-312: 2001, 312-07-02, modified – 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, 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 voltage reduction 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 may 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 – Reference to sinusoidal voltage has been removed and time interval has been changed to period of time]

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

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 dip/swell thresholds

3.16
active distribution system
ADS
distribution networks that have systems in place to control a combination of distributed energy resources (i.e., distributed generation, controllable loads or energy storage)

Note 1 to entry: Protection can also be included in ADS.

3.17
passive distribution system
PDS
distribution systems in which the energy balance is controlled by the voltage source (e.g., outside grid or battery)

3.18
droop in a DC system
ratio of per-unit change in voltage to the corresponding per-unit change in power of the demand

3.19
distribution network operator
DNO
party operating a distribution network

3.20
distribution system operator
DSO
party extending the function of a DNO to incorporate active management of some power resources

3.21
positive voltage
U+
voltage between the positive line and the midpoint

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

3.22
negative voltage
U-
voltage between the midpoint and the negative line

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

3.23
balanced voltage
U_b
average of the positive and the negative voltage

Note 1 to entry: $U_b = (U_p+U_n)/2$.

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

3.24
unbalanced voltage
U_u
average difference of the positive and the negative voltage

Note 1 to entry: $U_u = (U_p-U_n)/2$.

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

3.25
midpoint
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 60050-195:1998, 195-02-04, modified – The note to entry has been added]

3.26
under-voltage ride through
capability of equipment to stay connected and continue functioning during loss or drop of supply voltage

3.27
DC voltage
voltage equal to its average value during a defined time interval

3.28
over-voltage ride through
capability of equipment to stay connected and continue functioning during voltage swells

4 Structure of LVDC systems

4.1 General

A LVDC system is a combination of different electronic devices, whose operation is strongly based on different control strategies. Thus, as far as the recommended voltages and power qualities of certain LVDC systems are concerned, different analysis dimensions and elements should be taken into consideration, including different architectures, operation modes, etc..

4.2 Architecture

Several use cases concerning existing technologies and projects have been introduced to support the analysis and classification of LVDC systems, including but not limited to:

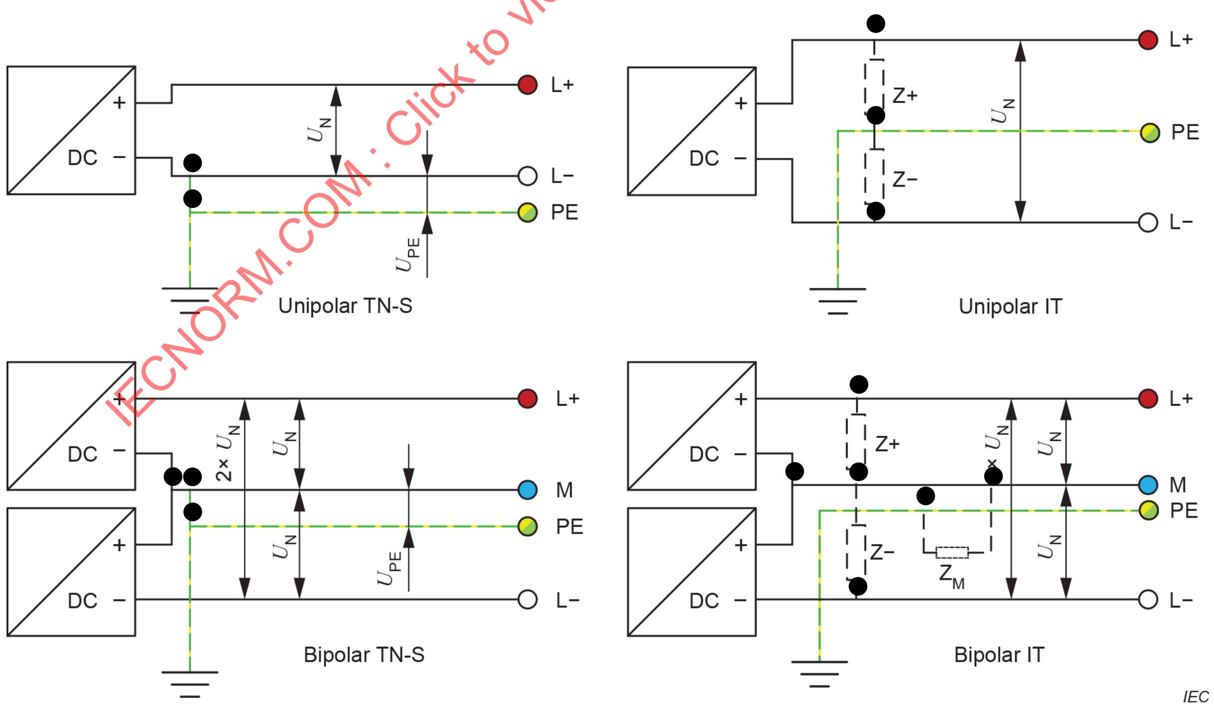
- LVDC system in buildings,
- LVDC systems between buildings.

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

Unipolar or bipolar DC systems can be designed with two or three output lines, respectively. Taking the earthing into account, it can be divided into TN-S system and IT system as Figure 1 shows.

In the TN-S system, the midpoint connection (M) is directly connected to the protective earth (PE) while in the IT system, the midpoint 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.

A list of differences between unipolar and bipolar systems can be seen in Table 1.



NOTE All IT systems will have impedances between conductors and earth. These impedances can be parasitic and poorly defined, or can be well designed.

Figure 1 – Unipolar, balanced and bipolar DC systems

Table 1 – Difference between unipolar and bipolar systems

Item	Unipolar	Bipolar
Cable utilization*	U*I / 2 (U * I / 3 with PE)	2 U* I / 3 (U* I / 2 with PE)
Available operating voltage(s)	U+ nominal	U+ nominal, U- nominal, 2 U nominal
Maximum fault voltage	U nominal	2 U nominal
Protection and Control Complexity	Low	Higher High in case of multiple sources
Connectors	2-pin (3-pin with PE)	3-pin (4-pin with PE)
Switching and breakers	Single-pole	Double-pole
RCD	2-pole	3-pole
* Cable utilisation = (Max voltage to ground) × (Max conductor current) / (number of conductors)		

NOTE Both positive earthing and negative earthing are possible. However, the positive earthed system will introduce negative leakage currents, and in the case of very high voltages, the metal structure of DC systems including earthing conductors might become more brittle. On the other hand, the negative earthed system will introduce positive leakage currents that can result in corrosion issues.

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. The system voltage can only vary within a narrow range under normal operating conditions.

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 frequently based on drooped control and the energy balance of the system is realized automatically by tracing the U-I curves configured in the devices. In this case, the voltage can fluctuate in a wider range than that in passive DC systems, which is regarded as voltage band. The normal operation voltage band can be adjusted by different configurations of control parameters in devices. A wider voltage band brings higher technical requirements to the system and equipment.

5 LVDC voltage division

5.1 General

In active DC systems, 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 and in the centre U_n for continuous and steady state operation.

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.

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. Ui is corresponding to the upper limit of band Bi (i=1,2,3,4,5,6).

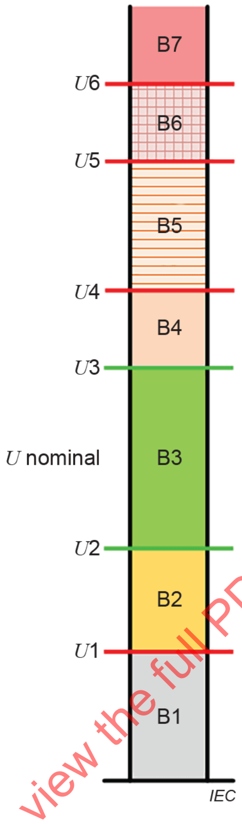


Figure 2 – Voltage bands in DC systems

B1: Blackout band

In this voltage band, only short dips to zero (State S1, as shown in Figure 3) are allowed. Longer events will cause a shutdown of the whole system in S2 to S4.

B2: Emergency band

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

NOTE Emergency devices and infrastructure relevant devices can operate in this voltage band.

B3: Nominal band

This is the normal operation band (between $U2$ and $U3$; see Figure 2).

B4: Switching, commutation and protection devices operation band

In this band, the voltage may overshoot or rise due to a sudden change of current. Surge protection devices do not operate in this band.

B5: Overvoltage protection devices operation band

This band is dedicated to the operation of the overvoltage protection devices. Above B5, semiconductors can be destroyed by an overvoltage lasting for a very short time.

B6: Overvoltage trip band

In this band, voltages are not tolerated by the equipment and are likely to cause breakdown.

B7: Prohibited band

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 states are defined, of which 3 states (S1 to S3) are transient states and 1 state (S4) is the steady state. These states may occur routinely or in exceptional situations. In each state, the allowed overvoltage and dynamics are different. Voltage bands are divided in these 4 states. See Figure 3.

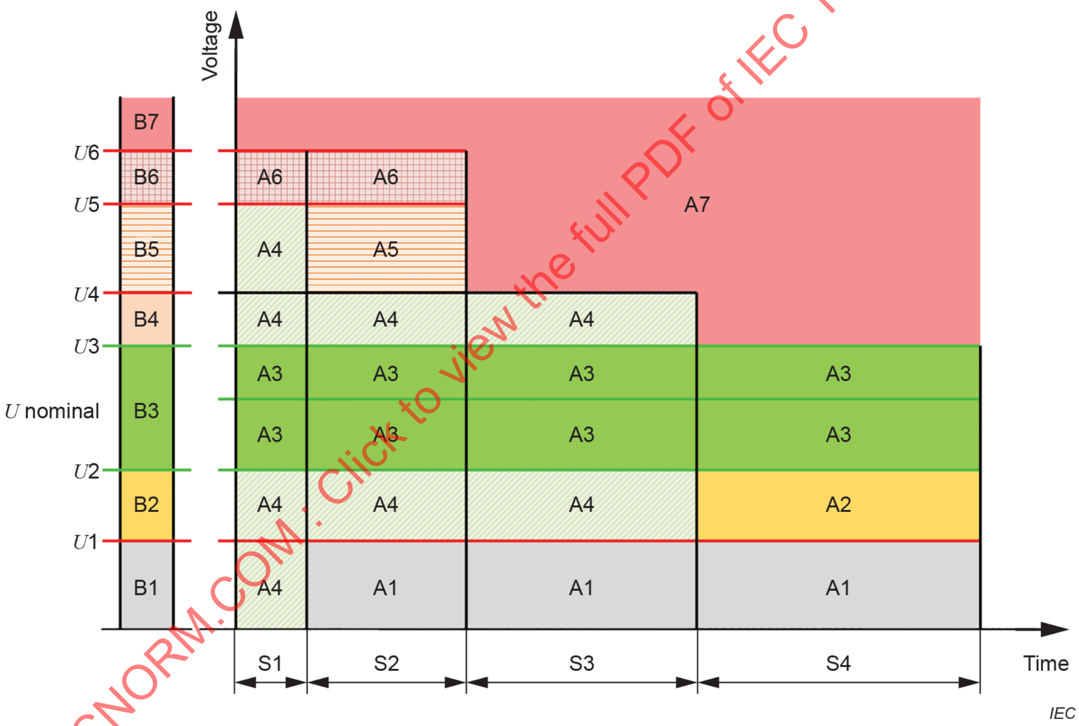


Figure 3 – DC Voltage areas for safe interoperability

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 widths of the states only indicate that:

S1 < S2 < S3 < Continuous operation (S4)

States S1 through S3 are transient states and can have different durations.

S1: 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.

S2: Fault range

A system state which involves, or is the result of, failure of a system circuit or item of system plant or equipment or apparatus and which 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. [IEC 60050-448:1995, 448-13-02, modified]

S3: Voltage control range

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

S4: Steady range

The system may 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 should still be able to operate correctly, but perhaps not meet all performance requirements. Action may be taken to reduce the stress on the system, for example through load-shedding or the introduction of additional power sources.

A3: Normal operating band/nominal band (U_2 to U_3)

For the normal operation of a DC system, the voltage difference between the power terminals should be maintained between U_2 and U_3 under all conditions. All equipment performance requirements should be 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 should be within this band allowing for IR voltage drop in cabling.

The nominal voltage (U_n: U nominal)

As stated in IEC 60050-161:1985, 601-01-21, nominal voltage is a suitable approximate value of voltage used to designate or identify a system. The nominal voltage U_n is within the nominal band but is not always half-way between U_2 and U_3; however, we may say that in all cases,

$$U_2 \leq U_n \leq U_3$$

A4: Abnormal state

In exceptional circumstances, voltage may stray into this area for an extended period. Installation and equipment shall be designed to withstand this, and continue to operate normally, but possibly with reduced performance. Overvoltage protection devices shall not operate. Action may be taken to modify power input to rebalance the system.

A5: Overvoltage state without clamping

Area in which the voltage may overshoot due to operation of switching or protection devices. Overvoltage clamping shall not clamp these voltage overshoots.

A6: Overvoltage with clamping

In this area, overvoltage protection devices shall operate to clamp overvoltage.

A7: Prohibited state

In this area, permanent equipment damage is very likely. If technically possible, all power sources shall be 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 shall be specified in order to provide a system designer with a reference to design the supply, load and distribution system. Voltage quality requirements may be different for different use cases and respective system layouts. Designers' responsibility is 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 or disturbances. These deviations outside this band or disturbances may be continuous and discontinuous.

Use case, application and electromagnetic environment specific compatibility levels shall be defined for temporary voltage variation, voltage dips and swells, flicker, and the maximum duration and magnitudes of DC voltage fluctuations.

The characteristics of good power quality are:

- Voltage is maintained within agreed limits in normal operation (Subclause 6.2 to Subclause 6.8);
- Ripple and high frequency voltages/current disturbances are below permissible limits (6.4).

6.2 Relationships between voltage band and power quality in LVDC systems

For the normal operation of a DC system, the voltage at a certain node should be 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 shall be 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-midpoint DC voltage in IT systems shall remain within the normal operating range of the DC voltage.

There are some events that may cause the DC voltage to deviate transiently or temporarily from the normal operating band or to fluctuate. The irregular operating or the trip of a station may result in a steep voltage dip, high voltage rise or fluctuation 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.

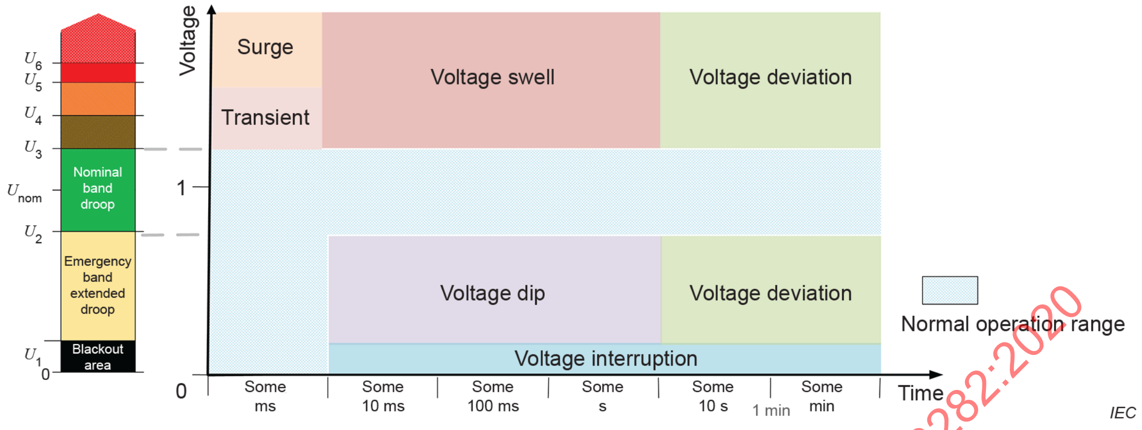


Figure 4 – Relationships between voltage band and power quality in LVDC systems

6.3 Supply voltage deviation

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

The above considerations apply to undisturbed operation. Possible deviations may be related to the following:

– If the operating DC voltage is outside the steady-state DC voltage band, then the system and system elements may 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 may malfunction, breakdown or become irreversibly damaged.

The equipment shall withstand those excursions and fluctuations for the defined limited period of time without damage. Active elements shall operate safely and contribute to a damping of these excursions and fluctuations. Trips of protective devices should be avoided as they may result in even more severe excursions and fluctuations. However, equipment should have the right to disconnect in case of unsafe operation or potential equipment damage.

Particular attention should be 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 needs to be a balance between the power injected into the DC system and the power withdrawn from the DC system, including losses. If this balance is disturbed, the DC voltage will rapidly deviate from the nominal voltage band. 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.

6.4 Ripple and high frequency noise

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. But a comparison of average DC and AC RMS values might be the basis for setting power quality indices for LVDC systems.

Since a solid-state 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 shall be evaluated. Any non-DC component of load current that flows over 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. Fast switching of converters and rapid change of potentials in specific commutation schemes can generate Common Mode (CM) voltage level shifts, which can interfere with communication or control systems. Perturbations in both Differential Mode (DM) and Common Mode have to be considered.

If a pulse width modulated (PWM) inverter is used to produce the DC voltage, a high-frequency waveform resulting from pulse width modulation switching is superimposed on the DC and AC side and this often is called noise. Noise also can come from the inverter-based loads connected to the DC bus.

Maximum RMS ripple amplitude: The root mean square voltage of all the AC components.

Periodic and random variations shall be given for the following three bands:

a) low-frequency noise:

   source frequency and its harmonics only (a.c. sources only);

b) switching noise:

   power converters switching frequency and its harmonics;

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

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

Beside additional losses, the main adverse effect of ripple on neighbouring systems is the disturbance of communication systems. An indicator to assess the degree of disturbances is the equivalent disturbing current.

LVDC converters generate characteristic and non-characteristic ripple voltages on the DC side. 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, unbalance between impedances and possibly asymmetry in the AC system voltage feeding the converter. Resonance conditions within the DC system resulting in potential amplifications are to be considered.

As it can be expected that more than one user may affect the ripple levels at a certain DC node, sufficient headroom shall be specified between maximum acceptable ripple levels and the individual shares that each DC user has to respect. All users have to ensure by appropriate design that their individual contribution is within the allowed individual share. Resonance effects have to be taken into account. The DC system operator shall provide information to evaluate potential ripple resonances.

The connection should not result in levels of distortion or fluctuation of the existing DC system voltage and current at the connection point, exceeding that allocated to them.

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

There will also be harmonic distortion requirements for the new connection for power export to the AC system.

6.5 Voltage swell

Voltage swell phenomena may frequently occur, but it is unpredictable and random. Depending on the magnitude and duration, voltage swell may affect different types of load differently for the same voltage swell event. Recommended limitations of voltage swells 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 bipolar systems, it is recommended that the number of lines affected by each event is detected and stored.

All connections will be required 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 will be 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 should also be consistent with the operation of the existing DC system.

An example of voltage swell can be seen in Figure 5. Normally, swell threshold and time duration are used to identify a voltage swell event.

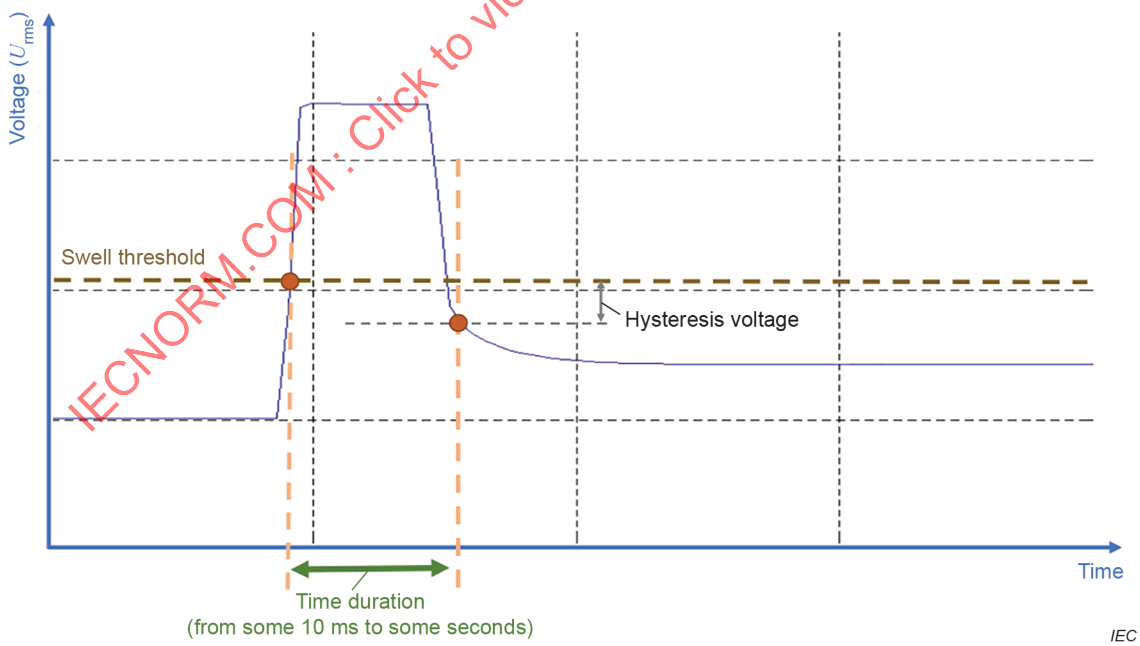


Figure 5 – Voltage swell example

6.6 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 line, by residual voltage and duration, despite the specific shape of the voltage variation.

For bipolar measurements, it is recommended that the number of lines affected by each event is detected and stored.

Generally, according to the network user connection, or the concrete situation, line-to-line, line-to-earth and line-to-midpoint voltage shall be considered.

All connections will be required 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 should also be defined. Following fault clearance, the connection should return to normal operating conditions subject to normal DC voltage and power control, within a defined time period. The under-voltage ride through requirements shall be defined to ensure desired behaviour.

DC voltage excursions may be experienced in the whole DC system. Power exports from or imports to the DC system shall be in 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 may result in a steep voltage dip or high voltage rise depending on its function as power import or export. The number and magnitude of the events leading to these DC voltage excursions or fluctuations need to be limited.

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

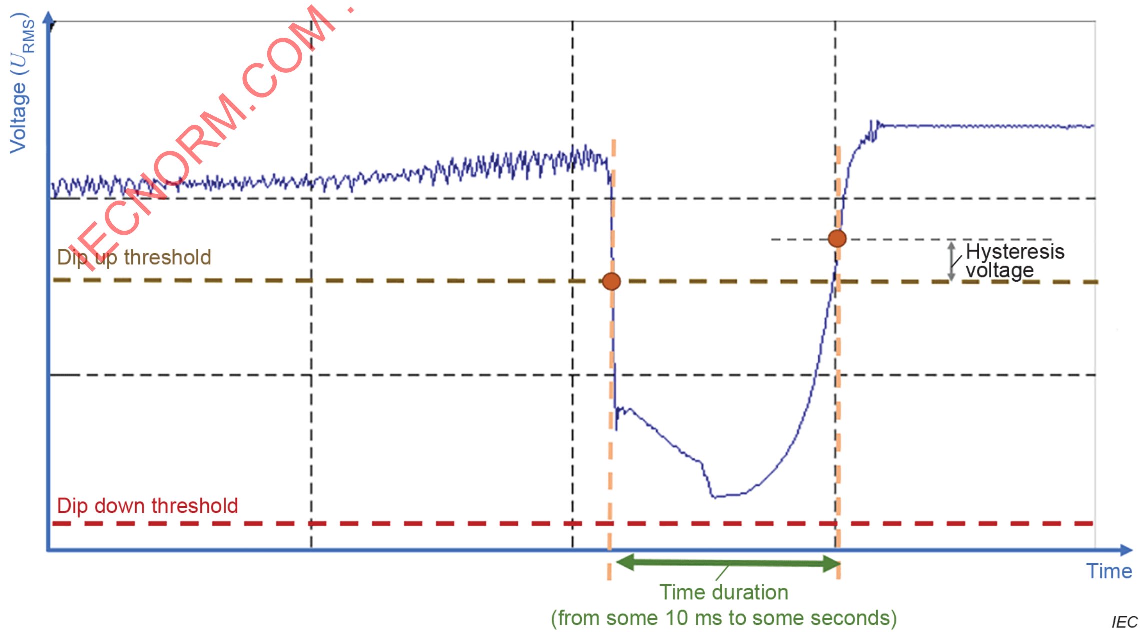


Figure 6 – Voltage dip example

Similar to AC systems, voltage dips in DC systems are likely to cause equipment and devices 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 in case the interconnecting inverter is actively controlling the DC voltage. In data center, today the overall reliability of power distribution in the AC installation is based on the use of UPS systems and could be similarly insured by active DC systems with the appropriate requirements. Electronic loads, such as computers and lighting, can be used in systems where these loads cannot be affected by disturbances on the utility system. Both the software and the hardware of important computer systems may be damaged due to voltage transients or power outages, and lighting which is used to illuminate emergency exits or important processes that cannot be shut off either.

6.7 Voltage supply interruption

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

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

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

6.8 Rapid voltage change (RVC)

Under normal operating conditions (excluding events), rapid voltage changes should 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 to be 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 7. Normally, the threshold of RVC in voltage amplitude is between the swell threshold and the dip up threshold.

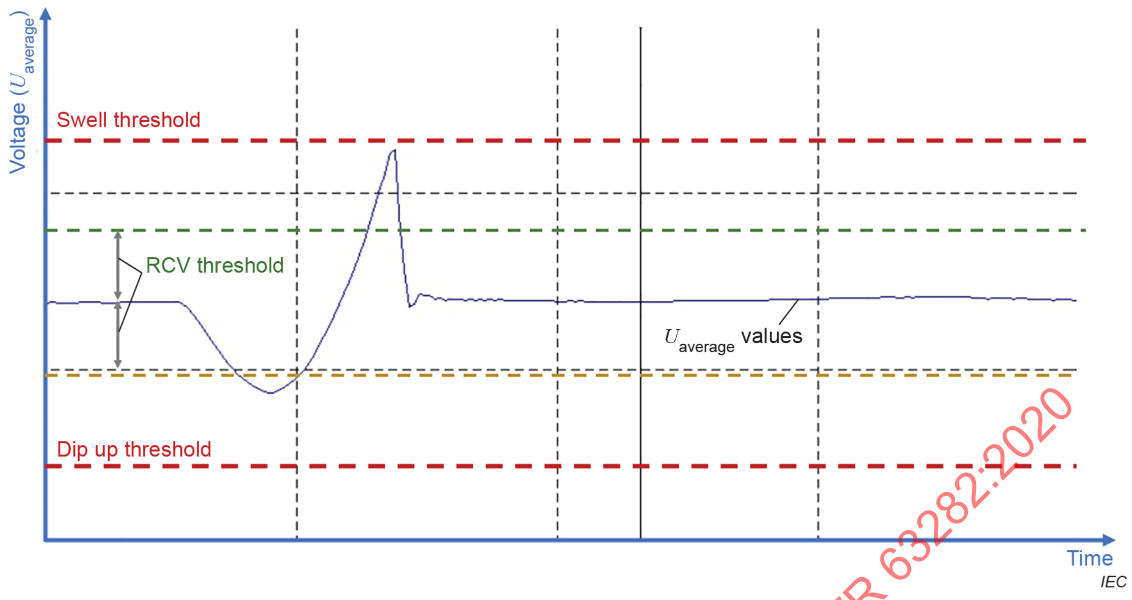


Figure 7 – RVC event: example of a change in average voltage that results in an RVC event

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

6.9 Voltage surges

Voltage surges are transient overvoltages with durations of several milliseconds. 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 8 gives an example of voltage surge in a real system.

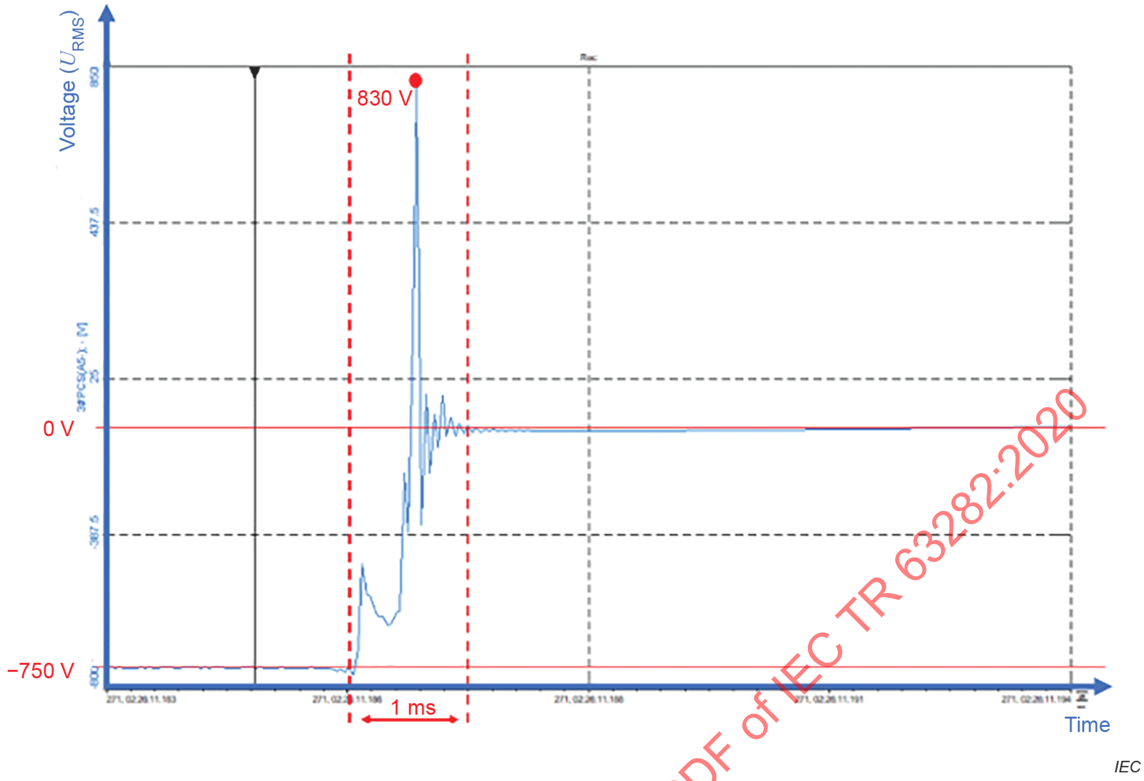


Figure 8 – Example of voltage surge

When a circuit is struck by lightning or switched on/off inductance load or large load, it often produces a high switching overvoltage This high switching overvoltage is called voltage surge (or current surge) and it is a transient interference. For example, when the coil relay of DC 6 V is disconnected, the voltage surge of 300 V to 600 V will appear. When the incandescent lamp is connected, the current surge of 8 to 10 times the rated current will appear. When the large capacitive load is connected, such as capacitor bank, the current surge impact will often occur, which will make the power supply voltage drop suddenly. Operating overvoltage up to 8 to 10 times the rated voltage will occur. Voltage surge phenomenon is increasingly endangering the safety of the automation equipment. Eliminating surge noise interference and preventing surge damage have always been the core issues related to the safe and reliable operation of automation equipment. The integration of modern electronic devices is increasing, but their ability to resist voltage surge is declining. In most cases, voltage surge will damage the 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.

In IEC 61204 (all parts), the limits of surge for DC power input/output in different conditions are indicated. And they should also be considered for the limits in LVDC system level.

6.10 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 will become unequal. The condition in which the positive and negative voltages differ is referred to as *voltage unbalance*. The amount of voltage unbalance varies continuously as the loads and generators in the system are randomly turned on or off by the customers.

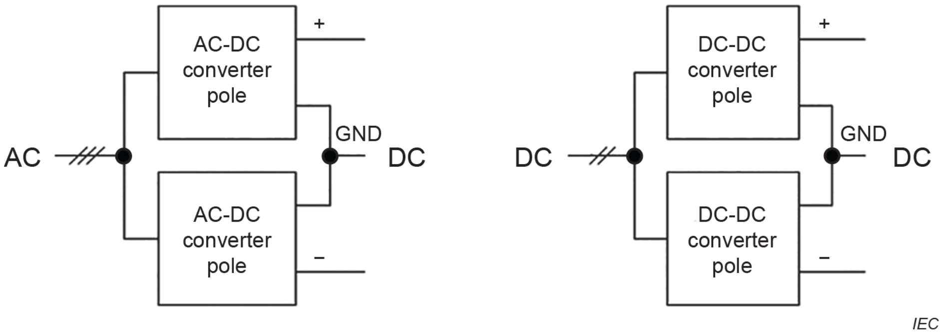


Figure 9 – A schematic of a bipolar system (the CIGRE B4 DC test system)

The bipolar LVDC system can be regarded as two series-connected unipolar LVDC systems, namely a positive and a negative part (see Figure 9). 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 inverters and three-level DC-DC converters. Instead of controlling the positive and the negative line-to-midpoint voltage, three-terminal converters control the balanced and unbalanced voltage, as defined in Clause 8.

7 Recommendations

7.1 General

The purpose of this document is to offer technical input to several TCs in charge of the standardization of different issues and coordinated by SyC LVDC.

The document makes recommendations on the following topics: standard voltages in 7.2 (TC8), EMC requirements in 7.3 (SC77A), Power quality in 7.4 (TC8), and measurement methods in 7.5 (SC77A).

TC64, TC109, TC21, TC22, TC23, SC 121A, SC121B, SC32B and TC 82 are also invited to consider information relating to their scopes.

NOTE The low voltage limits in IEC 61140 are considered to be the U_3 limit of the nominal band.

7.2 Recommended voltages

Considering different factors such as topology, load distance, insulation, cable economy, control strategies, protection requirements, equipment characteristic, etc., different common used voltages have been listed in use cases which have been included in Table 2 and Table 3. ELVDC voltages, such as 12 V, 24 V, 48 V, etc. have not been listed as an example of recommended voltages in the following tables but they could be included as LVDC voltages for some distribution purposes.

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.

Table 2 – Voltage between lines (unipolar systems) or line and midpoint (bipolar systems)

$U_{Nominal}$	U_2	U_3
350 V	320 V	380 V*
		440 V**
700 V	640 V	760 V
* for commercial		
** for non-commercial		

Table 3 – Voltage between lines (bipolar systems)

$U_{Nominal}$	U_2	U_3
±350/700 V	640 V	760 V*
		880 V**
±700/1 400 V	1 280 V	1 500 V
* for commercial		
** for non-commercial		

7.3 EMC and compatibility levels

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 waves. This means that each piece of equipment emitting electromagnetic disturbance shall have it limited to a certain level and that each individual equipment shall have adequate immunity to electromagnetic disturbance in the environment it is meant to operate in.

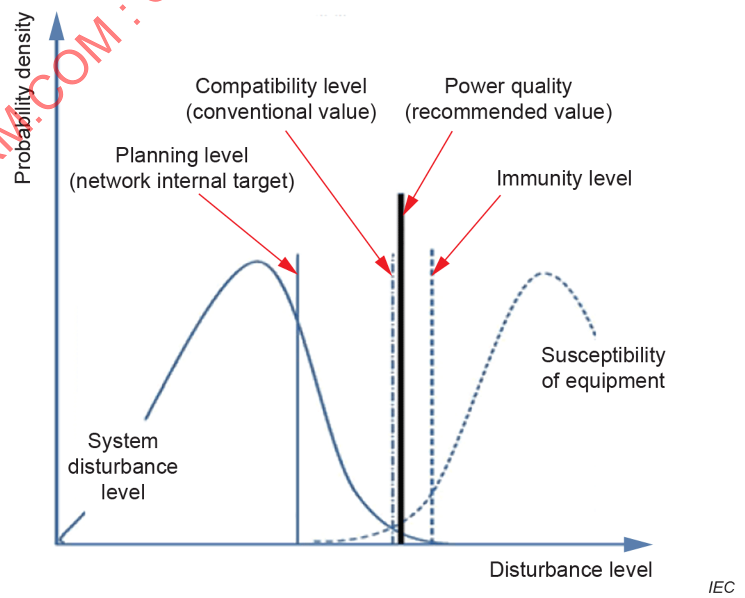


Figure 10 – Relation between disturbance levels (schematic significance only)

Power quality requirements need to be 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 10).

Some existing standards dealing with compatibility levels and immunity levels should be taken into account in the context of LVDC distribution:

- IEC 61000-2-2
- IEC 61000-2-12
- IEC 61000-2-4
- IEC 61000-4-13
- IEC 61000-4-19
- IEC 61000-4-17
- IEC 61000-4-29,
- IEC 61204-3,
- IEC TS 62053-41,
- IEC 61869-14:2018,
- IEC 61869-15:2018.

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 under SC77A leadership 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 have to be specified for each LVDC phenomenon as a driver for defining power quality requirement and EMC requirements (emission and immunity, see Table 4 and Table 5).

Example: comparison of existing LVAC voltage compatibility and immunity levels (for class 2 device, see Figure 11):

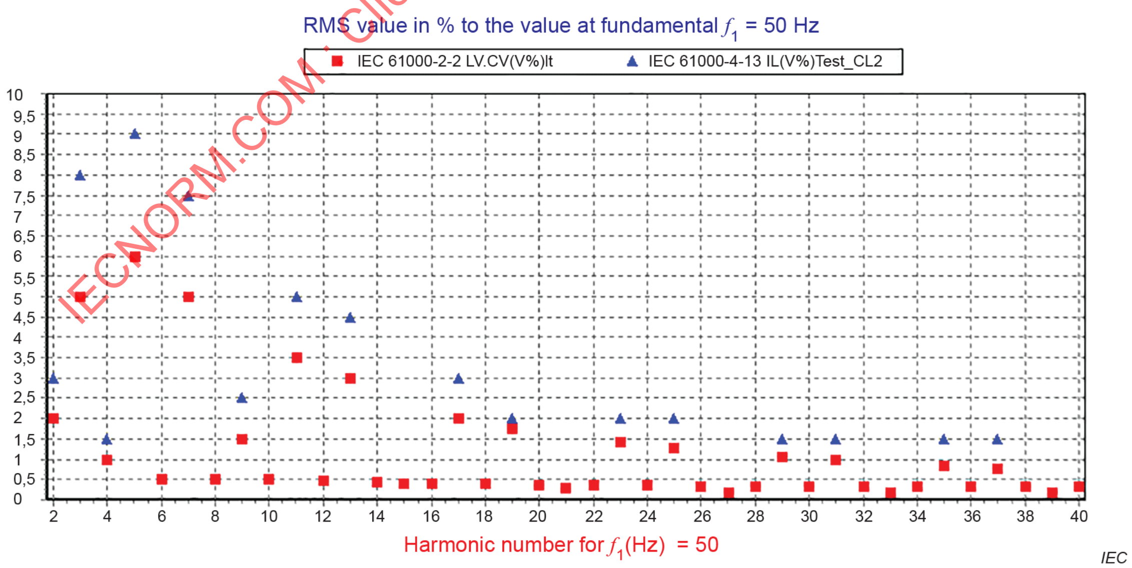


Figure 11 – LVAC voltage compatibility and immunity levels

Table 4 – Immunity: DC input and output power ports, residential, commercial and light industrial environment

Environmental phenomenon	Test item	Test specification	Unit	Basic standard
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)	s	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 5 – Immunity: DC input and output power ports – Industrial environment

Environmental phenomenon	Test item	Test specification	Unit	Basic standard
Fast transients	Peak line-to-ground voltage	±2	kV	IEC 61000-4-4
	Tr/*T*h	5/50	ns	
	Repetition frequency	100	kHz	
Surges	*Tr*/*T*h	1,2/50 (8/20)	s	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 AM (1 kHz)	10	V	
		80	%	

7.4 Power quality recommendations

TC8 should specify power quality requirements covering the relevant phenomena in view of the operation of the LVDC system. Joint work should be done with SC77A in order to define DC power quality assessment methods.

- A voltage ripple indicator paying attention to aggregation time interval and sampling frequency.
- To decide upon utilizing the RMS or averaging operator in order to evaluate voltage dips and swells in LVDC systems, and the associated aggregation time interval to apply. Current aggregation time intervals for AC systems are inadequate to detect power quality deviations. It is recommended to adopt the averaging operator.

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 should be taken into account in the context of LVDC systems:

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

7.5 Measurement methods

7.5.1 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 C for detailed explications).

SC77A/TC8 are invited to propose appropriate measurement methods.

7.5.2 DC system RMS value integration time

DC system RMS value integration time or measurement window length should be defined according to the power quality domain; the following are recommended:

- 200 ms and 10 min values for continuous phenomena;
- 10 ms for transient values such as voltage dip/surge, in line with most existing UVRT (under voltage rid-through) curves.

7.5.3 DC power quality measurement methods

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

- for conducted disturbances < 9 kHz, SC77A, measurement method appears relevant;
- for conducted disturbances 9 kHz to 150 kHz, the methods defined by IEC SC 77A/TC8 could be adopted or re-adopted for DC application.

Annex A
(informative)

PQ waveforms collected from a certain LVDC project

Worthy 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 a practical ±750 V/±375 V LVDC system in Tongli, China.

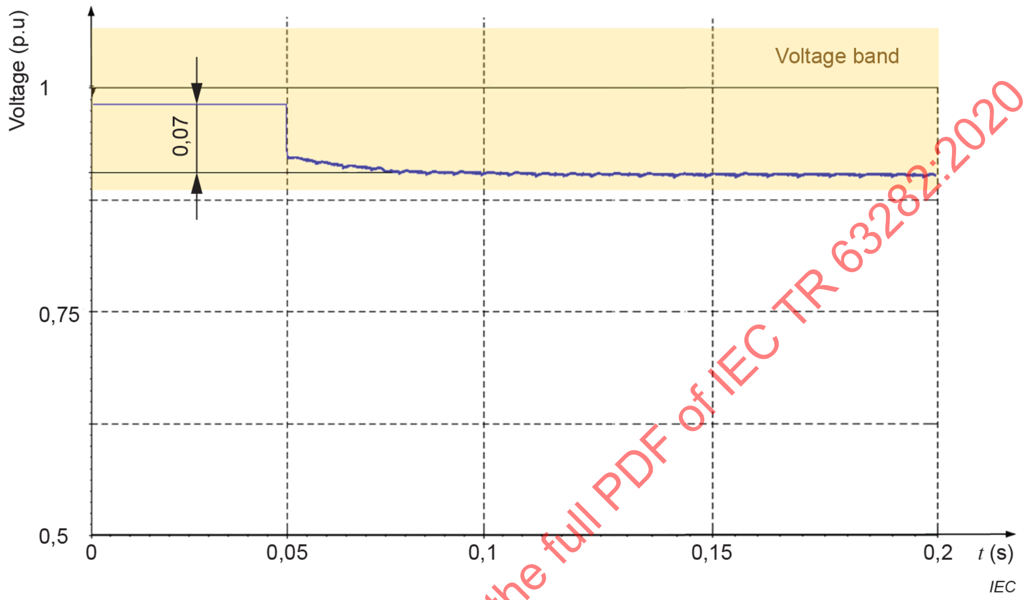


Figure A.1 – Voltage deviation caused by load switching

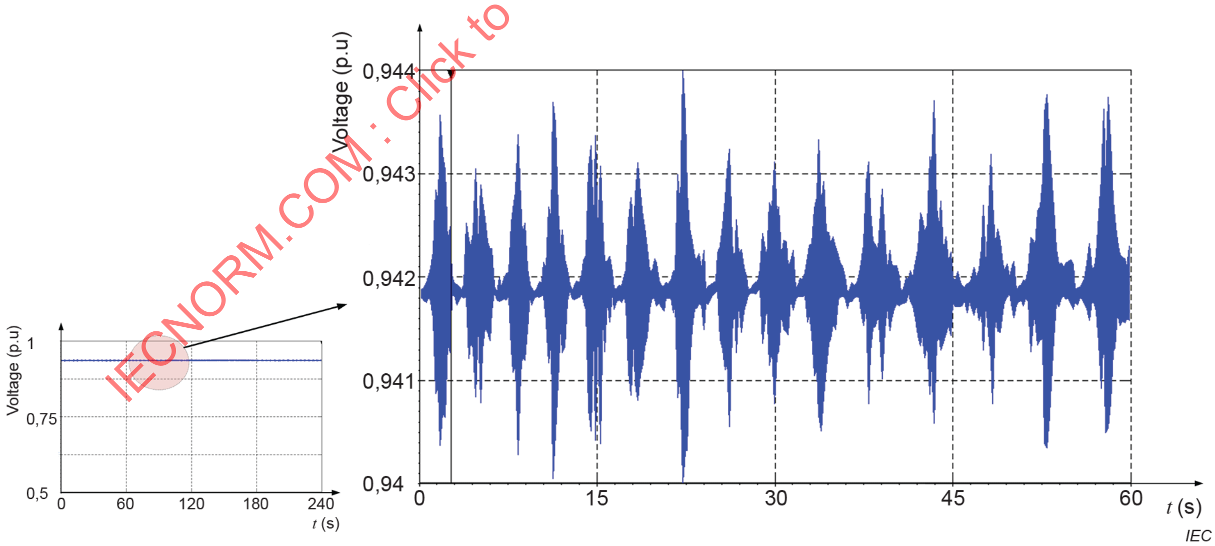


Figure A.2 – Voltage ripple in steady state

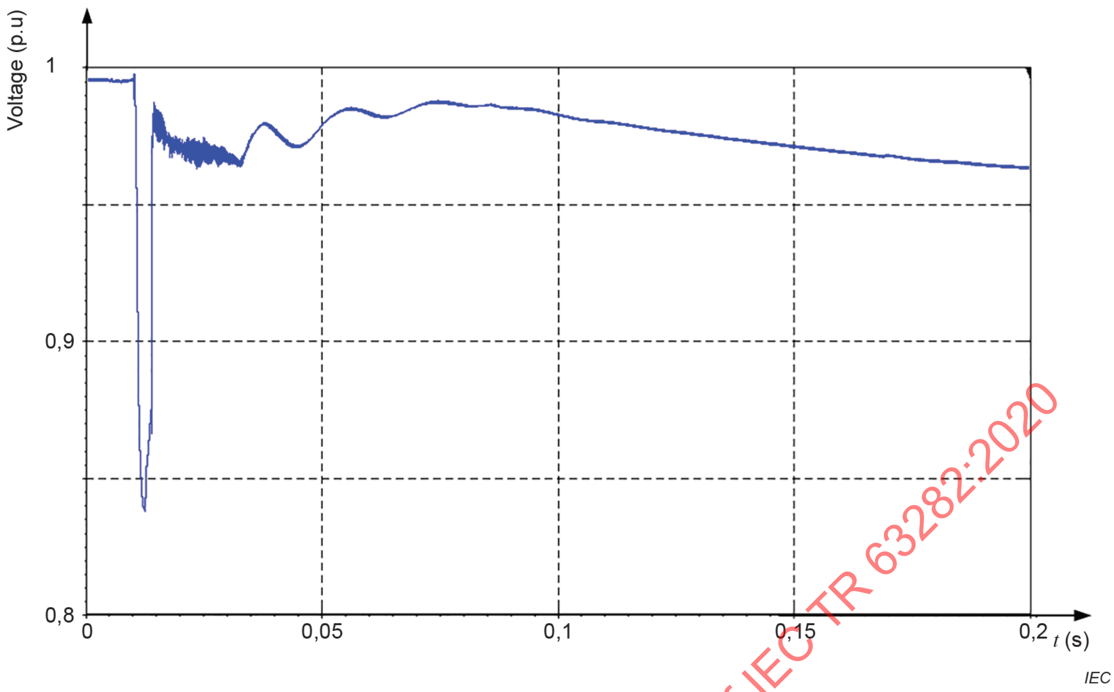


Figure A.3 – Voltage dip caused by the start-up of motor load

Annex B
(informative)

Load distance in DC distribution systems

Load distance calculation in DC distribution systems should consider voltage level, conductor nominal section, maximum long-term operating temperature and other factors. The load distance calculation of the DC distribution system should be based on the content of voltage deviation in different voltage levels in Clause 7 of this technical report. Considering that the conductor temperature and the DC resistance of overhead lines increasing with the growing transmission current, the load distance 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 B.1 and Table B.2 (based on the preferred DC voltages in China).

Table B.1 – 1,5 (±0,75) kV typical load distance of overhead DC lines

(unit: kW·km)

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

Table B.2 – 750 (±375) V, 220 (±110) V typical section load distance 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 load distance values of 750 (±375) V and 220 (±110) V overhead lines are based on an aluminium strand conductor.				

Annex C
(informative)

Electric power and power quality computation in DC systems

C.1 DC RMS value of voltage or current

The DC RMS value is the root mean square value of the DC component (or mean value) and RMS value of all AC components in a given measurement window's length, i.e.:

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

$$V_{\mathrm{RMS}} = \sqrt{\frac{1}{T}\int_0^T V^2(t)\,\mathrm{d}t}$$

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

$$V_{\mathrm{DCRMS}} = \sqrt{\sum_{k=0}^{n} V_k^2}$$

where

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

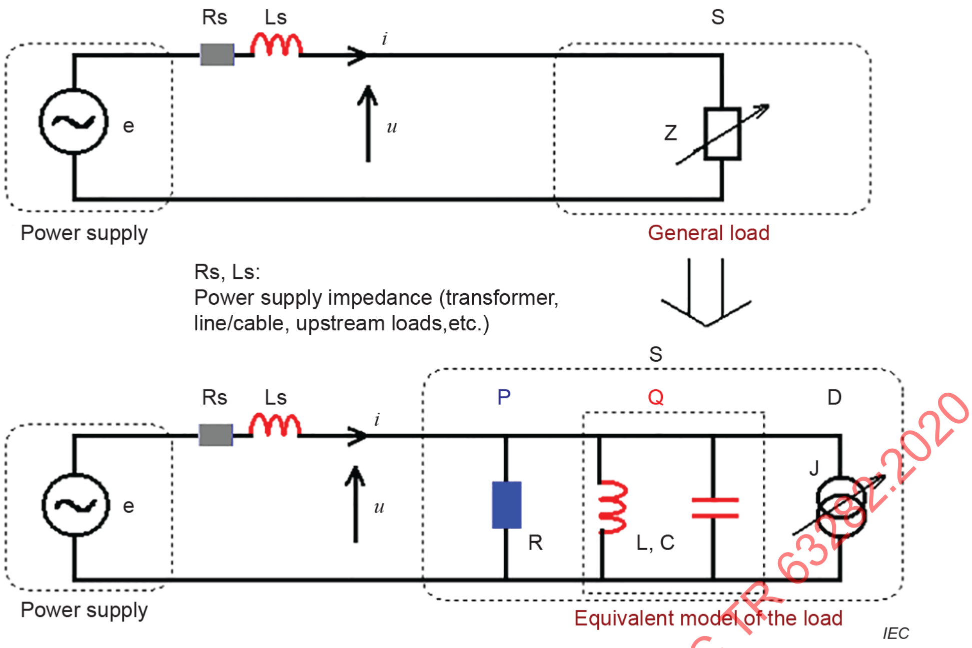
V_{k} is the RMS value at indice k, i.e. at frequency $k*fw$;

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

k=0 is the DC component.

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

In an electric power system, an electric load may call different types of currents from power grid: sinusoidal wave forms with different phase angles, and non-sinusoidal wave forms. In the general case, load consumption can be represented by linear and nonlinear components referred to different electric powers (Figure C.1).



Key

S apparent power
P active power
Q reactive power
D deformation power resulted from deformation of voltage and current

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

C.3 Computation of electric powers and PQ indices

In time domain:

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

$$p(t) = u(t) \cdot i(t)$$

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

$$P = \frac{1}{T} \cdot \int_0^T p(t) \cdot \mathrm{d}t = \frac{1}{T} \cdot \int_0^T u(t) \cdot i(t) \cdot \mathrm{d}t$$

In the above formula, DC components are included.

RMS values of voltage U and current I:

$$U = \sqrt{\frac{1}{T} \cdot \int_0^T u(t)^2 \mathrm{d}t} \quad \text{and} \quad I = \sqrt{\frac{1}{T} \cdot \int_0^T i(t)^2 \mathrm{d}t}$$

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

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 Fourier transform within a defined window length; they are decomposed into frequency domain values as DC components and AC components (magnitude and phase):

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

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

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 may be computed with frequency domain components:

Root mean square values or RMS values:

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

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

Electric powers of single phase system:

$$S = U \cdot I$$

$$P = \sum_{k=0}^{n}\left[U_k \cdot I_k \cdot \cos(\phi_k)\right]$$

$$Q = \sum_{k=0}^{n}\left[U_k \cdot I_k \cdot \sin(\phi_k)\right]$$

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

where

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

ϕ_0: either 0 or π.

Total harmonic distortion T_{hd}:

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

Total voltage harmonic distortion: $T_{dh\_U} = \frac{1}{U_1}\sqrt{U_2^2 + U_3^2 + U_4^2 + ... + U_n^2} \cdot 100\,\%$

Total current harmonic distortion: $T_{dh\_I} = \frac{1}{I_1}\sqrt{I_2^2 + I_3^2 + I_4^2 + ... + I_n^2} \cdot 100\,\%$

In pure sine wave system: T_{dh} = 0.

According to IEC definitions, the total harmonic distortion 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 above formulas exceed 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 system.

The relation of different electric powers:

$$S = \sqrt{P^2 + Q^2 + D^2}$$

$$Q' = \sqrt{Q^2 + D^2}$$

Power factor is generally computed as:

$$P_F = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2 + D^2}}$$

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

$$P_F = \frac{P}{\sqrt{P^2 + Q^2}} = \cos(\varphi) \quad \text{and} \quad \mathrm{tg}(\phi) = \frac{Q}{P} \text{ (French case)}$$

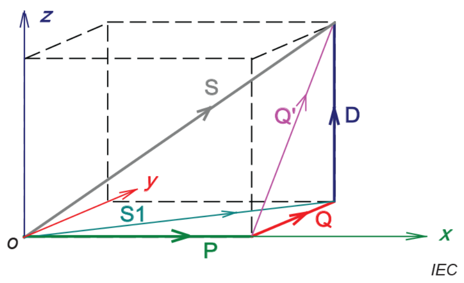
ϕ or φ: the phase angle difference between voltage and current at fundamental frequency.

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

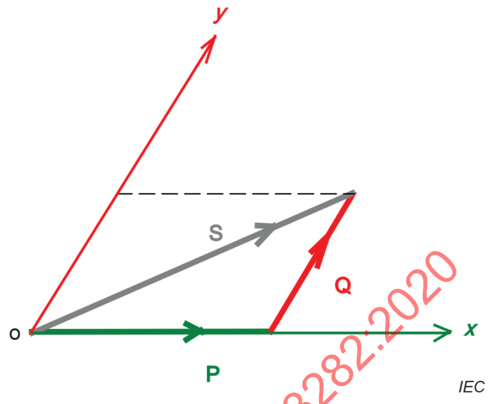
In a non-sinusoidal system, the power factor λ takes into account both reactive power Q and deformation power D, but the terms cos(ϕ) and tg(ϕ) take into account only the reactive power at fundamental frequency.

C.4 Representation of electric powers in AC system

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



a) General case (non-sinusoidal)



b) Particular case (sinusoidal)

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

C.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 C.3):

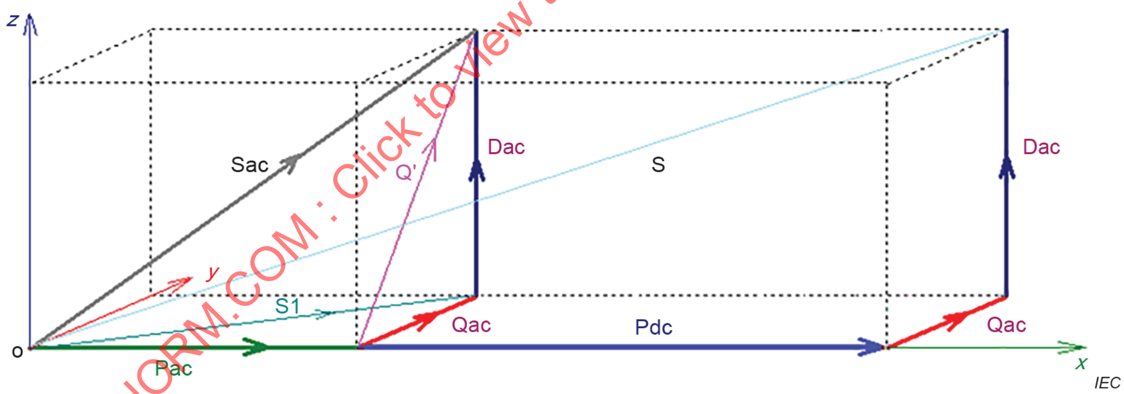


Figure C.3 – Representation of electric powers in DC system

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, $D = 0$, $Q = 0$, $P_{AC} = 0$.

<u>Remark:</u>

A DC system with the presence of AC components represents theoretically the general electric power system, that is to say, in a DC system, there may be some power quality issues 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: DC + AC;
- AC power system is a particular case: DC component is considered as negligible.

C.6 Power quality indices in DC system

The DC value may include ripples (or AC components) (see Figure C.4):

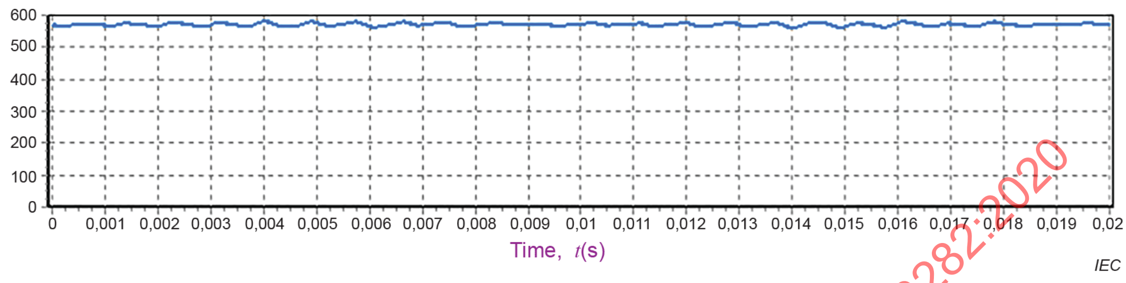


Figure C.4 – Ripples

Time domain computation with sampled values:

RMS values:

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

DC values (or mean values):

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

where n_s is the sampled number during the observed period.

DC ripple in RMS values:

$$U_{rpl}=\sqrt{U^2-U_0^2} \quad \text{and} \quad I_{rpl}=\sqrt{I^2-I_0^2}$$

DC ripple rates in %:

$$u_{rpl}=\frac{\sqrt{U^2-U_0^2}}{U_0}\cdot 100\ \% \quad \text{and} \quad i_{rpl}=\frac{\sqrt{I^2-I_0^2}}{I_0}\cdot 100\ \%$$

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

DC electric parameters and power quality values based on FFT (or DFT) transform:

RMS

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

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

Ripple in RMS

$$U_{\text{rpl}} = \sqrt{U_1^2 + U_2^2 + U_3^2 + U_4^2 + ... + U_m^2}$$

$$I_{\text{rpl}} = \sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + ... + I_m^2}$$

Ripple in %

$$u_{\text{rpl}} = \frac{U_{rpl}}{U_0} \cdot 100\,\% = \frac{\sqrt{U^2 - U_0^2}}{U_0} \cdot 100\,\%$$

$$i_{\text{rpl}} = \frac{I_{rpl}}{I_0} \cdot 100\,\% = \frac{\sqrt{I^2 + I_0^2}}{I_0} \cdot 100\,\%$$

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

The maximum measurement frequency f_{m} is to be defined. In compliance with on-going IEC EMC standards, it is recommended to choose:

– f_{m} > 2 kHz for harmonic frequency range defined by IEC;
– f_{m} >150 kHz for disturbances 2kHz to 150 kHz.

C.7 Illustration example of deformation 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 C.5):

Figure C.5 – DC powers

With these voltage and current, different powers can be computed during 20 ms (just as an example) (see Table C.1):

Table C.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)	4994,096
P_F (*)	0,707 336 1

C.8 Main conclusions on electric value computation in DC systems

- Active power may be smaller than apparent power in a DC system if nonlinear load is connected.
- Reactive power may be very small in a DC system if the ripple of DC supply voltage is negligible.
- Deformation power may be important in a DC system if a nonlinear load is connected. It should be taken into account in overall system design.
- Power factor P_F should be 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 deformation power (or increase P_F to 1) in order to increase the efficiency of DC power supply.

C.9 Need of characteristics of DC voltage

One of the assessments of DC power quality is to define characteristics of DC power supply voltage in public networks. Characteristics of DC voltage supply may be defined similar as:

- For disturbance frequencies less than 2 kHz: IEC TS 62749 (EN 50160 as well) is to be adapted into relevant DC voltage ripple values.
- Conducted disturbances 2 kHz to 150 kHz in LV AC network: IEC 61000-2-2 for compatibility voltage levels is to be adapted in DC systems (Figure C.6 below, measured in differential mode values with CISPR 16 measuring method). For LV DC, the extension of power quality phenomena to the frequency range < 150 kHz is necessary because DC power sources and loads are almost all with power electronic interfaces.

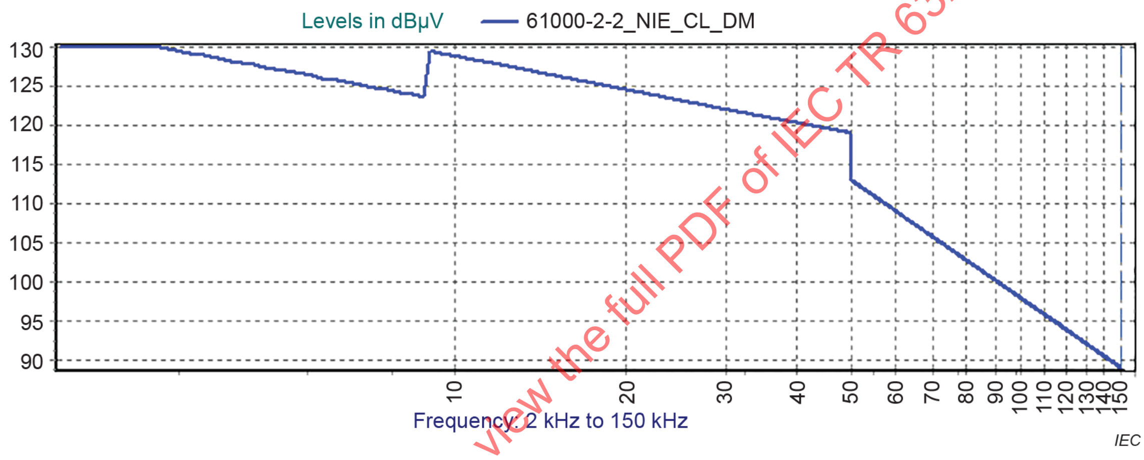


Figure C.6 – Compatibility level measured in differential mode values

Annex D
(informative)

District LVDC system demonstration project in Tongli, China

D.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, which is sponsored by the 2017 National key research and development project of China. This project is aimed at distributed green energy utilization in high penetration district, to explore power supply mode of different applications, develop high efficiency DC distribution equipment and display construction mode of low energy consumption DC building.

As Figure D.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.

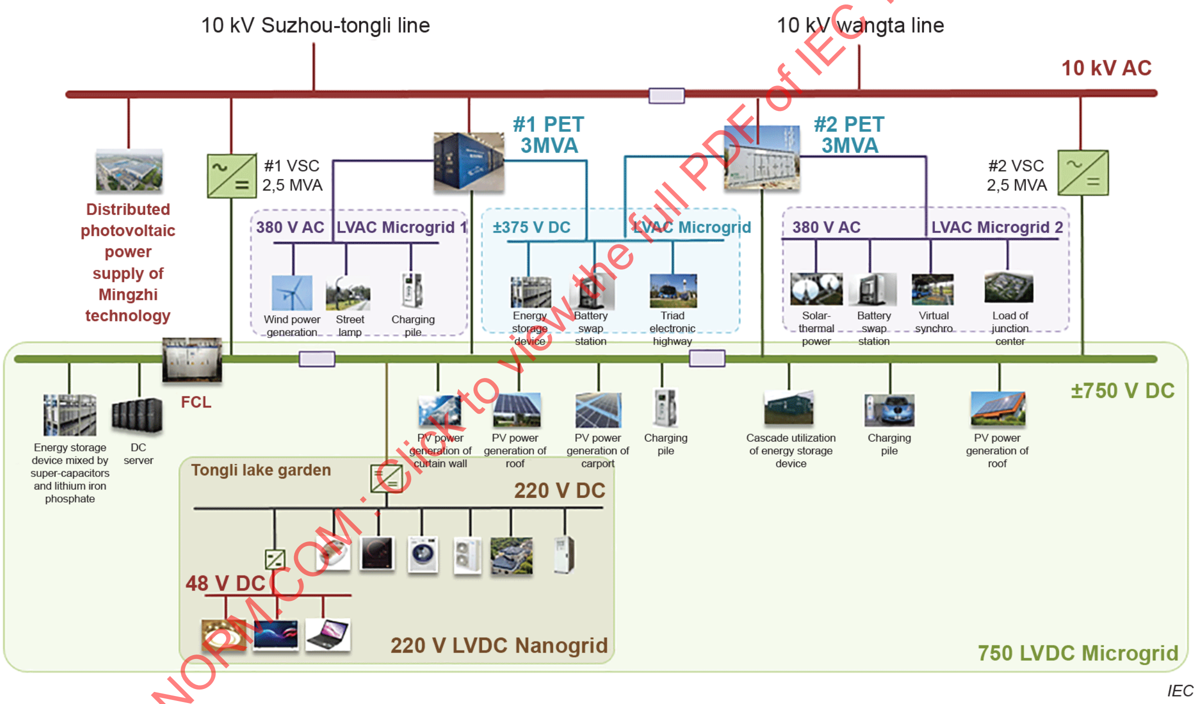


Figure D.1 – Architecture of the district LVDC system in Tongli

D.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 and relatively long transmission distance and large transmission capacity, the ± 750 V DC microgrid is connected to a 2,9 MW PV power and energy storage.

Similarly, the voltage between poles of ± 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 should be noted that as the tests and operations show, the DC modified appliances can withstand higher voltage and thus have 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.

D.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 our team to study related technical problems of LVDC system.

Annex E
(informative)

An office building with general building utilities and office work places

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 3 000 m^2 of meeting venues with LED and PV panels connected to a complete DC grid on 350 V DC. See Figure E.1.

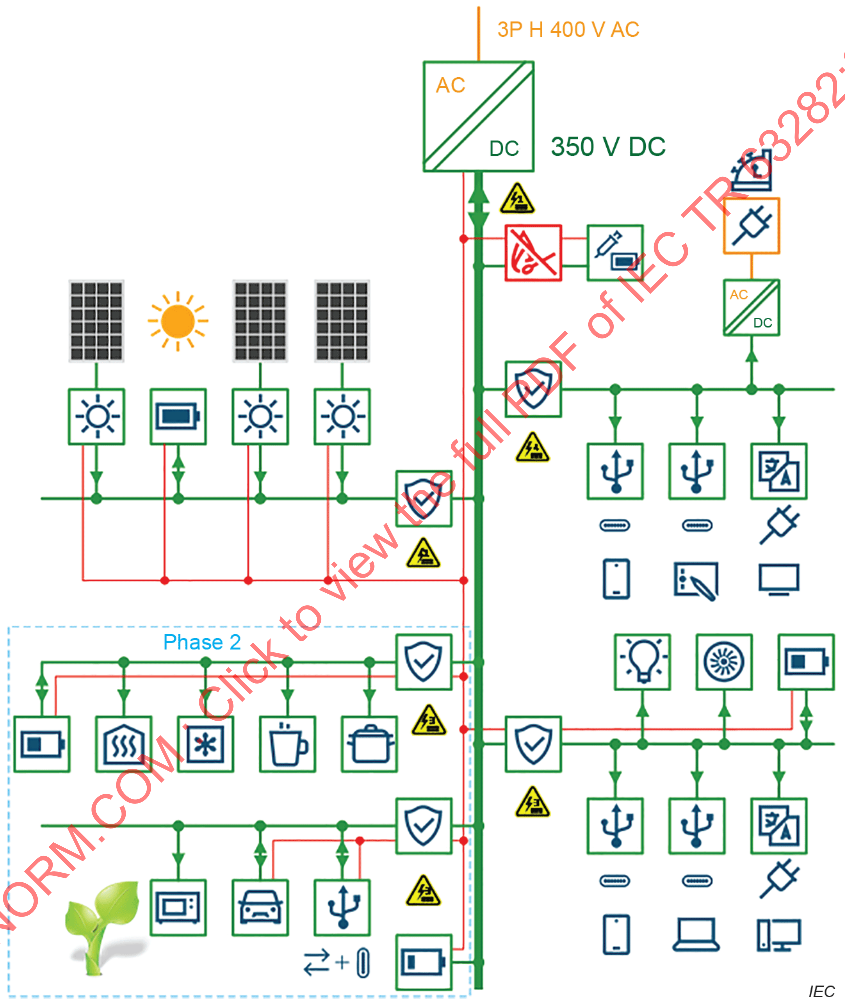


Figure E.1 – Office building with general building utilities and office work places

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:

1) 3 AFE (3 × 50 kW);
2) Solid state protection devices
   a) 16 A,
   b) RCD included;
3) PV installation 150 kW
   a) Every PV has his own optimizer (one defective panel will not infect the whole system);
4) Storage (Batteries)
   a) Peak shaving,
   b) UPS,
   c) Island mode;
5) USB-C (100 W)
   a) Flexible output voltage (5 V to 20 V output range),
   b) Power and data combined in one connector/cable;
6) 350 V_{DC} wall socket (protected by solid state)
7) DC/AC converter (230 V_{AC} 2 kW),
   a) For normal AC devices;
8) 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.

DC zones

This is part of the Dutch IEC 60364 (NEN1010). Figure E.2 shows an overview of DC-zones for DC systems. It is placed in zones because DC have different kind of sources; this means the protection will be different per DC zone. For example, a current limited converter with a fuse: the fuse will not be a protective device in fault conditions.

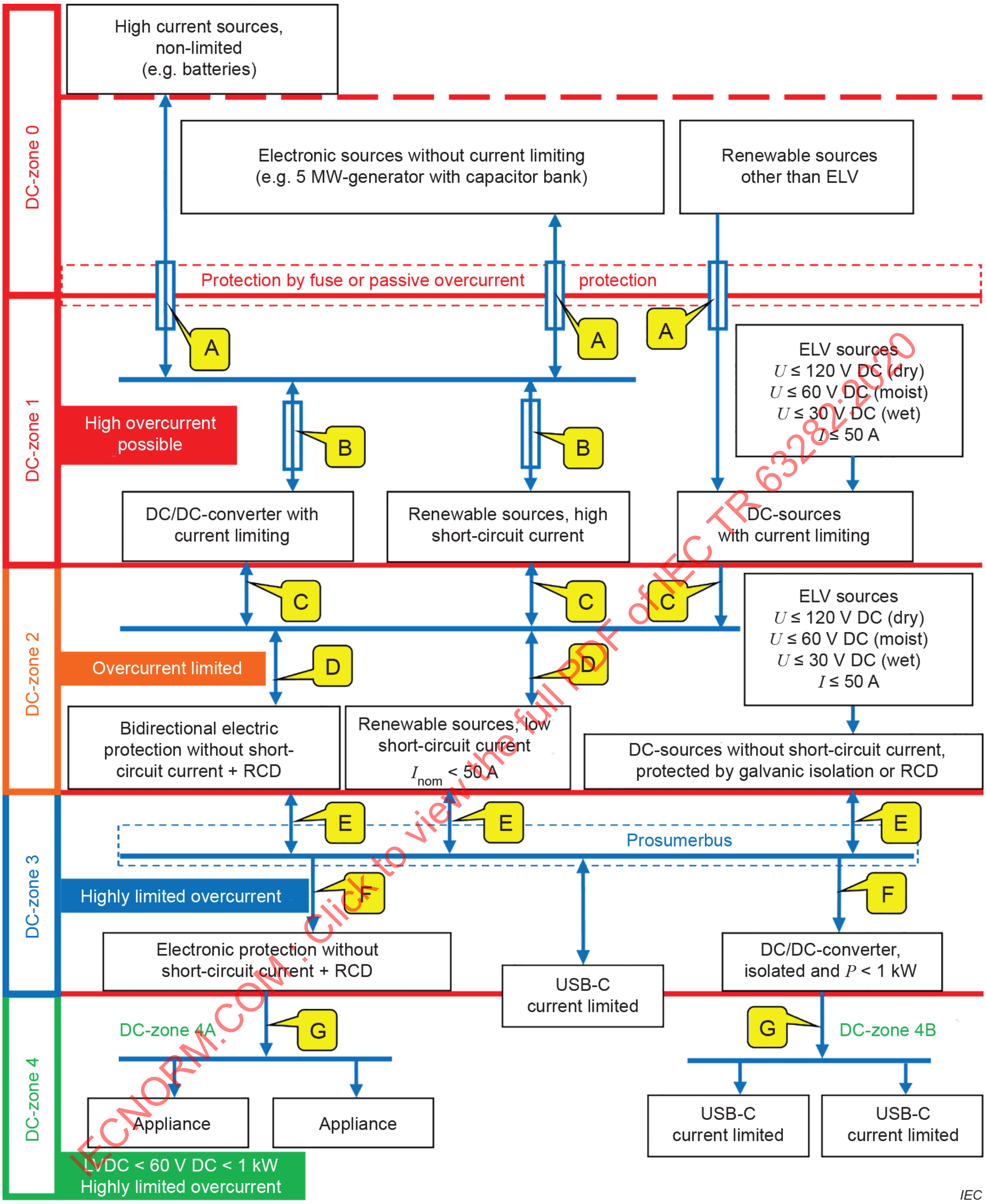


Figure E.2 – Overview of DC-zones for DC system

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 may be set on the knowledge, expertise and skills of the designer, fitter, installer and the operators.

DC zone 0: unprotected source

DC zone 0 features autonomous supply sources with high power. Examples of what is covered by this DC zone are:

– batteries (multiple batteries connected together or batteries with high energy content);
– synchronous machines;
– the public electricity network;
– large PV installations.

These power sources are characterized by their high power, impervious directly, and free from the current limitations of protected elements in this DC zone. The current can be bi-directional, depending on the nature of the source.

The following is characteristic of this DC zone:

– maximum voltage ≤ 1 500 V DC;
– no ELV: U_{nom} ≥ 30 V DC (wet environment) or U_{nom} ≥ 60 V DC (moist environment) or U_{nom} ≥ 120 V DC (dry environment);
– very high overcurrent possible;
– nominal current not limited;
– multiple sources possible.

DC zone 1: protected source with high short-circuit current

DC zone 1 features outgoing conductors (possibly combined in bus bars) from the supply sources from DC zone 0 on the secondary side – when viewed from the source – of a passive overcurrent protective device. This DC zone may also feature ELV sources (< 120 V DC or 60 V DC or respectively 30 V DC in moist or respectively wet environments).

The following is characteristic of this DC zone:

– maximum voltage ≤ 1 500 V DC;
– U_{nom} ≤ 30 V DC (wet environment) or U_{nom} ≤ 60 V DC (moist environment) or U_{nom} ≤ 120 V DC (dry environment);
– high overcurrent possible;
– nominal current ≤ 500 A;
– multiple sources possible.

DC zone 2: protected source with low (limited) short-circuit current

DC zone 2 only features limited current sources that remain active in a fault situation.

Characteristic of this DC zone is a further limitation of the current and possibly an adjusted voltage level.

The following is also characteristic of this DC zone:

– maximum voltage ≤ 1 500 V DC;
– U_{nom} ≤ 30 V DC (wet environment) or U_{nom} ≤ 60 V DC (moist environment) or U_{nom} ≤ 120 V DC (dry environment);
– I_{nom} ≤ 50 A (per device);
– overcurrent possibly too low for fuses or circuit breakers, preventing them from performing their protective functions;

– multiple sources possible;
– bi-directional current direction possible.

DC zone 3: electronic source

DC zone 3 may contain ‘prosumers’ (generators or consumers of current or a combination of these two).

Characteristic of this DC zone is the highly limited overcurrent. Where this is not inherent in the source, this will be provided by electronic systems that monitor current and voltage levels and intervene where necessary.

The following is characteristic of this DC zone:

– U_{nom} ≤ 400 V DC (to PE) or U_{nom} ≤ 800 V DC (between L+ and L−);
– I_{nom} ≤ 50 A (per device);
– highly limited overcurrent;
– multiple sources possible;
– bi-directional current direction possible.

DC zone 4: single electronic source

DC zone 4 only features consumers of electrical energy. Every load in this DC zone is powered from only one supply point.

The following is characteristic of this DC zone:

– U_{nom} ≤ 400 V DC (to PE) or U_{nom} ≤ 800 V DC (between L+ and L−);
– I_{nom} ≤ 50 A;
– no overcurrent of any relevance;
– multiple sources not allowed;
– direction of the current only towards the devices (not bi-directional).

The letters in the figure refer to the protection measures in Table E.1.

Table E.1 – Aspects regarding the DC zone classification in DC installation

Zone	**Limit zone 0-1**	**DC zone 1**	**DC zone 2**	**DC zone 2**	**DC zone 3**	**DC zone 3**	**DC zone 4a**	**DC zone 4b**
Location in diagram	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Aspect								
Residual current protective device	option	option	option	option	*	*	*	N/A
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**	manda-tory**	manda-tory**	N/A
Plug with an early-break contact	option	option	option	option	option	option	option	N/A
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)	N/A
Corrosion prevention (NEN 1010:2015 C 542)	mandatory	mandatory	mandatory	mandatory	mandatory	mandatory	mandatory	N/A
Temperature alarm	option	option	option	option	option	option	option	option

* 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 shall 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 shall be 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.

Annex F
(informative)

An example of configurations for active DC systems

F.1 General

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.

F.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 may be connected to a passive AC or DC system and may 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 needs to control the available energy. A principle diagram for the active grid in the last mile is shown in Figure F.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 need to be controlled.

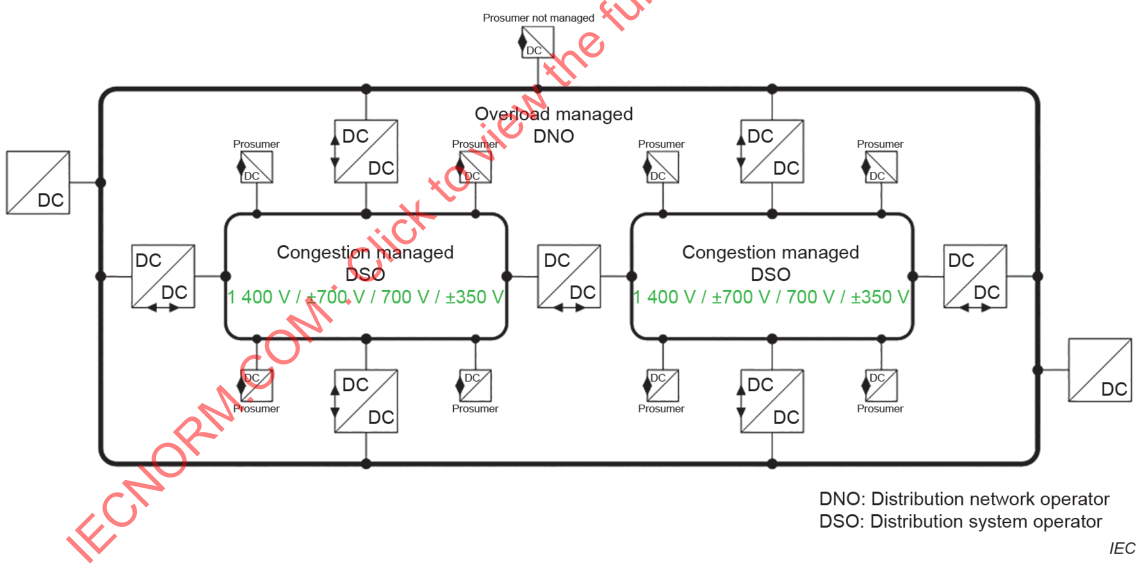


Figure F.1 – Active DC distribution system

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 may result in highly improved system organization.

F.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:

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

Table F.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 line to line shall stay below the 1 500 V DC limit.

The value of the maximum tolerated losses in active DC systems shall be as low as possible, as shown in Table F.1.

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

1) 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.
2) Going further and assuming 10 % is not a good choice either because such voltage drop would adversely influence earthing point design, because many diodes would be required to compensate circulations.
3) 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 a discrimination between users, smaller voltage drop is desired. If low cable loss and deviation is taken, then droop curves are not directly influenced.
4) The cable sizes. If 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 F.2.

Table F.2 – Allowed voltages cable drop

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

d) 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 grid can consist of more sources that should not be bigger in power than the dominant source and they contribute to balancing the congestion in the grid by means of voltage droop.

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

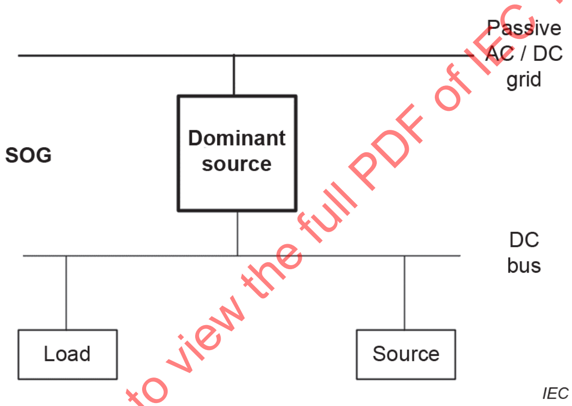


Figure F.2 – DC distribution system with one load and one source

If there is an energy 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 vehicle, are enabled to increase their own consumption. This voltage increase occurs up to a maximum voltage level (U_{max}), as shown in Figure F.3.

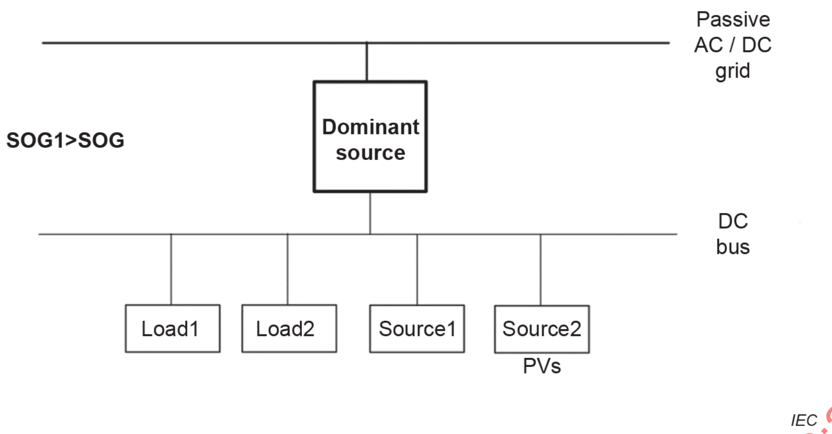


Figure F.3 – DC distribution system with more than one load and a source and increasing source power

When the voltage reaches U_{max} and excess power is getting higher than a maximum power of all loads combined, dump loads, if available, may be activated as shown in Figure F.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.

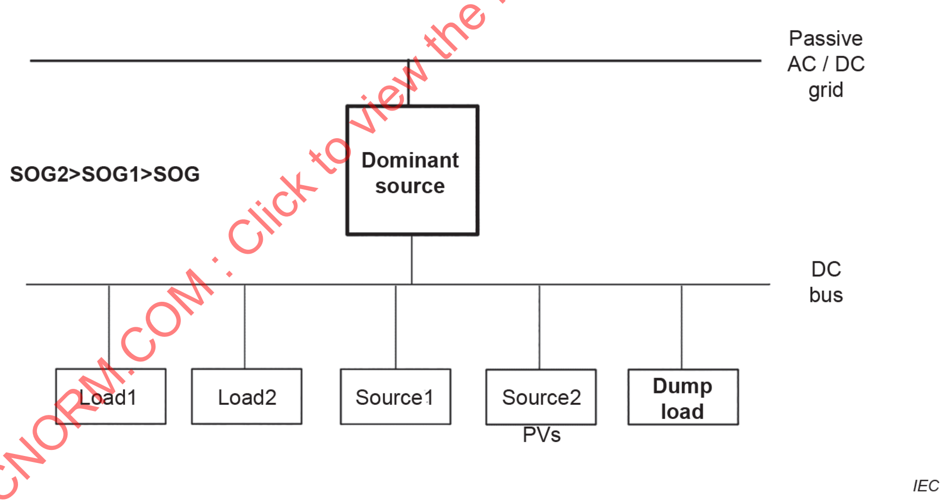


Figure F.4 – Distribution system with more than one load and a source and DUMP LOAD active

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 are allowed to still operate, as shown in Figure F.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.

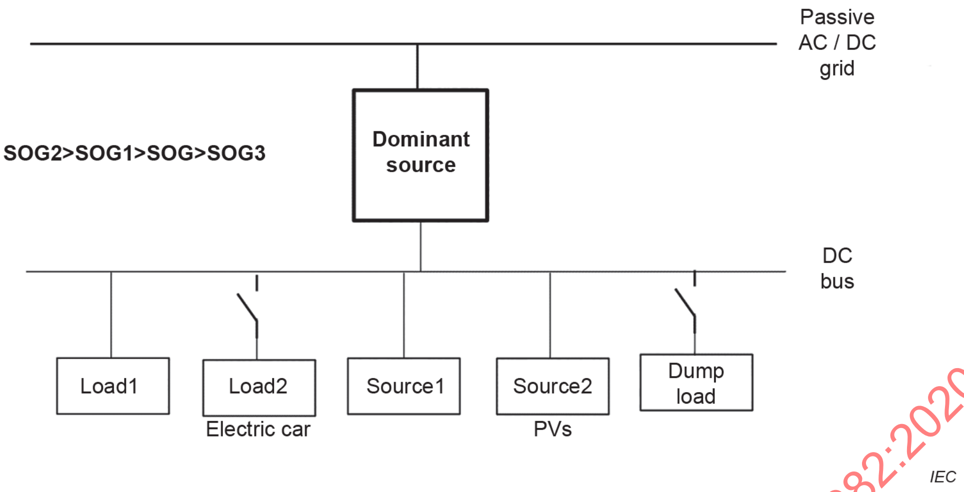


Figure F.5 – Distribution system with more than one load and source in overloaded mode

NOTE The dominant source is not the necessary component but in case that the dominant source is not available, the system might have to be differently configured and designed, specifically referring to protection scheme.

e) Control

Each active device connected to the DC system has to comply 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, µs).

Parameterizing is not time critical and is not used as a mean 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 behavior. 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.

f) Inertia

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.