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OF INTEREST TO THE FOLLOWING COMMITTEES:

TC 21,TC 22,TC 23,TC 64,SC 77A,TC 99,TC 109,TC 121,SyC LVDC

FUNCTIONS CONCERNED:

EMC

ENVIRONMENT

QUALITY ASSURANCE

SAFETY

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TITLE:

LVDC systems - Assessment of standard voltages and power quality requirements

PROPOSED STABILITY DATE: 2029

NOTE FROM TC/SC OFFICERS:

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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**LVDC SYSTEMS – ASSESSMENT OF STANDARD VOLTAGES AND POWER
QUALITY REQUIREMENTS**

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201

202

FOREWORD

203 1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising
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239 IEC TR 63282 has been prepared by IEC technical committee 8: System aspects of electrical
240 energy supply. It is a Technical Report.

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

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

245 a) Optimized terms and definitions in Clause 3:

246 DC system nominal voltage is modified. Oscillation is added. Active distribution system,
247 passive distribution system are deleted.

248 b) Modified the definition of voltage bands:

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

- 251 c) Distinguished the difference between oscillation and power quality phenomenon:
 252 In Clause 3, the definition of oscillation is added based on IEC 103-05-04. In 6.3, relationship
 253 between oscillation and power quality is clarified. Annex B gives a LDC oscillation typical
 254 example which has really happened in a MV&LVDC system in China.
- 255 d) Modified the recommended voltage for distribution DC network:
 256 The factors considered in voltage values definition is clarified. And the voltage is divided in
 257 two domains, distribution domain and installation domain. The voltage recommendation in
 258 LVDC is listed corresponding to voltage bands.
- 259 e) Modified the voltage immunity level assessment:
 260 It is mentioned in 7.2 that the assessment of voltage immunity levels of mass LVDC power
 261 electronic devices need to be further discussed, ripple as an example is introduced.
- 262 f) Added DC power quality measurement methods:
 263 In 7.3, DC power quality measurement methods is introduced based on AC methodologies.
 264 And some additional DC power quality indices are recommended to assess the DC system.
 265 DC electric power and power quality measurement methods are introduced in 7.4, defining
 266 the electric value integration time and frequency ranges.
 267 Typical electric power and power quality computation methods are modified in Annex D.
- 268 g) Added an annex on MVDC system:
 269 A use case of a typical MV&LVDC distribution system is added in Annex F, to support
 270 developments of TS of 8A and 8B on DC microgrids.
- 271 h) Added an annex on CurrentOS voltage level:
 272 The voltage level applied in CurrentOS is introduced in Annex L to give more information on
 273 the LVDC voltage level recommendation.

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

Draft	Report on voting
8/XX/DTR	8/XX/RVDTR

275
 276 Full information on the voting for its approval can be found in the report on voting indicated in
 277 the above table.

278 The language used for the development of this Technical Report is English.

279 This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in
 280 accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available
 281 at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are
 282 described in greater detail at www.iec.ch/publications.

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

- 286 • reconfirmed,
- 287 • withdrawn, or
- 288 • revised.

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290

INTRODUCTION

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

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

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

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

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

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

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

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

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

325

326 LVDC SYSTEMS – ASSESSMENT OF STANDARD VOLTAGES AND POWER 327 QUALITY REQUIREMENTS 328 329 330

331 1 Scope

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

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

338 Attention is paid to the definition of DC voltage.

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

341 Traction systems are excluded from this document.

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

344 2 Normative references

345 There are no normative references in this document.

346 3 Terms and definitions

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

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

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

352 3.1

353 nominal system voltage

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

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

357 3.2

358 DC supply voltage

359 line-to-line or line-to-midpoint voltage at the supply terminals

360 3.3

361 bipolar DC system

362 DC system comprising a positive and negative line, and a midpoint, distributed or not

363 **3.4**
364 **unipolar DC system**
365 DC system comprising a positive or a negative line, and a midpoint

366 **3.5**
367 **DC system nominal voltage**
368 U_n
369 value of the voltage by which the electrical installation or part of the electrical installation is
370 designated and identified

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

$$373 \quad U_2 \leq U_n \leq U_3$$

374 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} ".

375 **3.6**
376 **DC voltage deviation**
377 voltage deviation due to the slow change in power system operation state

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

381 **3.7**
382 **voltage unbalance**
383 condition in a bipolar system in which the line to mid-point voltages are not equal

384 **3.8**
385 **ripple**
386 set of unwanted periodic deviations with respect to the average value of the measured or
387 supplied quantity, occurring at frequencies which can be related to that of the mains supply, or
388 of some other definite source, such as a chopper or load changes

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

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

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

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

398 **3.9**
399 **over-voltage**
400 voltage the value of which exceeds a specified limiting value

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

402 **3.10**
403 **under-voltage**
404 voltage the value of which is lower than a specified limiting value

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

406 **3.11**
407 **voltage swell**
408 sudden increase of the voltage at a point in the electrical supply system followed by voltage
409 recovery after a short period of time

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

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

414 **3.12**
415 **voltage dip**
416 sudden decrease of the voltage at a point in the electrical supply system followed by voltage
417 recovery after a short period of time

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

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

424 **3.13**
425 **voltage surge**
426 transient voltage wave propagating along a line or a circuit and characterized by a rapid
427 increase followed by a slower decrease of the voltage

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

429 **3.14**
430 **voltage supply interruption**
431 disappearance of the supply voltage for a time interval whose duration is between two specified
432 limits

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

435 **3.15**
436 **rapid voltage change**
437 **RVC**
438 quick transition in voltage occurring between two steady-state conditions, and during which the
439 voltage does not exceed the under-voltage/over-voltage thresholds

440 **3.16**
441 **oscillation**
442 physical phenomenon characterized by one or more alternately increasing and decreasing
443 quantities

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

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

449 **3.17**
450 **DNO**
451 **distribution network operator**
452 party operating a distribution network

453 **3.18**
454 **DSO**
455 **distribution system operator**
456 party extending the function of a DNO to incorporate active management of some power
457 resources

458 **3.19**
459 U_+
460 **positive voltage**
461 voltage between the positive line and the midpoint

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

463 **3.20**
464 U_-
465 **negative voltage**
466 voltage between the negative line and the midpoint

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

468 **3.21**
469 **balanced voltage**
470 U_b
471 average of the positive and the negative voltage

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

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

474 **3.22**
475 **unbalanced voltage**
476 U_u
477 average difference of the positive and the negative voltage

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

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

480 **3.23**
481 **midpoint**
482 common point between two symmetrical circuit elements the opposite ends of which are
483 electrically connected to different line conductors of the same circuit

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

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

487 **3.24**
488 **under-voltage ride through**
489 capability of equipment to stay connected and continue functioning during voltage dips

490 **3.25**
491 **DC voltage**
492 voltage equal to its average value during a defined time interval

493 **3.26**
494 **over-voltage ride through**
495 capability of equipment to stay connected and continue functioning during voltage swells

496 **4 Structure of LVDC systems**

497 **4.1 General**

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

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

506 **4.2 Architecture**

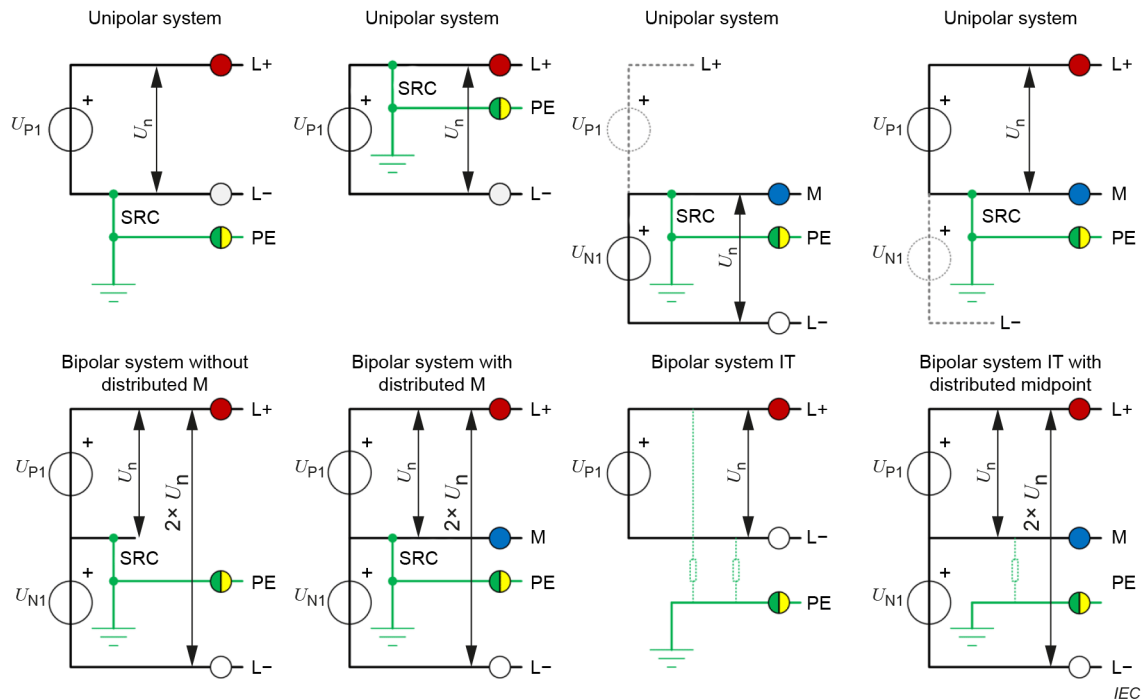
507 Several use cases concerning existing technologies and projects have been introduced to
508 support the analysis and classification of LVDC systems, including but not limited to:

- 509 – LVDC system in buildings,
- 510 – LVDC systems between buildings.

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

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

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



520

521 **Key**522 U_{P1} voltage source between the positive line and the midpoint523 U_{N1} voltage source between the negative line and the midpoint524 U_n DC system nominal voltage

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

527 **Figure 1 – Unipolar, balanced and bipolar DC systems**528 **4.3 Operation modes**529 **4.3.1 Passive DC systems**

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

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

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

540 **4.3.2 Active DC systems**

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

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

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

551 5 LVDC voltage division

552 5.1 General

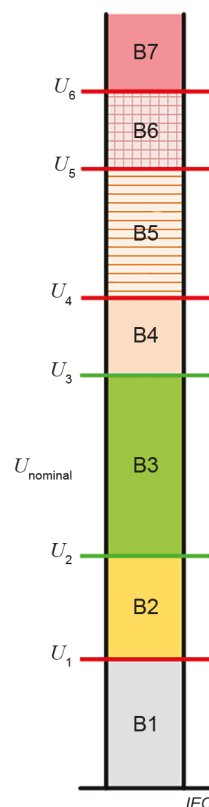
553 The voltages are divided into different levels for temporary and continuous operation.

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

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

558 5.2 Voltage bands

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



562

563 **Figure 2 – Voltage bands in DC systems**

564 – U_1 : Undervoltage disconnecting voltage

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

567 – U_2 : Minimum voltage for continuous operation with full functionality

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

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

571 – U_3 : Maximum continuous operating voltage

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

574 – U_4 : Maximum temporary operating voltage

575 The maximum temporary voltage level below which devices can operate.

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

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

581 – U_5 : Overvoltage disconnecting voltage

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

583 NOTE 3 This is sometimes called breakdown voltage.

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

586 – U_6 : Maximum voltage that equipment overvoltage protection devices clamp

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

589 NOTE 4 The overvoltage protection is normally in conformity with the overvoltage category and ensures that
590 U_6 is not exceeded.

591 – B1: Blackout band ($0 \dots U_1$)

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

594 – B2: Critical band ($U_1 \dots U_2$)

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

597 NOTE 5 Critical devices can operate in this voltage band.

598 – B3: Nominal band ($U_2 \dots U_3$)

599 This is the normal operation band.

600 – B4: Switching, commutation and protection devices operation band ($U_3 \dots U_4$)

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

602 – B5: Overvoltage protection devices non-operating band ($U_4 \dots U_5$)

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

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

606 – B6: Overvoltage protection devices operation band ($U_5 \dots U_6$)

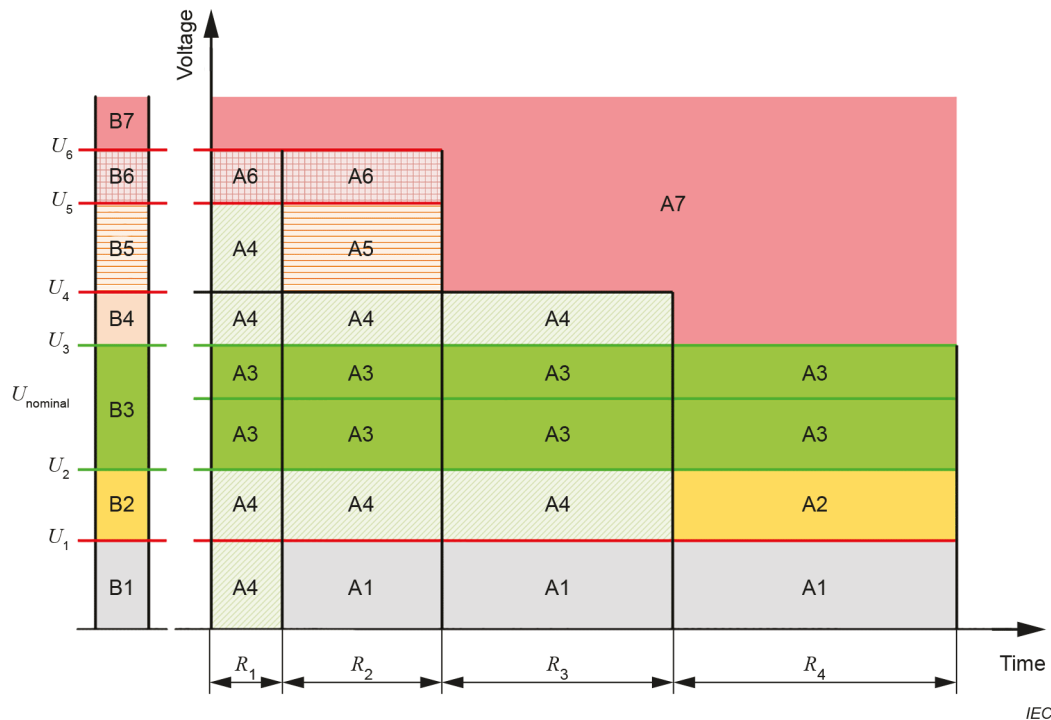
607 Surge protection devices clamp the voltage in this band.

608 – B7: Prohibited band ($U_6 \dots \infty$)

609 In this band, permanent equipment damage is very likely.

610 **5.3 Operation ranges with respect to DC voltage and time**

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



615

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616 **Figure 3 – DC Voltage areas for safe interoperability**

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

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

$$620 \quad R1 < R2 < R3 < \text{Continuous operation (R4)}$$

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

622 – R1: Transient range

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

625 – R2: System fault range

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

630 – R3: Voltage control range

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

632 – R4: Continuous operating range

633 The system can remain in this state indefinitely.

634 5.4 States

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

636 – A1: Blackout state

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

638 – A2: Emergency state

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

643 – A3: Normal state

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

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

651 – A4: Abnormal state

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

656 – A5: Overvoltage state without clamping

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

659 – A6: Overvoltage state with clamping

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

662 – A7: Prohibited state

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

665 6 Power quality phenomena relevant to LVDC networks

666 6.1 General

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

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

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

682 The characteristics of good power quality are:

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

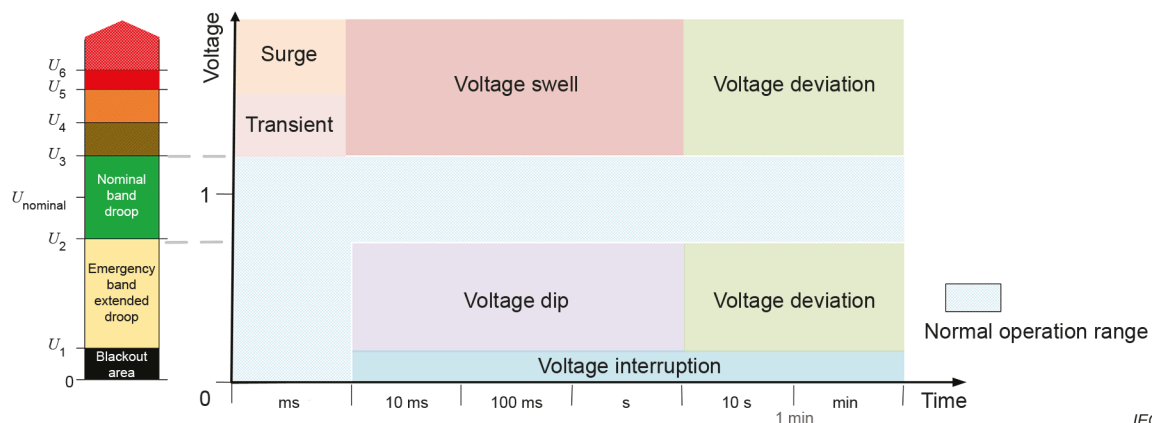
685 6.2 Relationships between voltage band and power quality in LVDC systems

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

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

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

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



701

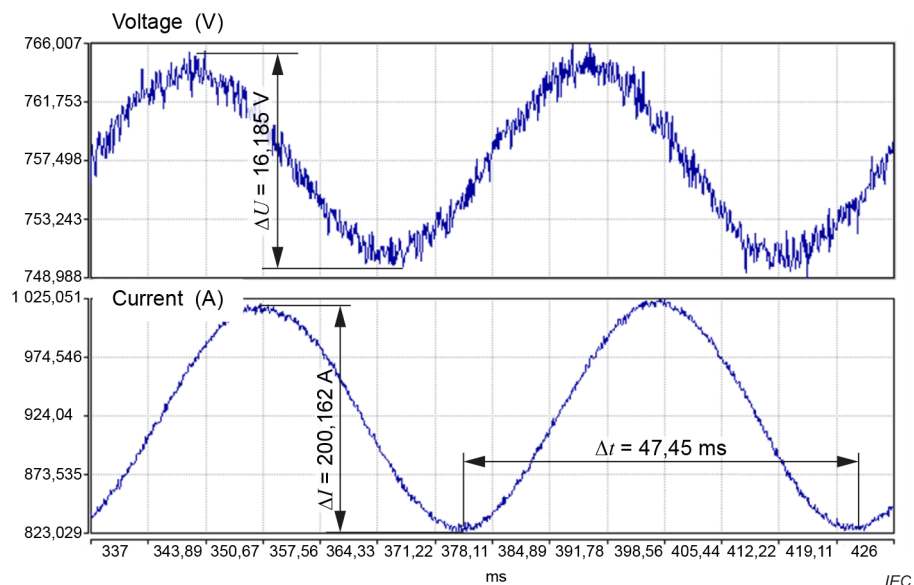
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702 **Figure 4 – Relationships between voltage band and power quality in LVDC systems**

703 6.3 Relationship between oscillation and power quality in LVDC systems

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

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



711

712

Figure 5 – Oscillation example

713 Figure 5 shows that an oscillation with a frequency of about 153 Hz occurs in the system, the
 714 voltage oscillation amplitude is about 1 kV, the current oscillation amplitude is about 47 A, and
 715 the oscillation amplitude is divergent. Finally, the system protection acts and stops the
 716 oscillation.

717 See Annex B for details on the oscillation characteristics.

718 The oscillation phenomenon is closely related to the load.

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

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

725 **6.4 Supply voltage deviation**

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

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

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

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

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

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

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

752 **6.5 Ripple and high frequency interference**

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

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

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

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

773 a) low-frequency interference:

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

777 b) switching interference:

778 power converters switching frequency and its harmonics;

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

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

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

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

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

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

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

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

804 **6.6 Voltage swell**

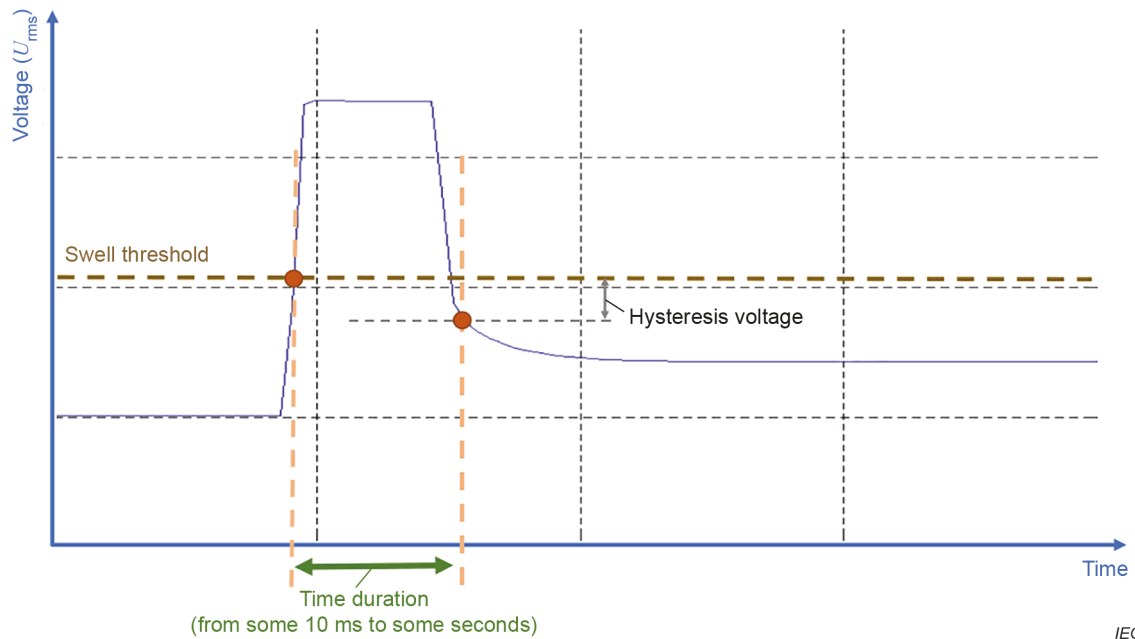
805 Voltage swell phenomena can frequently occur, but it is unpredictable and random. Depending
806 on the magnitude and duration, voltage swell can affect different types of loads differently for
807 the same voltage swell event. Recommended limitations of voltage swells A4 and A5 in Figure 3
808 are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

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

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

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

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



820

821

Figure 6 – Voltage swell example

822 6.7 Voltage dip

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

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

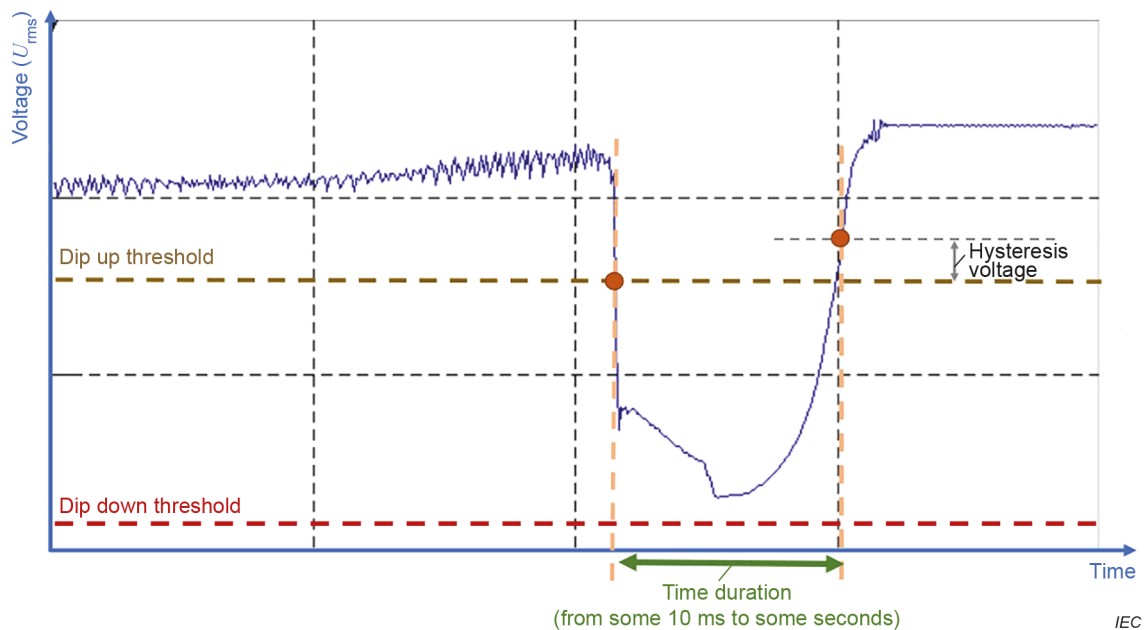
830 For DC measurements, the number of equipment affected in each event can be detected and
 831 stored for more information.

832 Generally, according to the network user connection, or the concrete situation, line-to-line, line-
 833 to-earth and line-to-midpoint voltages are considered.

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

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

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



848

849

Figure 7 – Voltage dip example

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

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

860 **6.8 Voltage supply interruption**

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

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

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

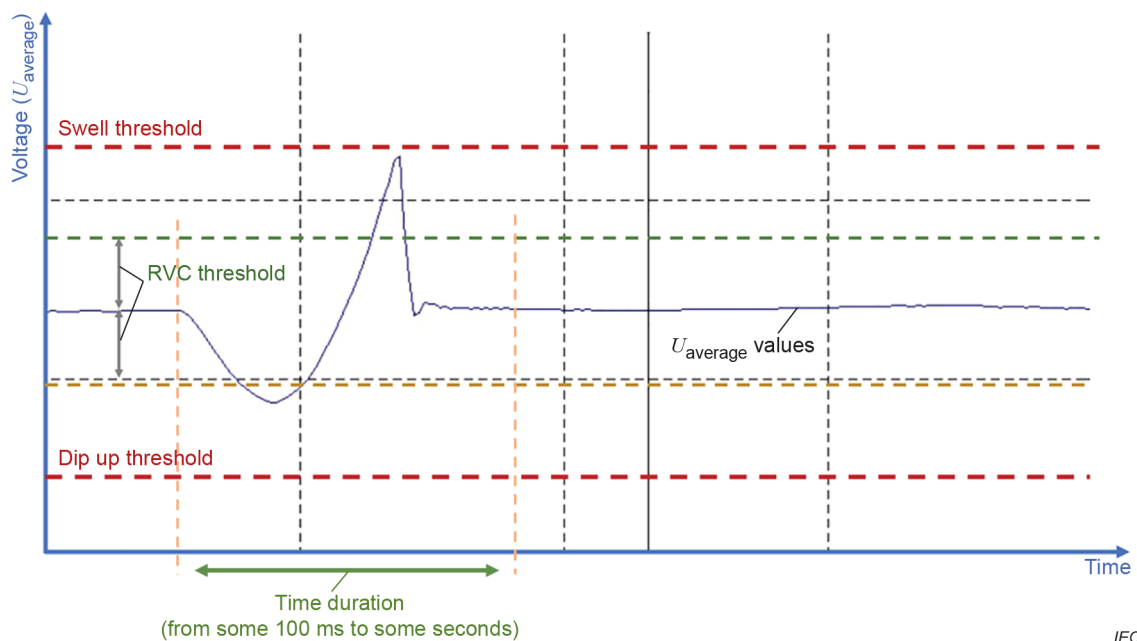
866 **6.9 Rapid voltage change (RVC)**

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

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

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

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



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

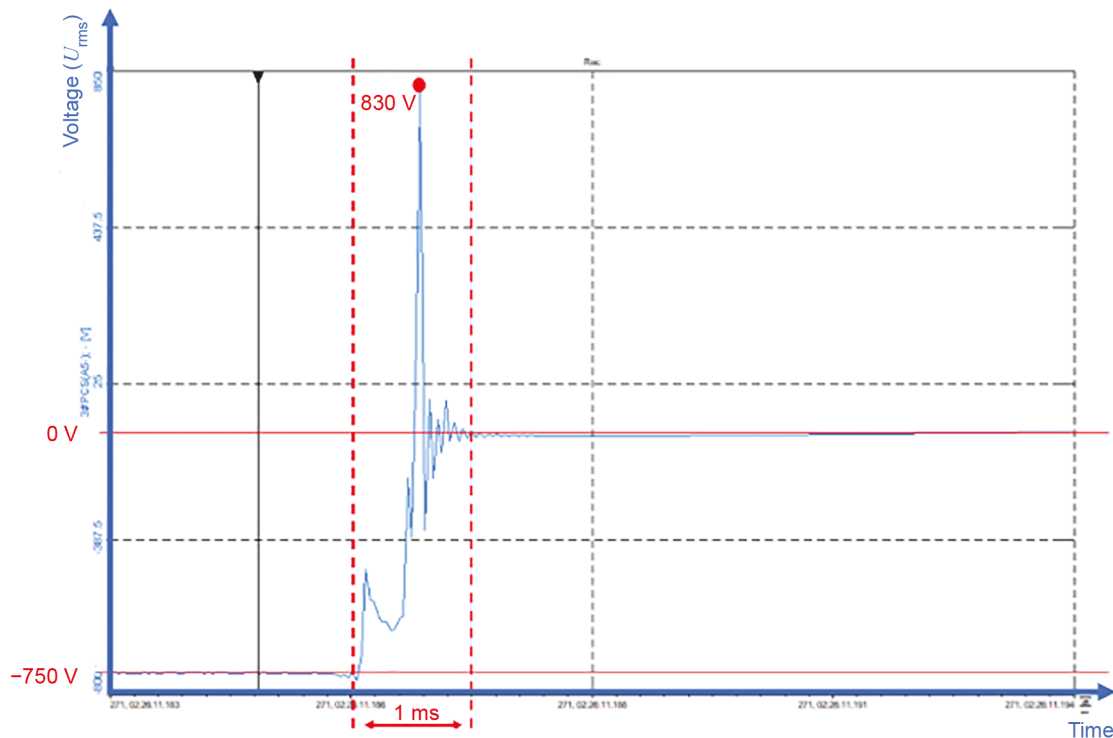
878

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

881 6.10 Voltage surges

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

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



886

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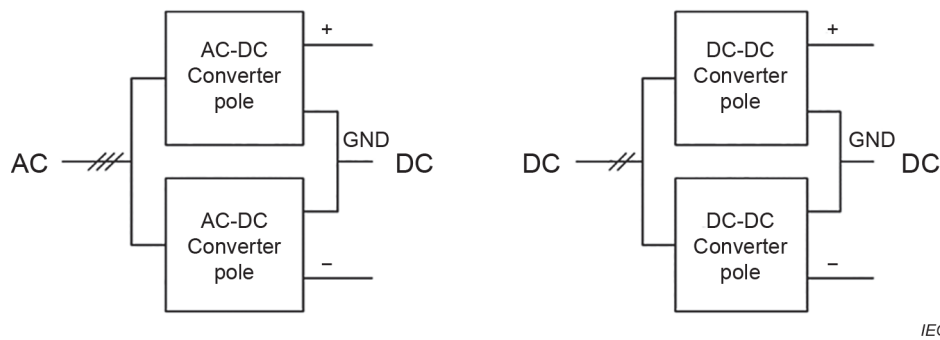
Figure 9 – Example of voltage surge

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

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

901 **6.11 Voltage unbalance**

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



907

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

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

916 7 Guidance for voltages and power quality in LVDC system

917 7.1 Considerations for voltages in distribution DC networks

918 7.1.1 General

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

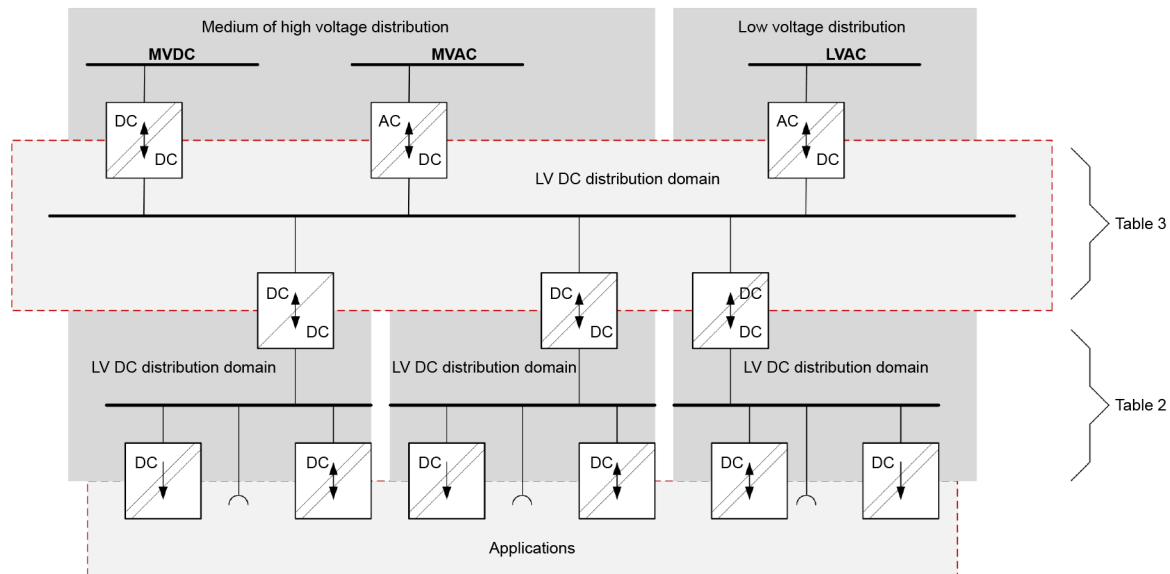
922 NOTE Information on preferred voltage values in different countries are provided in Annex I.

923 7.1.2 Factors considered to define voltage values

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

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

940 Finally, two different tables of DC voltages are proposed:



941

IEC

942 **Figure 11 – LVDC distribution domain and installation domain**

943 – one for distribution domain:

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

946 – one for installation domain:

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

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

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

952 **Table 1 – Voltage between lines (unipolar systems) or line and midpoint (bipolar
953 systems) for installation domain**

Nominal U (system)	U_1	U_2	U_3	U_4	U_5	U_6
Rated U (equipment)	V	V	V	V	V	V
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.

954

955
956**Table 2 – Voltage between lines (unipolar systems) or line and midpoint (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_4 V	U_5 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.

957

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

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

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

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

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

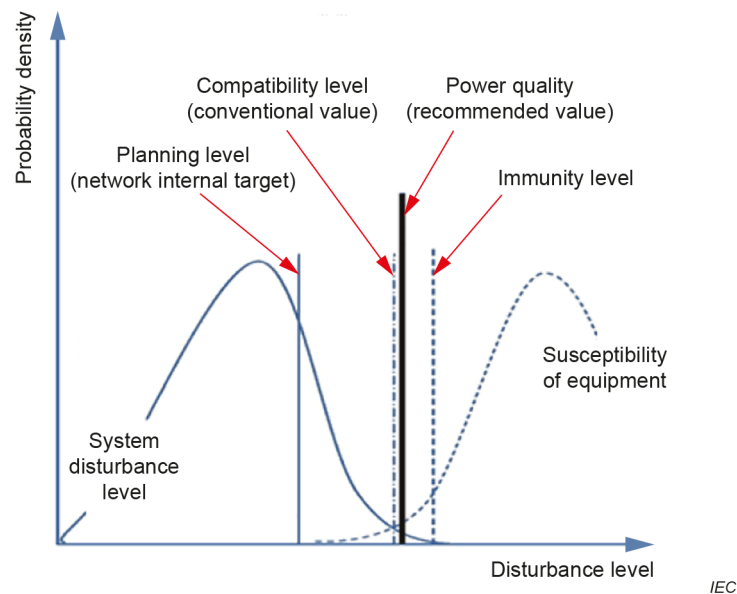
980 7.1.3 DC voltages

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

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

988 7.2 EMC, compatibility and testing of equipment

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



994

IEC

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

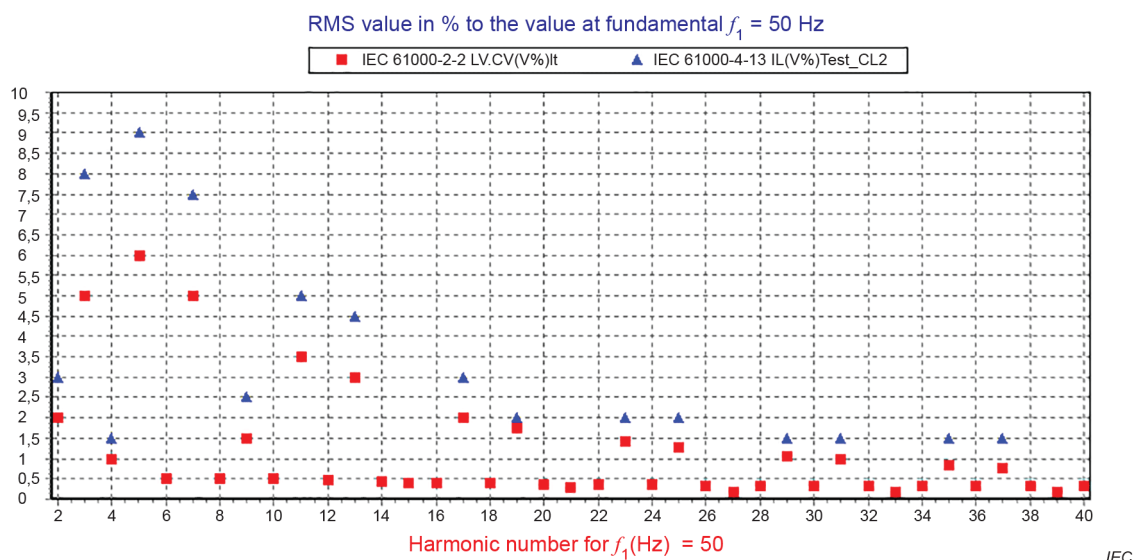
996 Power quality requirements are consistent with EMC conceptions. As described in EN 50160
 997 and IEC TS 62749 for AC, they are usually identical or close to compatibility levels for the
 998 related phenomena (see Figure 12).

999 Existing standards dealing with EMC emission and EMC immunity levels can be adapted in the
 1000 context of LVDC distribution (refer to IEC 61000-2-2:2002, IEC 61000-2-12:2003,
 1001 IEC 61000-2-4:2002, IEC 61000-4-13:2002, IEC 61000-4-19:2014, IEC 61000-4-17:2009,
 1002 IEC 61000-4-29:2000, CISPR 16-2-1:2014, CISPR 16-2-1:2014/AMD1:2017 and
 1003 CISPR 16-3:2020).

1004 NOTE IEC 61000-6-1 and 61000-6-2 (generic immunity standards) cover high frequency phenomena for DC input
 1005 output power ports.

1006 For LVDC application, joint work is expected to be carried out in order to review whether
 1007 environments defined for AC (e.g. public, residential, commercial and light industry/industrial
 1008 environments) are relevant for establishing DC compatibility levels. Then compatibility levels
 1009 will be specified for each LVDC phenomenon as reference benchmark for defining EMC and
 1010 power quality requirements (coordination of emission and immunity levels, see Table 3, Table 4
 1011 and Table 5 for some existing levels).

1012 Example for steady state phenomena < 2 kHz: Figure 13 illustrates the existing LVAC voltage
 1013 compatibility and immunity levels (for class 2 of IEC 61000-4-13):



1014

1015

Figure 13 – LVAC voltage compatibility and immunity levels

1016 Concerning the phenomena 2 kHz to 150 kHz in LVAC systems, relevant compatibility levels
 1017 are illustrated in Annex D (Figure D.7). Therefore, the definition of relevant emission and
 1018 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

1020

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	%	

1021

1022
1023**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	±2	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 AM (1 kHz)	10	V	
		80	%	

1024

1025

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	IEC 61000-4-17
		2	5	
		3	10	
		4	15	
		x	x	

1026

1027 IEC 61000-4-17:1999 gives the immunity test method of DC ripple in peak-peak values, but the
 1028 test procedure mentioned does not apply to equipment connected to battery charger systems
 1029 incorporating switch mode converters. In the new DC distribution system, almost all converters
 1030 are controlled in switch mode. This document needs to be completed or replaced.

1031 Therefore, one of the missing blocks in the standardization context is the assessment of EMC
 1032 immunity and allowed emission levels of mass LVDC power electronic devices. This step is
 1033 done in coordination with future definition of DC compatibility levels.

1034 7.3 Considerations for DC power quality

1035 The recommendations of some DC power quality measurement methods and indices are mainly
 1036 derived from existing AC power quality methodologies. The main reasons are to:

- 1037 – start DC power quality assessment with acquired know-how on AC power quality such as
 1038 frequency bands and measurement window lengths,
- 1039 – try to convert existing PQ monitoring technologies,
- 1040 – adapt simulation tools for DC grid PQ assessment.

1041 This is just first step and with arising development of DC applications, evolution of DC PQ
1042 assessment method will continue. The following DC power quality indices are proposed for
1043 future DC system:

- 1044 – Peak-peak ripple: under a given sampling frequency, it is the maximum difference between
1045 max RMS value and min RMS value during a given measurement duration ($T_w = 20$ ms for
1046 example) divided by DC component. The RMS values are computed during integration
1047 duration ($T_i = 200$ ms, 1 min, or 10 min for example).
- 1048 – Distortion in a DC system: DC distortion is defined as total RMS value of all alternating
1049 voltage components on the DC voltage during T_w .
- 1050 – DC RMS ripple or distortion factor. DC distortion factor is the ratio of the DC distortion to
1051 the mean DC voltage during T_w .
- 1052 – Ripple spectrum or distortion spectrum. The distortion spectrum quantifies AC components
1053 in terms of the amplitude and phase of each frequency component. The distortion spectrum
1054 includes the components resulting from amplitude and frequency modulation as well as AC
1055 components of the waveform, i.e., everything except the DC component.
- 1056 – RMS ripple (or integral value, or spectral energy) is measured in each frequency band of
1057 interest with adequate time and frequency resolutions. According to frequency ranges,
1058 measurement methods can be different (refer to IEC 61000-4-30:2015,
1059 IEC 61000-4-15:2010, IEC 61000-4-7:2002, CISPR 16-2-1:2014,
1060 CISPR 16-2-1:2014/AMD1:2017 and CISPR 16-3:2020).

1061 Joint work could be done in IEC technology committees and subcommittees in order to define
1062 DC power quality assessment methods, compatibility level, immunity level and emission level.

- 1063 – To finalize DC ripple indicator (DC distortion, ripple distortion and ripple spectrum),
1064 particular attention is paid on choosing aggregation time interval and sampling frequency.
- 1065 – To determine whether to use the RMS or averaging operator for assessing voltage dips and
1066 swells in LVDC systems, along with specifying the appropriate aggregation time interval.
1067 Current aggregation time intervals for AC systems can be inadequate to detect power quality
1068 deviations. The adequate averaging operator can be used.

1069 As for AC, power quality requirements in LVDC systems require coordination with the
1070 compatibility level (conventional value) and immunity level (protection) of equipment.

1071 Some existing standards which have already given some recommended values for the PQ
1072 indexes in LVDC distribution or equipment could be taken into account in the context of LVDC
1073 systems:

- 1074 – IEC 60092-101,
- 1075 – IEC 61000-4-29,
- 1076 – IEC 61204-3.

1077 **7.4 Measurement methods**

1078 **7.4.1 General**

1079 Most of the voltages stated in the document are DC values with AC components during a given
1080 time. DC RMS value is computed by the same formulas as in an AC system (see Annex D for
1081 detailed explanations).

1082 **7.4.2 DC system electric value integration time**

1083 The integration time or measurement window length of DC system RMS values and power
1084 quality indices are defined according to the power quality domain; it can be for example the
1085 following:

- 1086 – 200 ms and 10 min values can be used for continuous phenomena such as DC ripple,
1087 unbalance;
- 1088 – half cycle RMS can be used for transient values such as voltage dip/surge, in line with most
1089 existing UVRT (under voltage ride-through) curves.

1090 **7.4.3 Frequency ranges of ripple spectral analysis**

1091 At present stage for total DC distortion assessment and DC ripple spectral analysis, two
1092 frequency ranges can be for example:

- 1093 – The 0 kHz to 9 kHz range, referred to low frequency conducted disturbances of AC system,
1094 quantified with IEC methods (refer to IEC 61000-4-30:2015, IEC 61000-4-15:2010).
- 1095 – The > 9 kHz range, referred to conducted disturbances of AC system, quantified with
1096 quasi peak detector according to the specific testing environment requirements.

1097 **7.4.4 DC power quality measurement methods**

1098 For DC power supply systems, it is referred to IEC 61000-4-30. Further work is necessary to fill
1099 in the gap of DC power quality measurement methods in this and other relevant documents
1100 such as 61000-4-7 and 61000-4-15.

1101 **7.4.5 DC system electric power measurements**

1102 As analysis in Clause D.5 shows, in a DC system with ripples, three types of powers
1103 components can co-exist: active power, reactive power and distortion power. Apparent power
1104 is the key parameter to quantify supply capacity and active power is for metering system.

1105 Total active electric power P_{total} at a metering point includes AC and DC power components:

$$1106 \quad P_{\text{total}} = P_{\text{DC}} + P_{\text{AC}}$$

1107 **7.5 DC power quality standardization framework**

1108 DC power quality standardization contains:

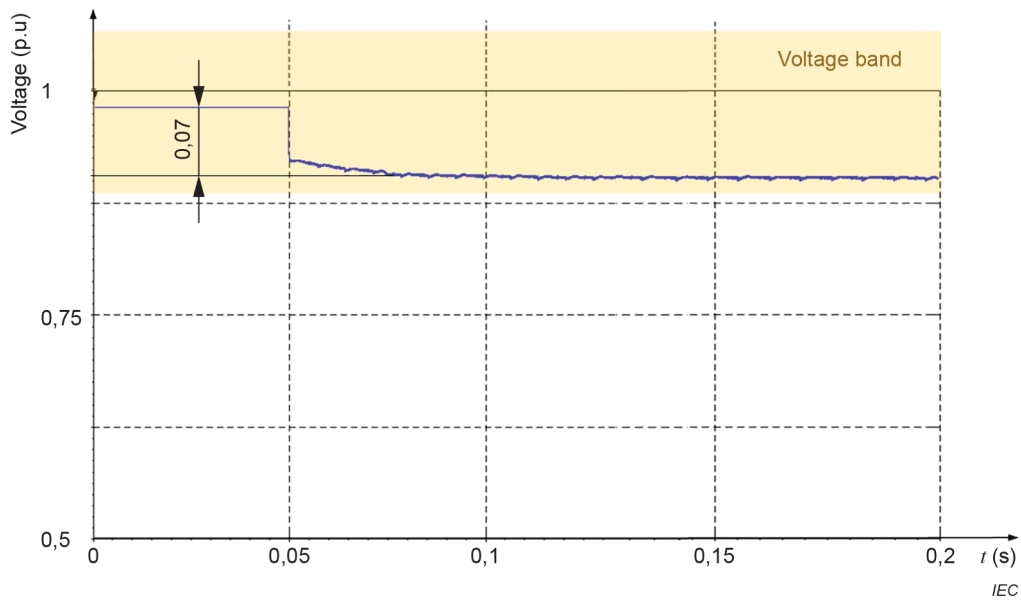
- 1109 – DC power quality terms. The specific terms in LVDC power quality need to be further
1110 optimized and defined.
- 1111 – Measurement. The specific measurement in LVDC power quality is surveyed in a separate
1112 project.
- 1113 – Index and recommendation. The power quality indices and recommendations in LVDC are
1114 different from AC systems. This needs to be surveyed in a separate project. It is the key in
1115 the LVDC power quality standardization.
- 1116 – DC power quality assessment. Based on the power quality index and recommendation in
1117 LVDC, assessment is the application of power quality data. The standardization in
1118 assessment will guide the LVDC power quality management and fieldwork.

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Annex A
(informative)

PQ waveforms collected from a certain LVDC project

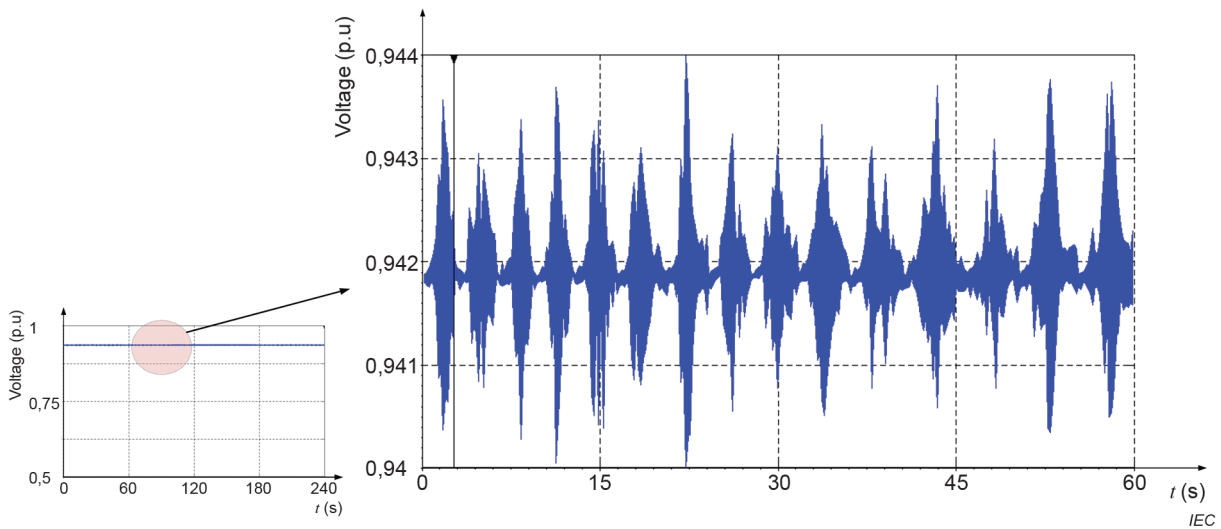
1123 Suitable PQ waveforms could be obtained from the operating projects. As supplementary
1124 information, Figure A.1 to Figure A.3 are parts of the waveforms corresponding to some PQ
1125 phenomena captured from an existing ± 750 V/ ± 375 V LVDC system in Tongli, China.



1126

1127

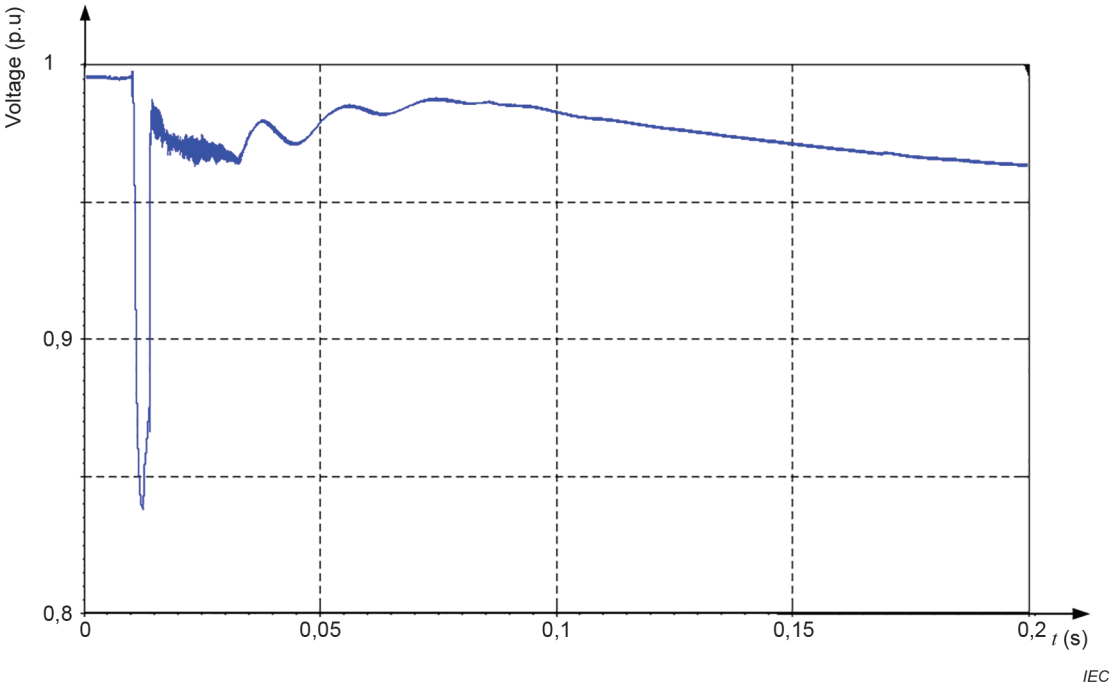
Figure A.1 – Voltage deviation caused by load switching



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Figure A.2 – Voltage ripple in steady state



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1131

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

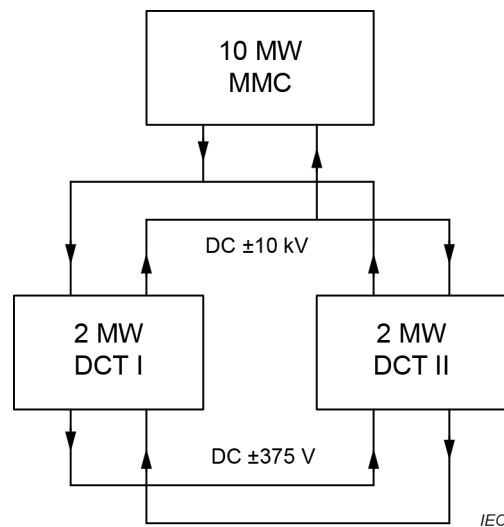
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Annex B (informative)

A LVDC oscillation typical example

1136 As an example of a LVDC oscillation, the scenario happened in an MV&LVDC system in China.
1137 During the commission process of the substation, the oscillation happened on a ± 375 V DC bus.
1138 Figure B.1 shows the equivalent topology of the whole system.

1139 DC transformer (DCT) I controls the power transmission, and the rated capacity is 2 MW. DC
1140 transformer II controls the DC voltage of ± 375 V and the rated capacity is 700 kW. The power
1141 flows between DCT I and DCT II.

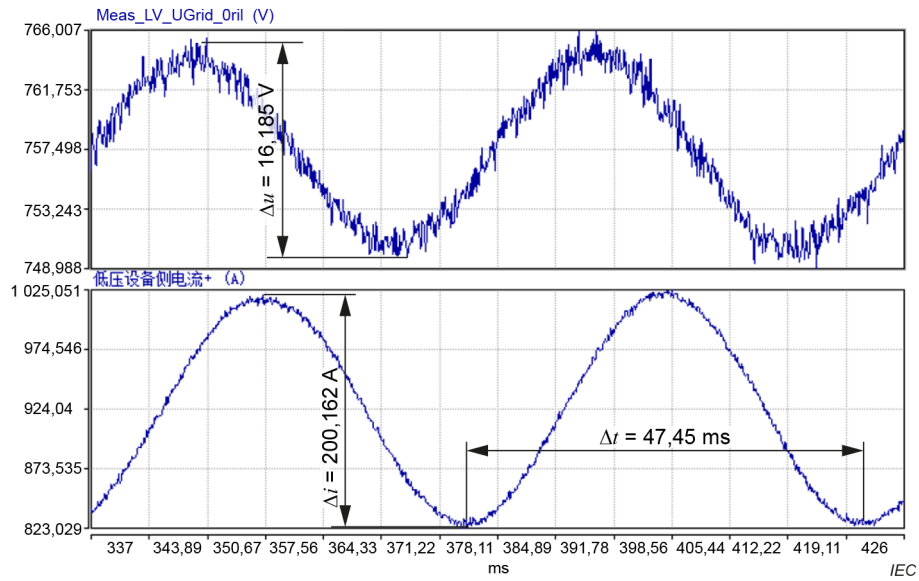


1142

1143

Figure B.1 – Equivalent topology of the substation

1144 Figure B.2 shows the oscillation waveform. The oscillation occurs at 21 Hz when the transmitted
1145 power increased from 500 kW to 700 kW. Voltage on the ± 375 V bus is changed around 748 V
1146 ~ 766 V. Current is changed around 823 A ~ 1 025 A. Power is changed around
1147 80,55 kW ~ 622,08 kW. The oscillation continues for 2,23 s and then overvoltage protection of
1148 the system acts and stops the oscillation.



1149

1150

Figure B.2 – The voltage and current oscillation waveform on $\pm 375 \text{ V}$ bus

1151 The oscillation is caused by the effect of negative input impedance. The oscillation could be
1152 avoided by optimizing the control parameter of the two DCTs to improve the system stability.

1153
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Annex C (informative)

Supply radius in DC distribution systems

1157 Supply radius calculation in DC distribution systems considers voltage level, conductor nominal
1158 section, maximum long-term operating temperature and other factors. The supply radius
1159 calculation of the DC distribution system is based on the content of voltage deviation in different
1160 voltage levels in Clause 7. Considering that the conductor temperature and the DC resistance
1161 of overhead lines increasing with the growing transmission current, the supply radius of all
1162 typical nominal sections at operating temperature of 70 °C in a DC distribution system is
1163 calculated based on the unit DC resistance of the overhead line conductor at 20 °C. The results
1164 of the load distance in different voltage levels are shown in Table C.1, Table C.2 (based on the
1165 preferred DC voltages in China).

1166 **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.

1167

1168 **Table C.2 – 750 (±375) V, 220 (±110) V typical section supply radius**
1169 **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.

1170

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1174

Annex D (informative)

Electric power and power quality computation in DC system

1175 D.1 DC mean and RMS values of voltage or current

1176 The mean value is usually used in DC electric systems to quantify voltage, current or power
1177 during a given period T , i.e., a measurement window's length:

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

1178

1179 More generally, the DC root mean square value (RMS) value is used to quantify all DC and AC
1180 components. It is the total RMS value of the DC component (or mean value) and RMS value of
1181 all AC components in a given measurement window's length T , i.e.:

1182 In the time domain, computation of the RMS value is identical in both DC and AC systems during
1183 the given measurement window:

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

1184

1185 In the frequency domain with FFT or DFT transforms, the DC RMS value is computed with the
1186 same formula as for AC systems during the given measurement window:

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

1187

1188 where

1189 T is measurement window's length;

1190 n is half of the sampling points during the given window FFT or DFT;

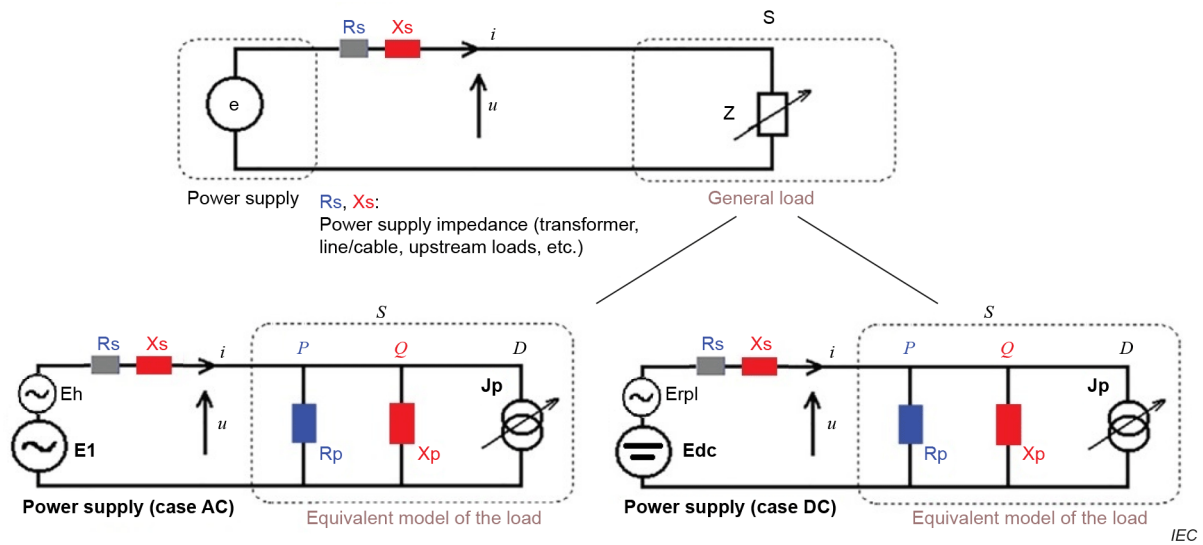
1191 V_k is the RMS value at index k , i.e. at frequency $k \times f_w$;

1192 f_w is the window frequency referred to the width of the Fourier transform window;

1193 $k = 0$ is the DC component.

1194 D.2 General electric power system: decomposition of a general electric load

1195 In an electric power system, an electric load can call different types of currents from power grid:
1196 DC current, sinusoidal current with different phase angles, and non-sinusoidal currents. In a
1197 general case, load consumption can be represented by linear and nonlinear components
1198 referred to different electric powers (see Figure D.1). From these decomposed equivalent
1199 circuits, it is observed that there is no important methodological difference in dealing with AC
1200 or DC power quality issues.



1201

1202 **Key**

- 1203 E1 fundamental voltage source of AC case
- 1204 R_s, X_s and E_h upstream grid equivalent model with frequency-dependent resistance, reactance and background disturbance voltages
- 1205
- 1206 E_{dc}, E_{rpl} DC voltage source and ripple component of DC case
- 1207 R_p, X_p and J_p frequency-dependent resistance, reactance and disturbance current injection
- 1208 S apparent power
- 1209 P active power
- 1210 Q reactive power
- 1211 D distortion power resulted from deformation of voltage and current

1212

Figure D.1 – Equivalent model of a general electric load1213 **D.3 Computation of electric powers and PQ indices**1214 **D.3.1 Computation of electric values in time domain**

1215 The instantaneous active power is defined by the multiplication of voltage and current in
1216 sampled values:

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

1217

1218 The mean value of active power P is computed by integration of the instantaneous power p
1219 during the pre-defined analysis period T :

$$P = \frac{1}{T} \int_0^T p(t) dt = \frac{1}{T} \int_0^T u(t) \times i(t) dt \quad (\text{D.5})$$

1220

1221 In the above formula, DC components are included.

1222 In simplified computation system, DC power can be measured with mean values of voltage and
1223 current:

$$P = V_{\text{mean}} \times I_{\text{mean}} \quad (\text{D.6})$$

1224

1225 In the above simplified formula, influence of AC components is neglected. If AC components
1226 are not negligible, Formula (D.5) is used to compute true active power.

1227 RMS values of voltage U and current I :

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

1228

1229 If waveforms U and I are sinusoidal: $P = I \times U \times \cos(\phi)$

1230 **D.3.2 Computation of electric values in frequency domain**

1231 Generally, in electric power system monitoring, electrical values such as voltage and current
1232 are sampled in the analogical time domain, by means of a Fourier transform within a defined
1233 window length; they are decomposed into frequency domain values as DC components and AC
1234 components (magnitude and phase):

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

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

1235

1236 where

1237 n is the maximal harmonic referred to measurement window frequency f_1 ;

1238 f_1 is the measurement window frequency, $\omega = 2\pi f_1$;

1239 U_0, I_0 are the DC components;

1240 U_k, I_k are the AC components ($k > 0$) in RMS values.

1241 Relevant electrical values can be computed with frequency domain components:

1242 Root mean square values or RMS values:

$$U = \sqrt{U_0^2 + U_1^2 + U_2^2 + U_3^2 + U_4^2 + \dots + U_n^2} = \sqrt{\sum_{k=0}^n U_k^2} \quad (\text{D.10})$$

$$I = \sqrt{I_0^2 + I_1^2 + I_2^2 + I_3^2 + I_4^2 + \dots + I_n^2} = \sqrt{\sum_{k=0}^n I_k^2} \quad (\text{D.11})$$

1243

1244 Electric powers of single-phase system:

$$S = U \times I \quad (\text{D.12})$$

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

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

$$D = \sqrt{S^2 - P^2 - Q^2} \quad (\text{D.15})$$

1245

1246 where

1247 ϕ_k is the phase angle difference between voltage and current at frequency $f = k f_1$ ($k > 0$)

1248 ϕ_0 is either 0 or π .

1249 The above active power formula gives exact power values even if AC components exist. In a
1250 simplified or economical way, it is possible to measure only DC power by mean values of voltage
1251 and current:

$$P_{\text{DC}} = U_{\text{DC}} \times I_{\text{DC}} \quad (\text{D.16})$$

1252

1253 **D.3.3 Total harmonic distortion T_{hd} used in AC system**

1254 Based on the frequency domain decomposition, the total harmonic distortion can be computed:

1255 Total voltage harmonic distortion:

$$T_{\text{dh}_U} = \frac{1}{U_1} \sqrt{U_2^2 + U_3^2 + U_4^2 + \dots + U_n^2} \times 100\% \quad (\text{D.17})$$

1256

1257 Total current harmonic distortion:

$$T_{\text{dh}_I} = \frac{1}{I_1} \sqrt{I_2^2 + I_3^2 + I_4^2 + \dots + I_n^2} \times 100\% \quad (\text{D.18})$$

1258

1259 In a pure sine wave system or in a pure DC system: $T_{\text{dh}} = 0$.

1260 According to IEC definitions, the total harmonic distortion for AC systems is computed up to
1261 harmonic number 40 or 50 (2 000 Hz or 2 500 Hz) depending on the countries. In Europe,
1262 harmonic frequency ends at 2 kHz.

1263 If the frequency range of the above formulas exceeds 2 kHz, it can be called as total distortion
1264 T_d instead of T_{hd} , so $T_d \geq T_{hd}$.

1265 Computation of other power quality indices: see IEC 61000-4-30 for AC systems.

1266 In a DC system, T_{dh} can be represented by the RMS ripple value, i.e. I_1 or U_1 are replaced by
1267 a mean DC component value during the measurement period. In fact, harmonic in DC system
1268 is not a correct term as the fundamental frequency does not exist, see Clause D.6 for ripple
1269 computations.

1270 **D.3.4 The relation of different electric powers**

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

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

1271

1272 Power factor is generally computed as:

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

1273

1274 In a pure sinusoidal system ($D = 0$), λ becomes:

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

1275 where

1276 ϕ is the phase angle difference between voltage and current at fundamental frequency.

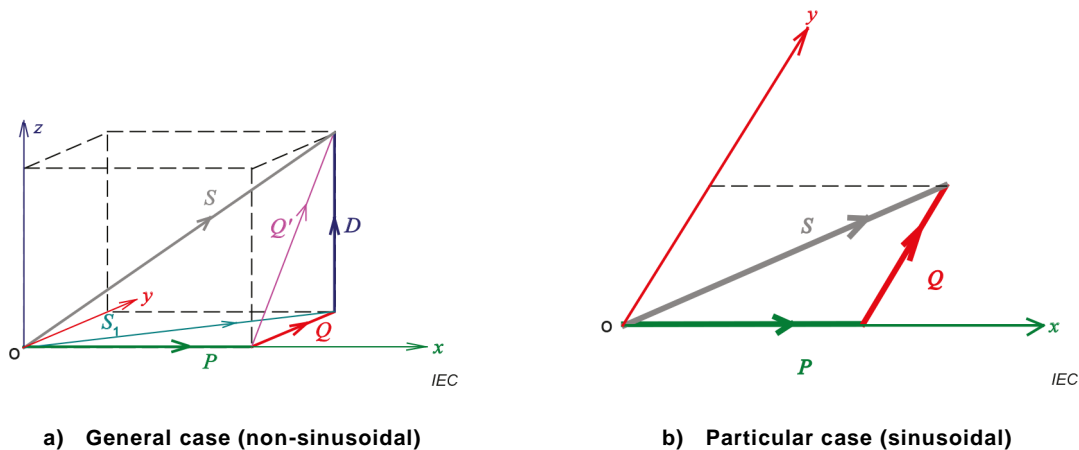
1277 The values of $\cos(\phi)$ and $\tan(\phi)$ are computed only by phase angle between voltage and
1278 current at fundamental frequency.

1279 In a non-sinusoidal system, the power factor λ takes into account both reactive power Q and
1280 distortion power D , but the terms $\cos(\phi)$ and $\tan(\phi)$ take into account only the reactive power
1281 at fundamental frequency.

1282 In DC systems, $\cos(\phi)$ and $\tan(\phi)$ cannot be significant because reactive power is near zero.
1283 Furthermore, S , P , D , P_f remain useful and are physically significant. D quantifies the existence
1284 of distortion power and P_f indicates the performance of a load, i.e., if P_f is near to 1, the load is
1285 grid-friendly in both AC and DC systems.

1286 **D.4 Representation of electric powers in AC system**

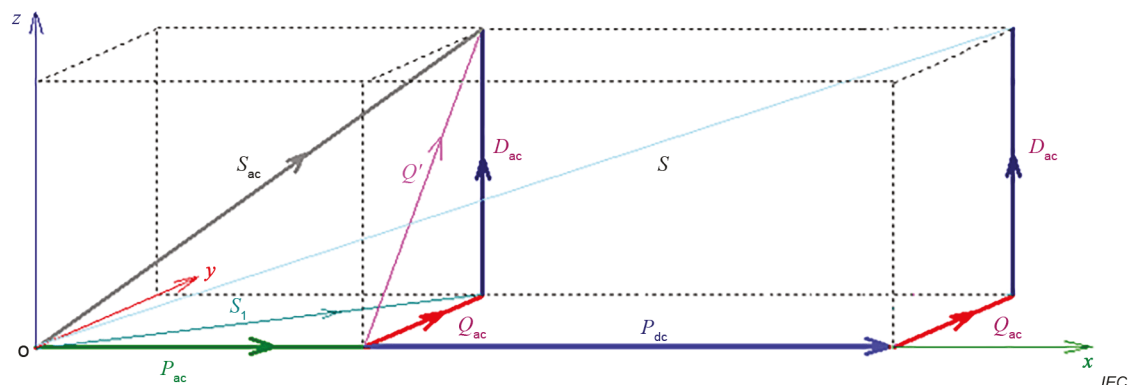
1287 These different powers can be represented by an equivalent 3D vector diagram. See Figure D.2.



1288 **Figure D.2 – Representation of electric powers in AC system**

1289 **D.5 Representation of electric powers in DC system**

1290 In a DC system with the presence of AC components (or disturbances in voltages and currents),
1291 the different electric parameters can be also represented by 3D vector diagram (see Figure D.3):



1292 **Figure D.3 – Representation of electric powers in DC system**

1294 The powers Q , D are only computed with AC components. Active power P_{AC} is resulted from
1295 the AC voltages and currents, and P_{DC} is resulted from of DC components.

1296 In a pure AC system, $P_{DC} = 0$.

1297 In a pure DC system, $D = 0$, $Q = 0$, $P_{AC} = 0$.

1298 In a DC system with ripples, total electric power at a metering point $P_{total} = P_{DC} + P_{AC}$. This
1299 could be considered in future DC metering systems.

1300 Remark:

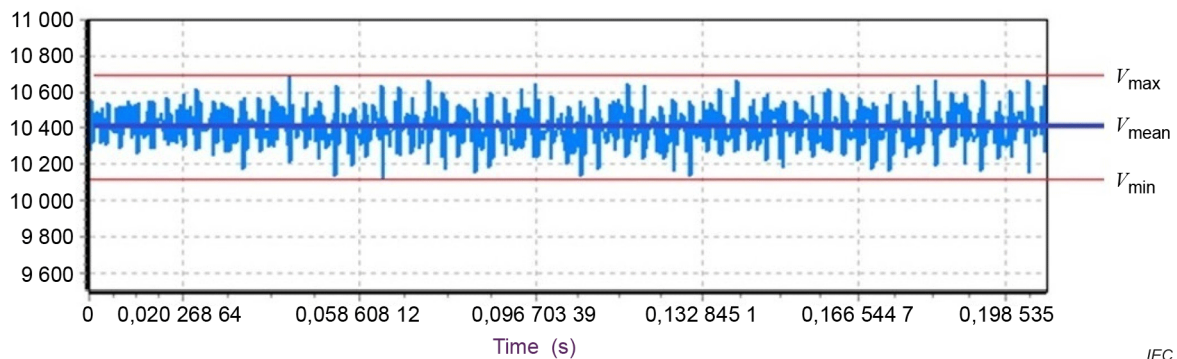
1301 A DC system with the presence of AC components represents theoretically the general electric
1302 power system, that is to say, in a DC system, some power quality issues can exist as well as in
1303 AC system. In so-called today's world-widely used AC power system, the DC components are
1304 very small and just considered as negligible.

- 1305 – General case of electric power system: presence of DC + AC components;
- 1306 – AC power system is a particular case: DC component is considered as negligible.

1307 D.6 Power quality indices in DC system

1308 D.6.1 General

1309 The DC value can include ripples (or AC components) (see Figure D.4):



1310

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1311 **Figure D.4 – Ripples of output DC voltage of positive of a PWM AC/DC converter**

1312 D.6.2 DC peak-peak ripples

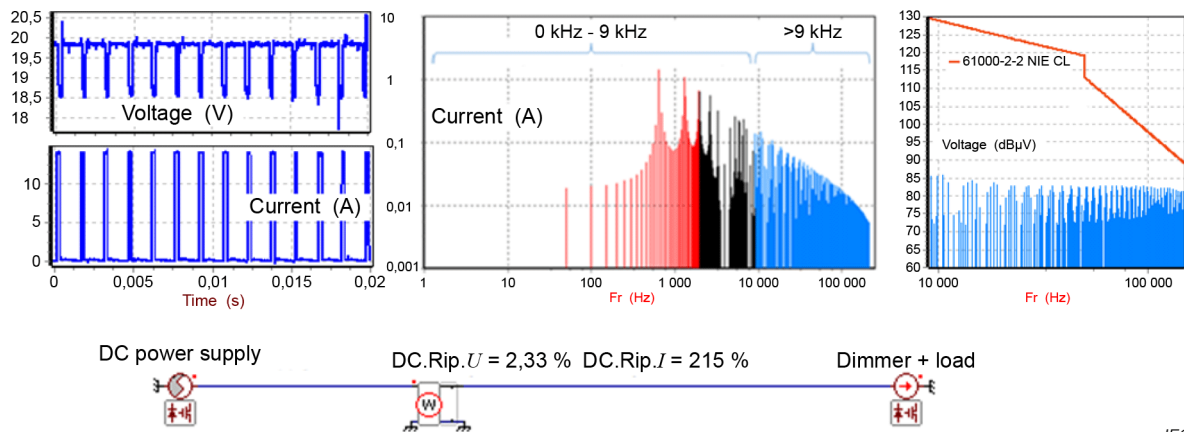
1313 For general DC power supply, the following formula is used to quantify DC ripple peak-peak
1314 value of each measurement period. Peak-peak ripple is the maximum difference between max
1315 RMS value and min RMS value during T_w divided by DC component.

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

1316

1317 D.6.3 Ripple spectra

1318 Figure D.5 illustrates DC voltage and current waveforms measured at the input of a new LVDC
1319 load (electronic dimmer) and their FFT analysis. The spectra show that the load current contains
1320 a large range of spectra covering mainly from 100 Hz to 150 kHz. The potential impacts of these
1321 spectra of DC voltage are surely different in each range of frequencies because the impedances
1322 of DC power supply and distribution links are function of frequency as well. In this case,
1323 computed DC PQ indices are: RMS ripple is 2,33 % for DC voltage and 215 % for DC current
1324 in the range of frequency < 9 kHz. For information, the observed disturbance voltage level
1325 9 kHz to 150 kHz is about 86 dB μ V which is lower than the existing AC voltage compatibility
1326 level. Furthermore, the definition of EMC emission limits is documented in CISPR 11 (Industrial,
1327 scientific and medical equipment) and CISPR 15 (electrical lighting and similar equipment).



1328

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1329 **Figure D.5 – Spectral analysis of DC voltage and current measured at the input of an**
 1330 **electronic load**

1331 D.6.4 DC RMS ripple or ripple distortion

1332 Time domain computation with sampled values:

1333 RMS values:

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

1334

1335 DC values (or mean values):

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

1336

1337 where n_s is the sampled number during the observed period.

1338 DC ripple in RMS values:

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

1339

1340 DC ripple rates in %:

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

1341

1342 Frequency domain computation of DC power quality values with sampled values:

1343 Based on DFT or FFT analysis of DC signal (voltage or current) during specified period, DC
1344 electric parameters and power quality indices are computed:

1345 RMS

$$U = \sqrt{U_0^2 + U_1^2 + U_2^2 + U_3^2 + U_4^2 + \dots + U_m^2} \quad (\text{D.28})$$

$$I = \sqrt{I_0^2 + I_1^2 + I_2^2 + I_3^2 + I_4^2 + \dots + I_m^2} \quad (\text{D.29})$$

1346

1347 Ripple in RMS

$$U_{\text{rpl}} = \sqrt{U_0^2 + U_1^2 + U_2^2 + U_3^2 + U_4^2 + \dots + U_m^2} \quad (\text{D.30})$$

$$I_{\text{rpl}} = \sqrt{I_0^2 + I_1^2 + I_2^2 + I_3^2 + I_4^2 + \dots + I_m^2} \quad (\text{D.31})$$

1348

1349 Ripple distortion in %

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

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

1350

1351 Where m is the maximal harmonic referred to windows' frequency f_1 .

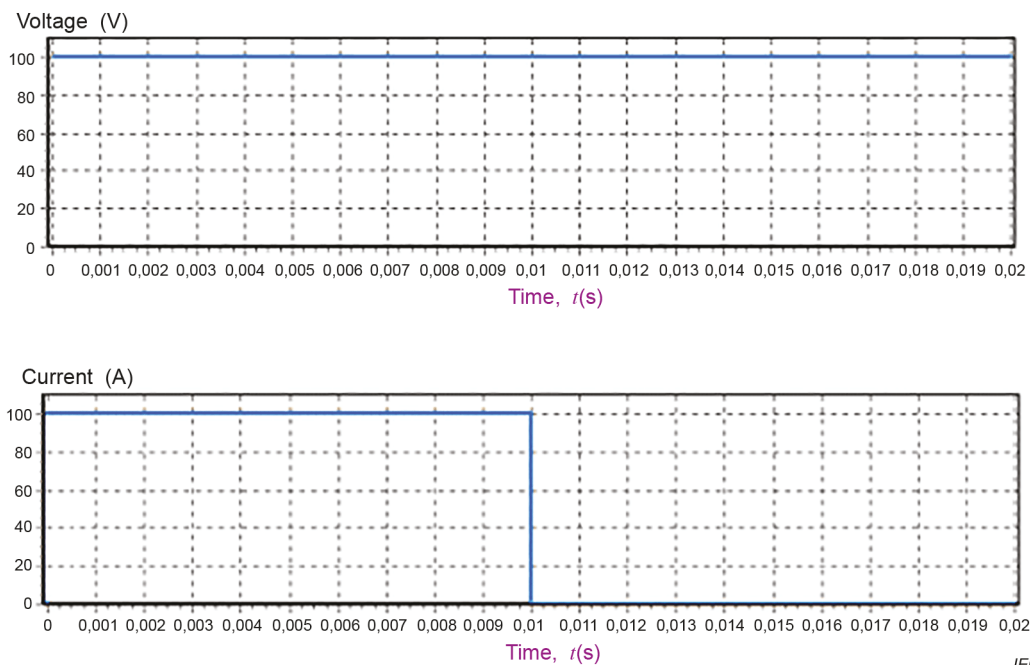
1352 The maximum measurement frequency f_m is defined in accordance with studied frequency
1353 domains. In compliance with on-going IEC EMC standards, f_m can be set as:

1354 – $f_m > 2$ kHz for harmonic frequency range defined by IEC;

1355 – $f_m > 150$ kHz for disturbances 2 kHz to 150 kHz.

1356 **D.7 Illustration example of distortion power in DC system**

1357 Computation of DC powers based on sampled values of U_{DC} and I_{DC} (512 points) during a
 1358 window of 20 ms (see Figure D.6, e.g. a repeatable load control). Even if the DC voltage is
 1359 almost perfect, distortion power exists:



1360 IEC

1361 **Figure D.6 – DC powers caused by intermittent DC current**

1362 With these voltage and current, different powers can be computed during 20 ms for a repeatable
 1363 load variation (just as an example, see computed electric values of this example in Table D.1):

1364 **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

1365

1366 **D.8 Main conclusions on electric value computation in DC system**

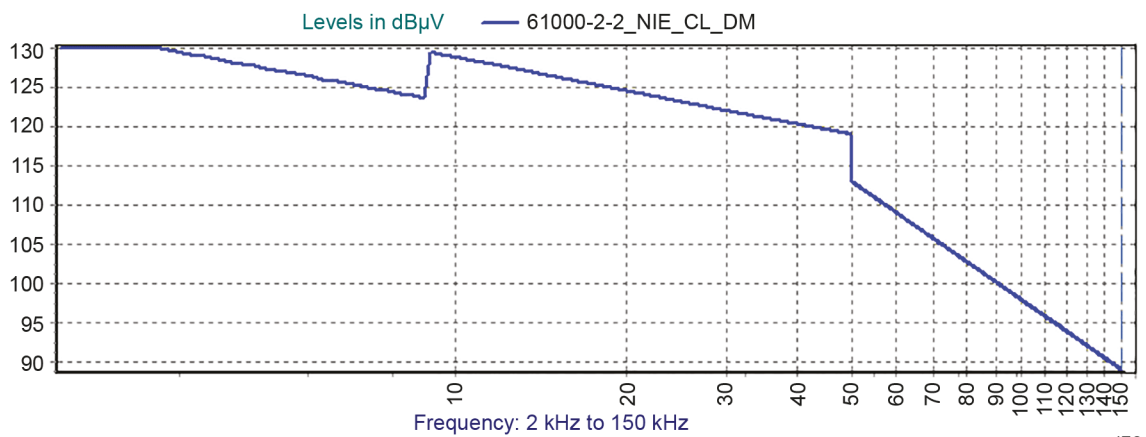
- 1367 – Active power is smaller than apparent power in a DC system if nonlinear load is connected.
 1368 – Reactive power can be very small in a DC system if the ripple of DC supply voltage is
 1369 negligible.
 1370 – Distortion power can be important in a DC system if a nonlinear load is connected. It is taken
 1371 into account in overall system design.
 1372 – Power factor P_F is taken into account in the DC load profile assessment.

- 1373 – DC system power quality mitigation: the key figure is to reduce as much as possible the
1374 distortion power (or increase P_F to 1) in order to increase the efficiency of DC power supply.

1375 D.9 Need of characteristics of DC voltage

1376 One of the key steps in assessing of DC power quality is to define characteristics of DC power
1377 supply voltage in public networks. Characteristics of DC voltage supply can be defined similar
1378 as follows:

- 1379 – For disturbance frequencies less than 2 kHz: IEC TS 62749 (EN 50160 as well) can be
1380 adapted to the relevant DC voltage ripple values.
- 1381 – Conducted disturbances levels 2 kHz to 150 kHz in LVAC network are defined based on the
1382 compatibility voltage levels of IEC 61000-2-2. They can be adapted in DC systems
1383 (Figure D.7 below illustrates LVAC compatibility voltage levels measured in differential
1384 mode values). For LVDC, the extension of power quality phenomena to the frequency range
1385 < 150 kHz is necessary because DC power sources and loads are almost all equipped with
1386 power electronic interfaces.



1387

1388

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

1389
1390
1391
1392

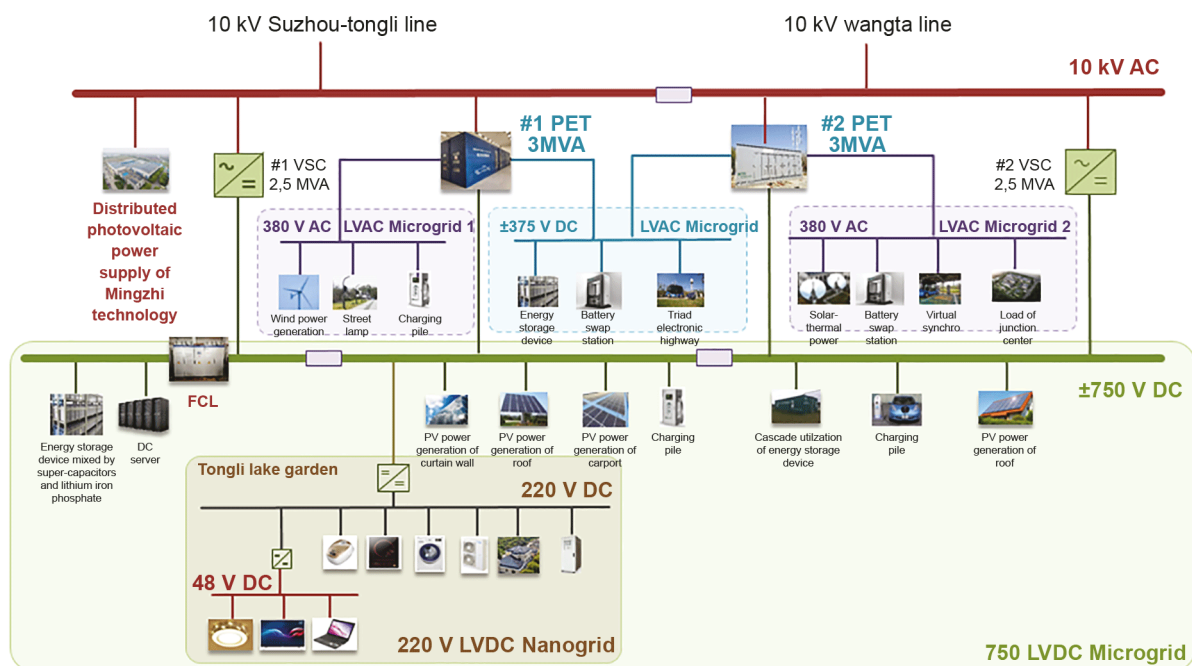
Annex E (informative)

District LVDC system demonstration project in Tongli, China

E.1 Project overview

1394 District LVDC system demonstration project in Tongli, China is composed of four different
1395 microgrids: ± 750 V LVDC, ± 375 V LVDC, 220 V LVDC and 380 V LVAC. It is sponsored by 2017
1396 National key research and development project of China. This project aims to distribute the use
1397 of green energy in high-penetration districts, explore the power supply mode of different
1398 applications, develop high-efficiency DC distribution equipment and introduce the construction
1399 mode of a low-energy DC building.

1400 As Figure E.1 shows, the above four microgrids are connected through power electronic
1401 transformers (PET), powered by a 10 kV AC line and can realize flexible power control and the
1402 interconnection and complementation of multiple energy sources.



1403

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1405 **Figure E.1 – Architecture of the district LVDC system in Tongli**

E.2 Voltage level selection principle

1407 Various types of sources and loads are connected to different voltage levels of the Tongli
1408 system. The selection principles are given as follows:

1409 Due to the adaptability of MPPT strategy range of PV string, the relatively long transmission
1410 distance and the large transmission capacity, the ± 750 V DC microgrid is connected to a
1411 2,9 MW PV power and energy storage.

1412 Similarly, the voltage between the poles of the ± 375 V LVDC grid is 750 V, which is connected
1413 to the energy storage equipment, battery swap station and electronic highway.

1414 Furthermore, there is a 220 V DC nanogrid connected to the bus of ± 750 V DC through a DC/DC
1415 converter, which provides the DC power for some home appliances in a residential community
1416 such as air conditioner, washing machine and some kitchen appliances. The reason for
1417 choosing 220 V DC as the voltage level is that there is a relatively complete supply chain
1418 foundation in the existing DC system of substation and data center. However, it could be noted
1419 that as in the tests and operations shown, the DC modified appliances can withstand higher
1420 voltage and have a correspondingly higher efficiency.

1421 As for the small household appliances whose power capacity is below 500 W, such as electric
1422 fans, air purifiers, etc., considering the safety and power supply radius, they are all powered by
1423 a 48 V DC bus which is connected to the 220 V nanogrid by a DC/DC converter.

1424 **E.3 System operation**

1425 The LVDC system in Tongli can operate in various modes according to the external power grid
1426 conditions. When the light intensity or/and energy storage capacity is sufficient, it can act as an
1427 active system and achieve self-sufficiency. The surplus power can be fed back to the external
1428 grid. When the PV power and energy storage is insufficient, the system can realize the optimal
1429 configuration by the control of PET. Besides, the system can be controlled in APF or STATCOM
1430 modes in different occasions to improve the power quality of AC power grid. Since its first
1431 operation in October, 2018, the Tongli LVDC system has been running stably for 18 months and
1432 provides valuable platform and data for the project team to study related technical problems of
1433 LVDC system.

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Annex F (informative)

A typical MV&LVDC distribution system in Wujiang, China

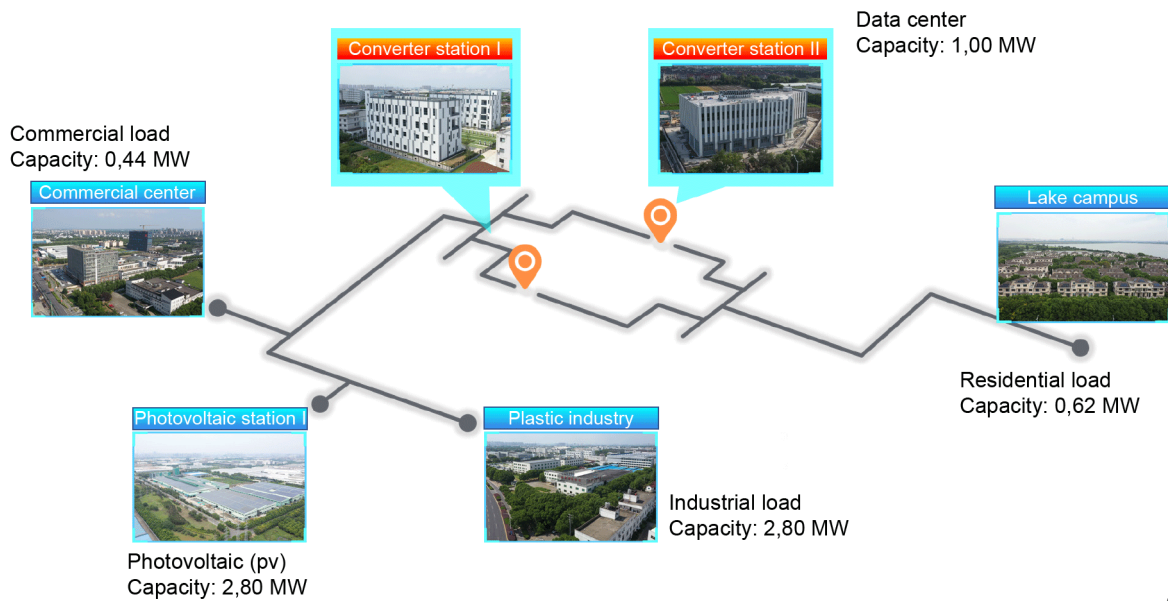
1438 F.1 Project overview

1439 A typical MV&LVDC project shown in Figure F.1 has been put into operation since June, 2021,
1440 which is located in Wujiang, China, in the developed Yangtze river delta with high load density.
1441 The capacity of this project is 20 MW, including 6,21 MW integrated PV generator. There are
1442 three stage of voltage levels in this system: ± 10 kV DC, ± 375 V DC and ± 48 V DC. The whole
1443 system supplies power to 10,54 MW of various kinds of loads, including resident load, data
1444 center, commercial load, industry load and charging station and provides electric energy for
1445 150 households. The project adopts the ring topology structure and develops a series of key
1446 MV&LVDC system components such as the DC transformer, the MVDC circuit breaker and the
1447 DC adapter. The whole system contains two 10 MW/ ± 10 kV AC/DC converters, 4 DC circuit
1448 breakers, 82 DC load-break switches, 19 DC transformers and 150 adapters (see Figure F.2).

1449 Besides, the project has proposed and applied typical design schemes for DC access in various
1450 scenarios such as industrial frequency conversion load, data center, household electric
1451 appliances and the integration of PV, energy storage and charging station. The following
1452 describes each scenario in detail:

- 1453 – Industry load: The project adopts DC power supply for the injection molding machine in
1454 Hongsheng factory with the capacity of 3,3 MW, which can omit the primary rectification link,
1455 and make full use of the feedback kinetic energy of frequent startup and shutdown of the
1456 rotor to improve the energy utilization rate.
- 1457 – Data center: The project provides DC power supply to Jiuli data center with the capacity of
1458 1 MW, omitting multi-level AC/DC conversion within the power supply of the data center,
1459 and the measured power efficiency is improved by 1,5 %.
- 1460 – Resident load: The project provides DC power to 150 households, develops 15 types of DC
1461 appliances, omits the rectification link and power factor correction (PFC) link in traditional
1462 appliances, breaks through the arc free breaking technology, and improves the
1463 comprehensive energy efficiency by 2 % through the third-party detection.
- 1464 – PV access: The project is connected to the roof photovoltaic of Baotong, Hongyi, Mingzhi
1465 and other industrial parks, with a total of 6,21 MW. When DC absorption is adopted for
1466 photovoltaic, the AC/DC link in the converter can be omitted and the operation energy
1467 efficiency can be improved.

1468 Furthermore, the project adopts floating grounding mode at the LV side, which can realize
1469 continuous operation under single pole grounding fault. At the same time, it is equipped with a
1470 leakage current protector and an insulation monitoring device, which can find the single pole
1471 fault point in time and ensure the safety of the system. The true bipolar connection is adopted,
1472 which can provide multiple voltage levels for the load side and improve the power supply
1473 reliability of the system. Besides, power quality monitoring system is deployed at both MV side
1474 and LV side to monitor the ripple, dip, oscillation and other power quality problems of DC system
1475 in real time, which can provide the basis for power quality control of the DC system.



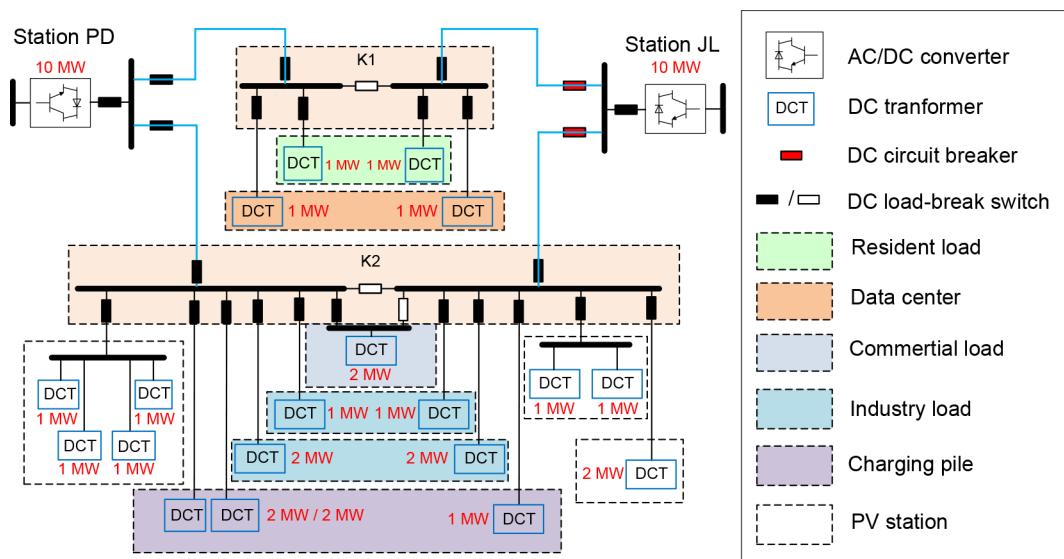
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1478

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



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1481

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

F.2 Voltage selection

1483 The typical medium AC voltage levels in China are 110 kV, 35 kV, 10 kV. The typical medium
 1484 DC voltage level in China is ± 35 kV, ± 10 kV, ± 3 kV, 3 ($\pm 1,5$) kV.

1485 The MV&LVDC distribution system in Wujiang is connected to a 10 kV AC grid. There are three
 1486 stages of voltage levels in this system: ± 10 kV DC, ± 375 V DC and ± 48 V DC.

1487 – System capacity

1488 The current-carrying capacity of a DC cable is 1,03 to 1,04 times of the AC cable. The typical
 1489 current-carrying capacity of cables is listed in Table F.1. The transmission capacity of AC
 1490 and DC cable can also be calculated. With the same transmission capacity, the DC
 1491 distribution voltage level corresponding to the AC system is listed in Table F.2.

1492 **Table F.1 – The current-carrying capacity of medium AC&DC cable**

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	-
		Calandria	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
		Calandria	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	-
		Calandria	433 A	515 A	587 A	690 A	-
		Direct burial	500 A	582 A	659 A	757 A	-

1493

1494 **Table F.2 – The voltage level corresponding relationship between AC and DC with the**
1495 **same transmission capacity**

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

1496

1497 The transmission capacity of the ±10 kV DC system is larger than that of the 10 kV AC
 1498 system. The load capacity of the whole project is 10,61 MW, with 6,2 MW PV and 2 MWh
 1499 storage. In order to satisfy the power supply requirements, the medium DC voltage level
 1500 ±10 kV is suitable for the for the MV&LVDC distribution system.

1501 – Transmission distance

1502 The voltage drop on the cable is an important factor to consider in the voltage level selection.
 1503 In this system, all the power electric equipment has the ability of ±10 % voltage adjustments.
 1504 A ±10 kV DC cable has a longer transmission distance than a 10 kV AC cable.

1505 – Converter adjustments

1506 For a converter, the modulation ratio is defined as the ratio of the peak value of AC phase
 1507 voltage to the single pole output DC voltage. In the application, the modulation ratio is set
 1508 as 0,7 to 0,95, for better voltage utilization and power quality.

1509 The modulation ratio M is

$$M = \frac{2\sqrt{2}U_{ac}}{\sqrt{3}U_{dc}} \quad (\text{F.1})$$

1510

1511 where

1512 U_{ac} is the RMS of AC system voltage;

1513 U_{dc} is the converter DC voltage.

1514 The voltage between two poles of the converter ΔU_{dc} is calculated in Table F.3 with a
1515 modulation ratio of 0,7 and 0,95.

1516 **Table F.3 – DC voltage range with modulation ratio limit**

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

1517

1518 The voltage between two poles is suggested to range within the interval in the table. The
1519 medium DC voltage in this system is ± 10 kV, allowing full use to be made of the 10 kV AC
1520 voltage, with improved power quality.

1521
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Annex G (informative)

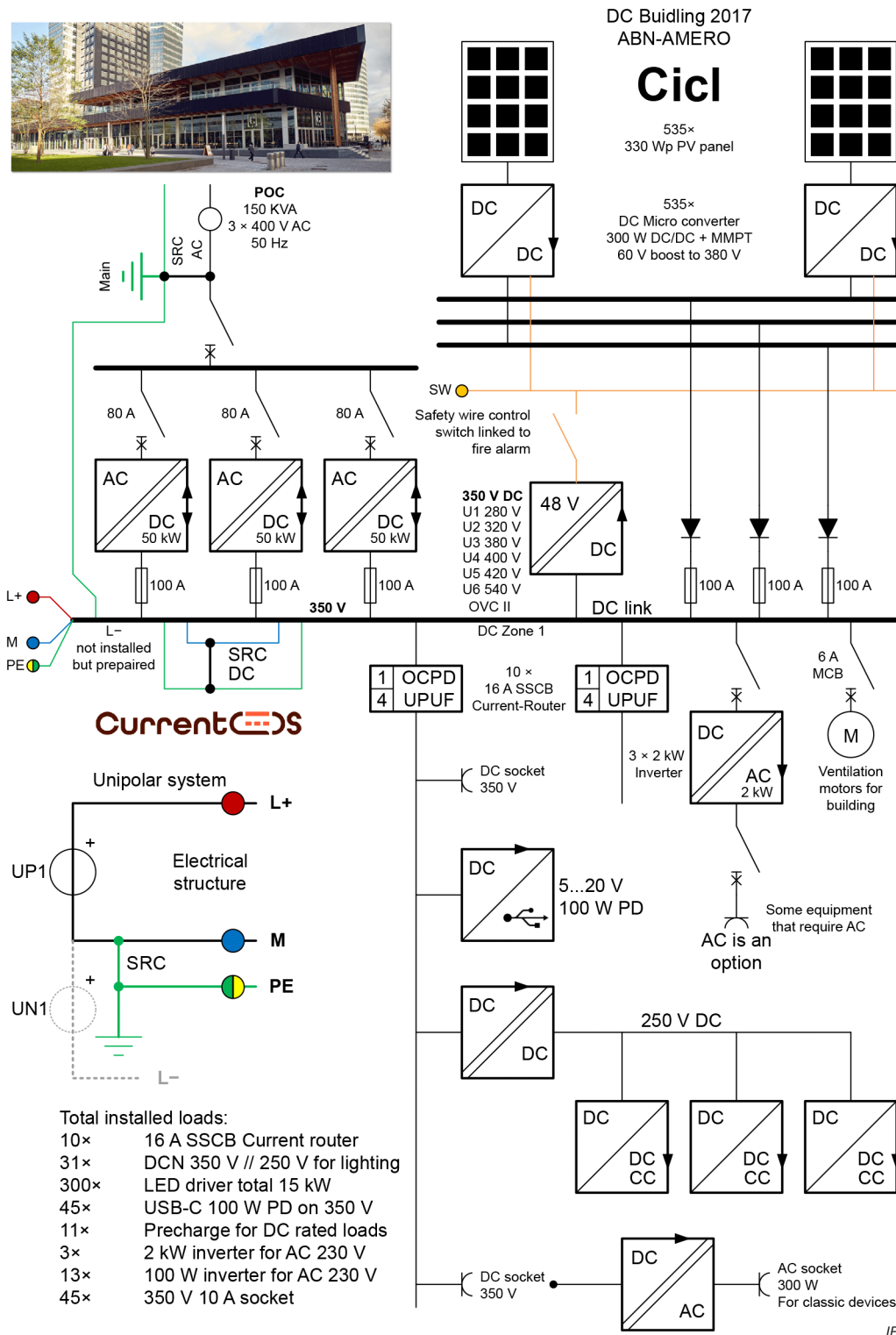
An office building with general building utilities and office workplaces

1525

G.1 Sustainable circular building

1526
1527
1528

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 m² of meeting venues with LED lighting and PV panels connected to a complete DC grid on 350 V DC. See Figure G.1.



1529

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1531 **Figure G.1 – Office building with general building utilities and office work places**

1532 This use case shows an office building with general building utilities and office workplaces
 1533 where mainly information equipment is connected.

1534 The office is designed to operate CO₂ neutral, through generation of renewable energy with
 1535 solar power and energy storage by means of batteries.

- 1536 The main operating voltage between L+ and M is in the voltage band 320 V DC to 380 V DC.
- 1537 There is an AC/DC converter that serves as a reference for the voltage and exchange of excess
1538 energy and energy source in case of energy shortage in the system.
- 1539 On the side of the users there is also a storage unit and there is the building lighting by means
1540 of LED's and power outlets by means of USB-C (5/12/20 V up to 100 W). Users that require
1541 more power than 100 W can be connected to the 350 V level. On this level the user can plug-
1542 in his/her equipment for use.
- 1543 All the equipment, converters, switches, chargers are semiconductor based and bidirectional
1544 operating for current/power.
- 1545 For the proper functioning and protection of the equipment in the installation, zones are defined.
1546 These zones are marked with a yellow triangle. See overview for DC zones.
- 1547 DC zones are separated by protection devices. The protection is an electronic switch that can
1548 be controlled by the operating system manager that manages the energy supply and the
1549 demand in the installation.
- 1550 Active DC installation consists of:
- 1551 a) 3 active front end (3 × 50 kW);
- 1552 b) Solid state protection devices
- 1553 – 16 A,
- 1554 – RCD included;
- 1555 c) PV installation 150 kW
- 1556 – Every PV has his own optimizer (one defective panel will not infect the whole system);
- 1557 d) Storage (batteries)
- 1558 – Peak shaving,
- 1559 – UPS,
- 1560 – Island mode;
- 1561 e) USB-C (100 W)
- 1562 – Flexible output voltage (5 V to 20 V output range),
- 1563 – Power and data combined in one connector/cable;
- 1564 f) 350 V DC wall socket (protected by solid state circuit breaker);
- 1565 g) DC/AC converter (230 VAC 2 kW),
- 1566 – For normal AC devices;
- 1567 h) Mobile DC/AC converters (For users to charge laptop without USB-C).

1568 Advantages:

- 1569 – additional functions;
- 1570 – integrated UPS;
- 1571 – less conversion losses;
- 1572 – island mode enabled;
- 1573 – congestion management is easier with droop curves implementation;
- 1574 – connected to the fire alarm.

1575 Risk classification of DC installations:

1576 Depending on the design, a certain risk can be assigned to a DC installation. Based on the
1577 energy stored in batteries and the power that can be delivered by the installation at a certain
1578 point, a classification into hazardous and less hazardous installation components can be made.
1579 Five different risk categories have been defined for DC installations, ranging from DC zone 0
1580 (highest risk) to DC zone 4 (lowest risk). These DC zones are described here.

1581 Depending on the DC zone in question, different requirements could be set on the knowledge,
1582 expertise and skills of the designer, fitter, installer and the operators.

1583 **G.2 Zone system**

1584 DC zones are part of the Dutch NEN NPR9090:2018 and part of CurrentOS. In CurrentOS, the
1585 DC zones are more precisely described.

1586 Electrical hazards associated with all electrical installation include

- 1587 – electric shock and burns from contact with live parts,
- 1588 – injury from exposure to arcing, fire from faulty electrical equipment or installations.

1589 To ease design and operation of DC installations, circuits or group of circuits are classified in
1590 5 zones numbered from zone 0 to zone 4. Different installation rules apply in the different zones.

1591 Most of existing DC installations are in zone 0, 1 and 2. These are already covered in the
1592 IEC 60364 series.

1593 Zones 3 and 4 are protected by new semiconductor power distribution components, namely
1594 current source converter and semiconductor circuit breakers. Fault energies and consequent
1595 risks are lower in these zones.

1596 Different zones are connected by means of devices able to limit the flow of the fault energy
1597 from one zone to the other.

1598 Zone 0 – Unprotected source:

1599 In this zone there are high-power voltage sources or sources with similar behaviour during the
1600 fault, such as batteries (multiple linked batteries or batteries with large energy content), the
1601 public electricity grid, capacitor and supercapacitor banks, including the connection circuits to
1602 the protective device.

1603 Circuits downstream of power converters with large capacitors are also classified in zone 0.
1604 The rationale for this and criteria for classification are under consideration.

1605 Characteristics of zone 0 are:

- 1606 – multiple power sources not possible,
- 1607 – bi-directional power flow possible,
- 1608 – very high fault current and energy,
- 1609 – high arc-flash incident energy.

1610 As arc-flash risk can be very high, zone 0 circuits have limited extension and are housed in an
1611 enclosure, e.g., in a battery rack or in a panel, only accessible to highly skilled people wearing
1612 appropriate personal protection equipment (PPE). NFPA-70E:2024 standard for arc flash could
1613 be considered.

1614 In the system shown in Figure G.2, the batteries connected in a string can yield a very high
1615 fault energy and are therefore classified as zone 0.

1616 Zone 1 – Protected circuits with high short-circuit energy:

1617 Power distribution circuits, typically busbars, powered from sources in zone 0 and protected
1618 from zone 0 by electromechanical circuit breaker or fuses are classified as zone 1.

1619 The main characteristics in zone 1 are:

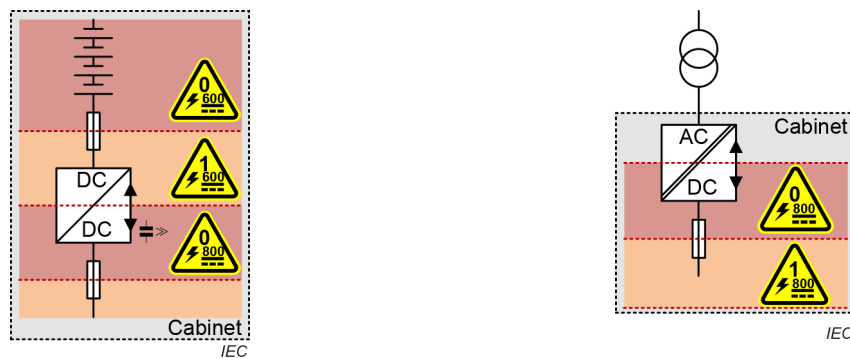
- 1620 – high overcurrent possible,
- 1621 – multiple sources possible, but all connected to the main distribution board, so that the circuit
1622 is fed from one end only,
- 1623 – bi-directional power flow,
- 1624 – high Arc-flash risk.

1625 These are typical characteristic values (for information only) of zone 1:

- 1626 – if J/cm^2 is below that of zone 0, then the system is in zone 1,
- 1627 – typical incident energies are in the range of 1 J/cm^2 to 5 J/cm^2 ,
- 1628 – typical time constants are in the range of 1 ms to 5 ms,
- 1629 – typical I^2t ratings are in the range of kA^2s .

1630 Circuits in zone 1 are distributed only at short distances, for example inside a container, from
1631 the battery compartment to the electronics compartment, or in a dedicated room.

1632 In Figure G.2, a cabinet used in a system is shown. Different zones are present within the same
1633 cabinet. The circuit protected by the fuse is classified in zone 1. The overcurrent protection
1634 device (OCPD), such as a fuse or a circuit breaker, connected after the battery string, can limit
1635 the fault energy according to its I^2t rating, and consequently limits the electric risk downstream.
1636 However, with a fuse or electromechanical circuit breaker, the residual fault energy and risk are
1637 still relatively high; this circuit is classified as zone 1. After the OCPD, a DC/DC converter is
1638 used to control the current to and from the batteries. The large DC-link capacitors downstream
1639 this converter can supply very large short-circuit current, before this is limited by the converter
1640 itself. So, this part of the cabinet is classified again as zone 0.



1641 **Figure G.2 – Example of zone 0 and zone 1**

1642 Zone 2 – Current-limited protected source:

1643 Circuits fed by current-limited power sources, for example PV string optimizers or DC/DC
 1644 converters with smaller capacitors are classified in zone 2. But also, hybrid breakers with strong
 1645 current limiting behaviour.

1646 More actionable criteria for distinguishing zone 1 and 2 (alternative to the capacitors size) are
 1647 under consideration.

1648 NOTE 1 Fault currents are too small to actuate conventional OCPD.

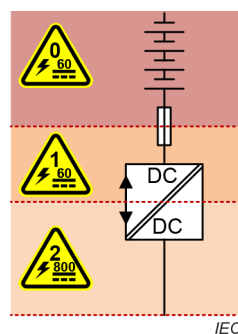
1649 The main characteristics in zone 2 are:

- 1650 – multiple sources possible,
- 1651 – bi-directional power flow,
- 1652 – limited arc-flash incident energy,
- 1653 – low fault current makes protection challenging.

1654 Characteristic values (for information only) below are under consideration:

- 1655 – typical time constants are in the range of xxx μ s,
- 1656 – typical I^2t ratings are in the range of a few kA^2s ,
- 1657 – needs voltage-based protection (detecting undervoltage).

1658 The example shown in Figure G.3 is very similar to the one in Figure G.2, but the DC-link
 1659 capacitor of the converter is much smaller and so is the fault energy. Therefore, the circuit is
 1660 classified as zone 2.

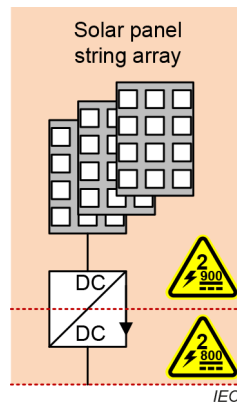


1661

1662

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

1663 An example of a purely zone 2 system is shown in Figure G.4, in which only current-limited
 1664 sources are included. As both the PV panels and the DC/DC converter have limited short-circuit
 1665 current, the full system is zone 2.



1666

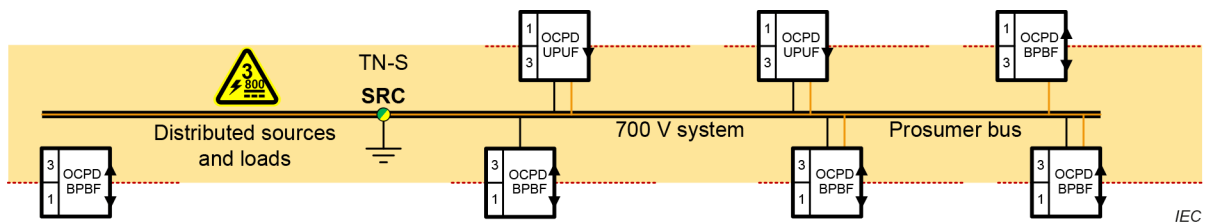
1667 **Figure G.4 – Example of zone 2 system**

1668 **Zones 3 – Multiple-sources circuits with electronic protection:**

1669 Circuits fed by multiple sources are in zone 3 when very low fault currents are ensured by
 1670 proper design rules (below) and use of fast semiconductor-based circuit breakers.

1671 NOTE 2 As zone 3 circuits are fed by multiple sources or bidirectional “prosumers” (e.g. battery systems), either
 1672 from a central location or distributed, the power flow does not have a predetermined direction.

1673 An example of zone 3 system is shown in Figure G.5. All the sources are connected to the bus
 1674 via a fast protection device, for example an SCCB.



1675

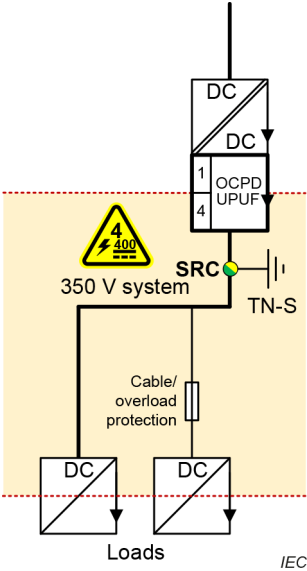
1676 **Figure G.5 – Purely zone 3 system with the protection devices of distributed sources**

1677 **Zone 4 – Single-source circuits with electronic protection:**

1678 Circuits fed by a single source are in zone 4 when very low fault currents are ensured by proper
 1679 design rules (below) and use of fast semiconductor-based circuit breakers.

1680 NOTE 3 Different to zone 3, the power flow in zone 4 circuits has a predetermined direction (upstream to
 1681 downstream) as circuits are fed by a single source.

1682 An example of zone 4 system is shown in Figure G.6.

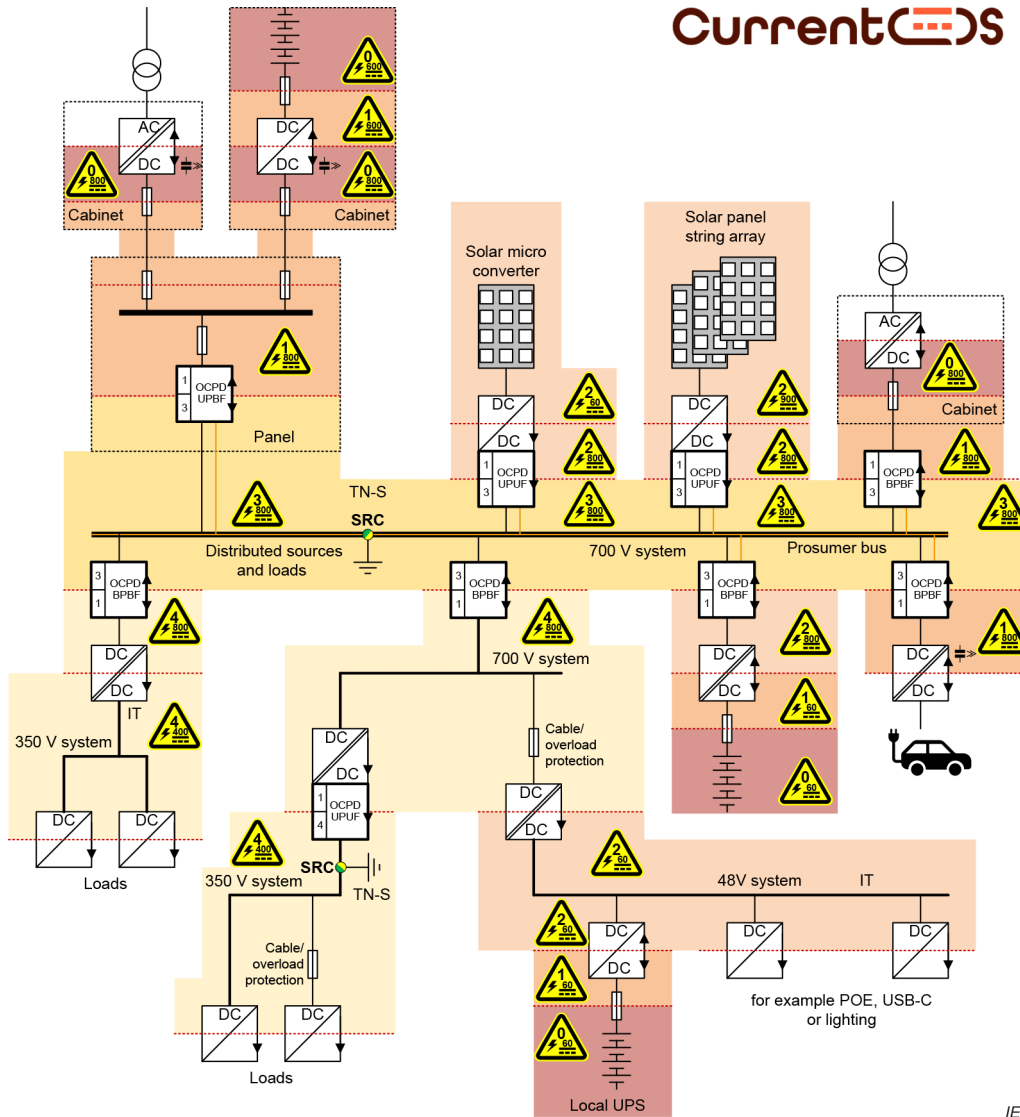


1683

1684

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

1685 An overview of a whole system as an example of four zones is shown in Figure G.7.



1686

IEC

1687 Reproduced with the permission of CurrentOS.

1688 **Figure G.7 – CurrentOS system overview and safety zones**

1689 Zone labelling:

1690 Distribution cabinets and busbars are marked with the label in Figure G.8, where:

1691 Z: Zone level (0 ... 4) [mandatory]

1692 V: Maximum zone pole to earth voltage U_4 [optional]



IEC

1693

1694 **Figure G.8 – DC zones label**

1695 Skilled installers and maintenance personnel will immediately recognize the risk of the
 1696 installation and can take proper measures.

1697 NOTE 4 indication of the voltage can be drawn in the label.

1698 Examples of labels are shown in Figure G.9.



1699

1700

Figure G.9 – Examples of DC zones labels

1701 Cabinets containing circuits in different zones are marked with the label of the lowest level. For
 1702 instance, in a panel including zone 0 and zone 1 circuits, the label is for zone 0.

1703 A coding system for cables is under consideration (see Table G.1).

1704

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	

1705

1706 **G.3 Aspects regarding the DC zone classification in DC installation**1707 **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)	Recommended	Recommended	Recommended	Recommended			
Isolation during maintenance (NEN 1010:2015 H 536)	Mandatory	Mandatory	Mandatory	Mandatory	Mandatory**	Mandatory**	Mandatory**
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
<p>* These combinations are mandatory as soon as the necessary protection components are available.</p> <p>Mandatory**: An alternative to isolation during maintenance is shorting and earthing.</p> <p>Advice: Ensure 1 m of cable between the fuse and the electronics to prevent the electronics being damaged by the heat of the fuses.</p>							

1708

1709 DC zones 2 and 3 are not always required to be present. For example, they are not required if
 1710 the installation does not contain any sources that are characteristic of these DC zones. DC
 1711 zone 0 always leads to DC zone 1, but it also is possible to go directly to DC zone 4 from DC
 1712 zone 1.

1713 Designers, fitters and installers take the limited short-circuit current into account in DC zones
 1714 2 and 3. This applies specifically when applying DC circuit breakers, DC fuses or DC devices
 1715 with fuses. The minimum short-circuit currents of the DC sources are included in the installation
 1716 documents.

1717 This also applies to the minimum currents needed to trip the circuit breakers or fuses applied,
 1718 also those in permanently installed devices (see Table G.2 for more details).

- 1747 Nominal state of grid is within the –droop to +droop range in the nominal voltage band.
- 1748 The SOG becomes negative when the voltage is below the nominal bus voltage.
- 1749 The SOG becomes positive when the voltage is above the nominal bus voltage.
- 1750 The SOG becomes > 100 % when the voltage is more than the maximum value of the nominal
1751 voltage band.
- 1752 The formula to calculate the SOG is as follows:

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

1753

1754

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

$U_{\text{bus}}(\text{actual})$ in 350 V DC	$U_{\text{bus}}(\text{actual})$ 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.		

1755

- 1756 The value of the maximum tolerated losses in active DC systems is as low as possible, as
1757 shown in Table H.1.

1758 There are several reasons why low allowed voltage drop on the cable is a good choice:

- 1759 a) Theoretically, in DC, losses up to 20 %, even 30 %, are possible. However, such a high
1760 voltage drop is not recommended if we want to achieve an efficient and strong system.
- 1761 b) Going further and assuming 10 % is not a good choice either because such voltage drop
1762 would adversely influence the earthing point's design, because many diodes would be
1763 required to compensate circulations.
- 1764 c) Third point are the droop curves. In case of for example ±10 % droop and 10 % cable losses,
1765 the end user will highly be influenced because of the high voltage difference and already
1766 implemented droop curves. To avoid discrimination between users, a smaller voltage drop
1767 is desired. If low cable loss and deviation is taken, then droop curves are not directly
1768 influenced.
- 1769 d) The cable sizes. If a higher voltage drop is allowed, it will directly impact dissipations and
1770 thermal characteristics of the cable, which will result in bigger investment in enabling bigger
1771 spacing for such an installation.

1772 The strong compromise between thermal losses, efficiency of the system, length of the
 1773 cable, protection schemes, earthing points and other aspects of importance is achieved, as
 1774 shown in Table H.2.

1775

Table H.2 – Allowed voltages cable drop

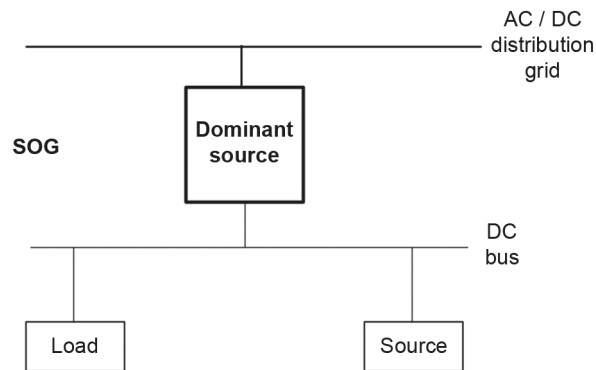
Nominal voltages V	Allowed voltages cable drop ΔU , $\Delta U \% = 1,4 \%$ V
350	±5
700	±10
1 400	±20

1776

1777 a) Droop mode

1778 There is one dominant voltage source that acts as a reference directing the state of the grid
 1779 of the system. The dominant source establishes the state of the grid. However, the sum of
 1780 the rated power levels of the non-dominant power sources cannot be higher than the rated
 1781 power of the dominant power source and the rated power of an electrical installation.

1782 The dominant source can represent the connection between an AC/DC distribution grid and
 1783 an active DC system. It serves as the voltage reference and it balances the power flow in
 1784 the grid, as shown in Figure H.2.

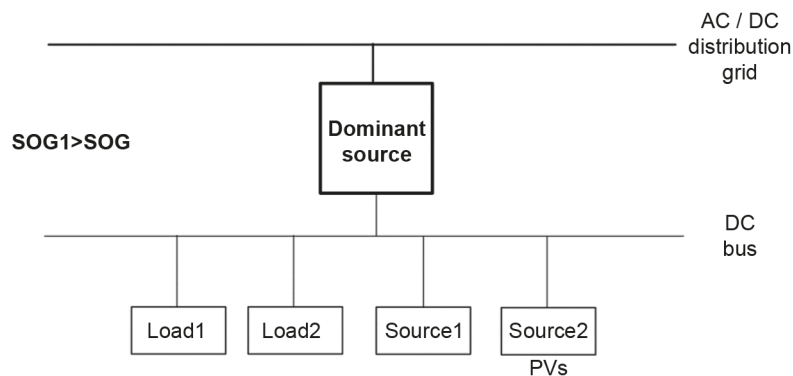


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1786

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

1787 If there is electricity production from the sources, for example PV, in the active grid, the voltage
 1788 level in the voltage band generally increases. This enables devices to be connected to the grid,
 1789 and currently connected dynamic loads, like electric vehicles, are enabled to increase their own
 1790 consumption. This voltage increase occurs up to a maximum voltage level (U_{max}), as shown in
 1791 Figure H.3.



1792

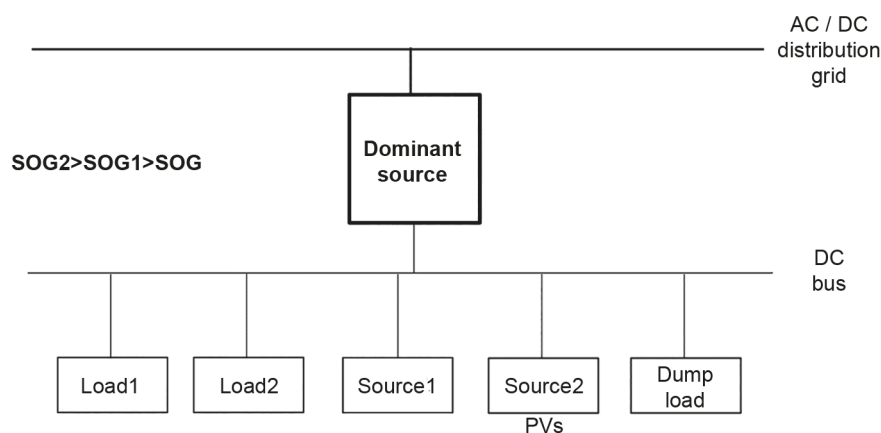
IEC

1793

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

1794

1795 When the voltage reaches U_{max} and excess power is getting higher than a maximum power of
 1796 all loads combined, dump loads, if available, can be activated, as shown in Figure H.4. This is
 1797 done in order to prevent the bus voltage from further rising and causing possible over-voltages.
 1798 In this case, active sources also get activated, limiting the power, if the voltage keeps increasing.
 1799 However, if none of this is enough to limit the rise of the bus voltage, then the system enters
 1800 the protection state.



1801

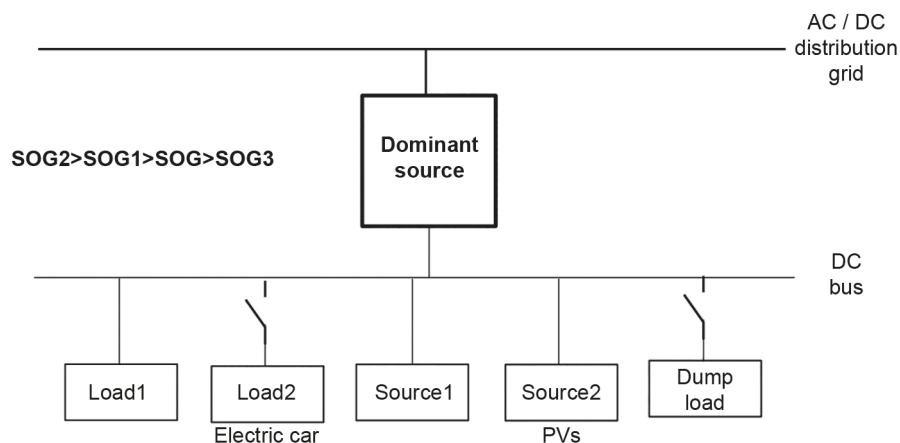
IEC

1802

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

1803

1804 On the other hand, as the voltage level of the grid decreases, due to the higher power
 1805 consumption and low production, only higher priority devices can still operate, as shown in
 1806 Figure H.5. When the voltage further decreases below its minimum level (U_{min}) and enters the
 1807 emergency area, the current that can be withdrawn is limited. If additional power is still required
 1808 from devices, the voltage is scaled down until it reaches its lowest value and the grid is then in
 1809 the down state.



1810

IEC

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

1811
1812

1813 NOTE The dominant source is not the necessary component, but where the dominant source is not available, the
1814 system can be configured and designed differently, particularly with regard to the protection scheme.

1815 b) Control

1816 Each active device connected to the DC system complies with the droop curves of the
1817 system. The droop curve is a set of parameters that are stated on each device when started
1818 up for the first time. The values of the droop curve related to a specific device can be
1819 modified during operation. These values (parameters) will determine under which operating
1820 voltages the consumer device can operate and how much power it can consume. In the case
1821 of sources, it will state under which operating conditions the source device will operate
1822 acting as a current source.

1823 The parameters are set in the device (converter) itself with the possibility of changing them
1824 in the future. Thus, external communication is not needed for the device to regulate. Once
1825 they are set, the device is expected to regulate its power on its own following the state of
1826 grid. The speed of regulation depends on the type of converter or device. Nevertheless, this
1827 is expected to be fast (order of ms, us).

1828 Parameterizing is not time critical and is not used as a means of fast control.

1829 Additionally, knowing that the load converters (converter + load) will follow and regulate
1830 looking at the state of grid, a source converter (source + converter) can also influence the
1831 system by changing its behaviour. For this, the source can also behave as a voltage source,
1832 providing a steady voltage with variable current. In this case, the state of grid can be
1833 influenced to increase/decrease load consumption.

1834 c) Inertia

1835 It depends on the source type. It is possible for some devices to deliver inertia, like AFE's
1836 or battery systems. Inertia in the system is important for stabilization and fast response of
1837 the system.

1838
1839
1840
1841

Annex I (informative)

Preferred voltage in different countries

1842 I.1 Preferred voltage in China

- 1843 The recommendation in China specifies standard voltage values which are intended to serve
- 1844 – as preferential values for the nominal voltage of electrical supply systems, and this is not
- 1845 an absolute rule, it depends on the concrete situation;
- 1846 – as reference values for equipment and system design.

1847 DC nominal voltage between 110 V and 1 500 V is preferred, to be chosen from Table I.1. DC

1848 nominal voltage for ELVDC equipment below 110 V is selected from the values given in

1849 Table I.2.

1850 **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)
<p>NOTE 1 The unmarked voltage values correspond to unipolar DC lines, and the voltage values with plus-minus sign correspond to bipolar DC lines.</p> <p>NOTE 2 For technical and economic reasons, additional voltages can be required for certain specific fields of application.</p> <p>NOTE 3 The preferred value is expected to be a priority for new systems to be constructed in the future.</p>	

- 1851
- 1852 a) Preferred value 1 500 V:
- 1853 – Recommended by IEC 60038 and IEC 60850, 1 500 V is one of the preferred DC traction
- 1854 voltages, which is also the traction voltage of Metro in some areas of China.
- 1855 – In some industrial parks, the DC voltage of the industrial loads is 750 V.
- 1856 b) Preferred value 750 V:
- 1857 – Recommended by IEC 60038, the preferred voltage for equipment is 750 V, which is
- 1858 convenient to connect into three-phase AC 220 V/380 V.
- 1859 c) Preferred value 220 V:
- 1860 – Recommended by IEC 60038, it is compatible with the internal DC voltage of converter
- 1861 air conditioners, converter washing machines and converter refrigerators, etc.

- 1862 d) Supplementary value 440 V:
 1863 – Recommended by IEC 60038.
 1864 e) Supplementary value 400 V:
 1865 – Recommended by ITU-TL.1200, the preferred voltage is 400 V.
 1866 f) Supplementary value 336 V:
 1867 – DC supply voltage of data center is 336 V in some areas of China.
 1868 – 336 V is close to the input voltage of an electric vehicle.
 1869 g) Supplementary value 240 V (250 V), 110 V:
 1870 – DC supply voltage of data center is 240 V in some areas of China.
 1871 – 250 V is recommended by IEC 60038.
 1872 – 110 V is recommended by IEC 60038.

1873

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

1874

1875 The nominal voltage of equipment below 120 V DC references IEC 60038 directly.

- 1876 a) The preferred DC voltage level for the following load is 48 V:
 1877 – communication equipment;
 1878 – household type photovoltaic, wind power, battery storage system and fuel cell.
 1879 b) Because the voltage of the primary and secondary cells is below 2,4 V, and the choice of
 1880 the type of cell to be used in various applications will be based on properties other than the
 1881 voltage, these values are not included in the table. The relevant IEC technical committees
 1882 can specify types of cells and related voltages for specific applications.
 1883 c) It is recognized that for technical and economic reasons, additional voltages can be required
 1884 for certain specific fields of application.

1885 I.2 Preferred voltage in the Netherlands

1886 The choice of a nominal voltage of an electrical installation has a bearing on the length of the
1887 cables and the measures to protect against electric shock.

1888 The Netherlands standards propose a nominal voltage of 350 V DC relative to earth (or +350 V
1889 DC and –350 V DC with an earthed central conductor). The main arguments for this are the
1890 following:

- 1891 a) A voltage level of 350 V DC relative to earth (of +350 V DC and –350 V DC with an earthed
1892 central conductor) can still offer protection comparable to that offered with 230 V AC
1893 systems. If a higher voltage is selected, this level of protection will no longer be possible
1894 due to the voltage variations that can be expected.
- 1895 b) 350 V DC and 700 V DC offer the possibility of an equivalent and fully-fledged system
1896 comparable to single-phase 230 V AC and respectively three-phase 400 V AC. See also
1897 Table I.3.
- 1898 c) If existing cabling for three-phase 400 V AC is used, at least the same power can be
1899 transferred.
- 1900 d) Due to voltage doubling (700 V DC, 1 400 V DC), 350 V DC offers the possibility of using
1901 virtually the entire voltage range up to 1 500 V DC as defined in IEC 60364 (all parts),
1902 HD 60364 (all parts) and NEN 1010:2015.
- 1903 e) 350 V is not used in AC systems. This prevents confusion and enhances safety.

1904 **Table I.3 – Comparison between DC and AC system voltages**

U_n DC	U_n AC	P_{max} at 16 ARMS
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)

1905

1906 Voltage tolerances:

1907 Where permanently installed secondary batteries are applied as a back-up power supply for the
1908 DC installation, the voltage level as supplied by these batteries can vary, depending on their
1909 charge levels. This particularly applies if no voltage regulator is applied after the battery.

1910 The occurrence of considerable voltage variations is taken into account in passive DC
1911 installations. If the voltage variations cannot be calculated, or if the battery details are missing,
1912 the following tolerances are assumed:

- 1913 – maximum voltage: $1,2 U_n$;
- 1914 – minimum voltage: $0,8 U_n$.

1915 In active DC installations where the voltages and currents that occur are monitored, agreements
1916 are made as to the maximum permissible voltage variations. The voltage variations that occur
1917 in active DC installations can give information about the operation of the installation in
1918 accordance with the network code of conduct.

1919 I.3 Preferred voltage in Germany

1920 Recommended voltages for distribution systems are given in Table I.4. There are four voltage
1921 classes (VC1-VC4) defined, that are used for controlled and for uncontrolled systems and for
1922 unipolar and bipolar systems. All the equipment used in these distribution systems is designed
1923 to fit to the voltage class selected and the class is indicated on the device.

1924 A DSO can choose a suitable voltage out of the voltage class and can operate in the full area
 1925 (U_2 - U_3) or in a subset of it. Bipolar systems use a VC between line and midpoint and VC+1
 1926 between line and line.

1927 NOTE 1 For example, one DSO is able to choose 380 V \pm 20 % for a VC1 distribution. Another DSO can choose a
 1928 distribution voltage of 350 V \pm 10 %. They both use the same equipment which fits to U_2 and U_3 as defined in
 1929 Table I.4.

1930 NOTE 2 A bipolar system with 380/760 V uses VC1 devices between line and midpoint and VC2 devices between
 1931 line and line. The same devices can also be used in 350/700 V systems.

1932
 1933

**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.			

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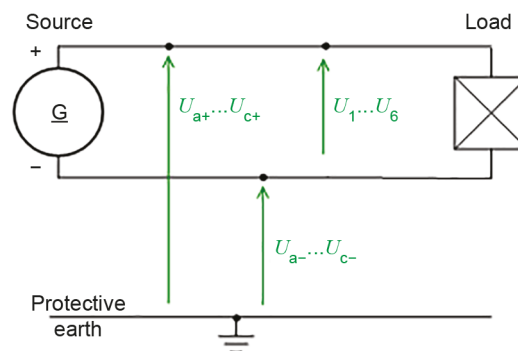
Annex J (informative)

Voltage with respect to earth

1939 All the content in this document relates to the differential mode, but a common mode description
1940 will be needed. There are lot of aspects to this topic, but it fully depends on the earthing
1941 structure, and has nothing to do with the differential aspects.

1942 Clause 5 and Clause 7 relate exclusively to the voltage potential difference generated across
1943 the power terminals of the supply, or from which the load can draw current. There are also
1944 maximum limits for the voltage between either power terminal and earth. Generally, these
1945 maximum voltage limits will be absolute values – polarity is not important.

1946 These limits are important for considerations of safety, insulation breakdown, lighting protection
1947 and transmission of, or immunity to, radio interference, but they are not relevant to the powering
1948 of the equipment itself – so there are no minimum voltage limits to earth.



1949

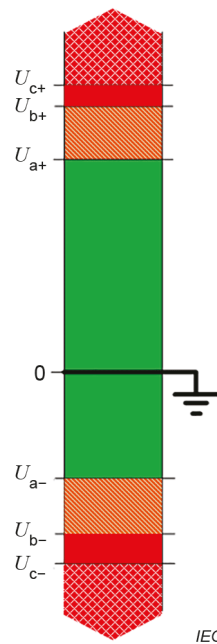
IEC

1950

Figure J.1 – DC voltage definitions

1951 Six additional voltage limits are defined: U_{a+} , U_{b+} , U_{c+} , U_{a-} , U_{b-} , U_{c-} (see Figure J.1).
1952 These maximum limits become of critical importance when there are protection devices between
1953 power terminals and earth.

1954 Unipolar systems will have significant differences between the potentials to earth of the power
1955 terminals. They can therefore have different limits for $U_a \dots U_c$. For example, in a negative-
1956 earth system, U_{a-} , U_{b-} and U_{c-} can only be a volt or so (see Figure J.2 and Figure J.3).



1957

1958

Figure J.2 – DC voltage bands relative to earth

1959 – Below U_a : Normal operation

1960 Under all normal circumstances, voltages to earth will be in this region.

1961 – $U_a - U_b$: Overvoltage protection band

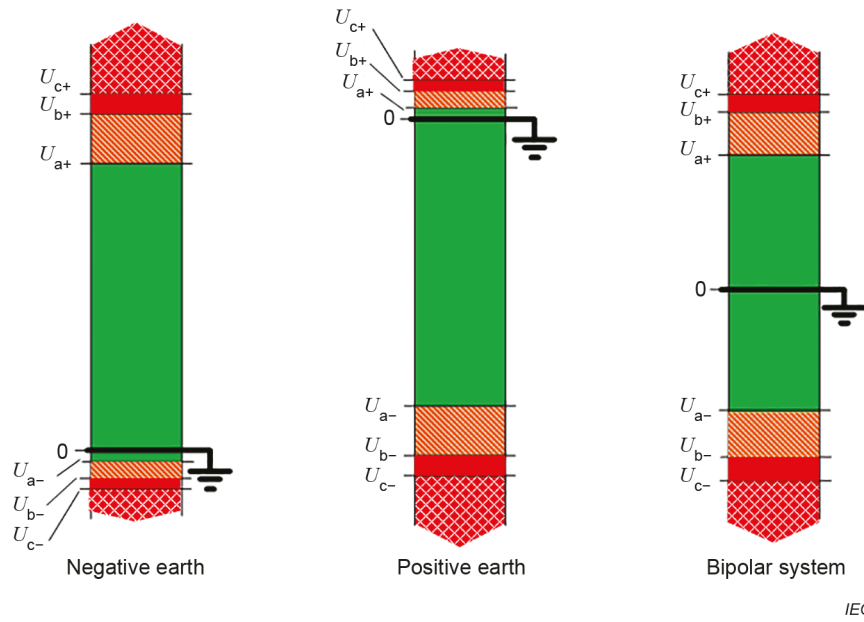
1962 Transient voltages can only remain in this band for very short periods. Non-linear surge
1963 protection devices with limited energy absorption capabilities can activate.

1964 – $U_b - U_c$: Safety margin for electrical installation

1965 In this region, dielectric breakdown within components and consequently permanent equipment
1966 damage are likely. Insulation will not break down. Devices that can break down in this region
1967 will not expose users to risk of electric shock.

1968 – Above U_c : Insulation breakdown

1969 In this region, permanent equipment damage is very likely. Users can be exposed to risk of
1970 electric shock.



1971

1972

Figure J.3 – DC voltages to earth – examples

1973 NOTE Whilst in a bipolar system U_{a+} will be positive and U_{a-} negative, this is not necessarily always the case. For
 1974 an extreme example, a 6 V DC heater supply for the cathode of a 25 kV electron microscope will have $U_n = 6$ V, but
 1975 U_{a+} and U_{a-} could be $-25,000$ V and $-25,006$ V.

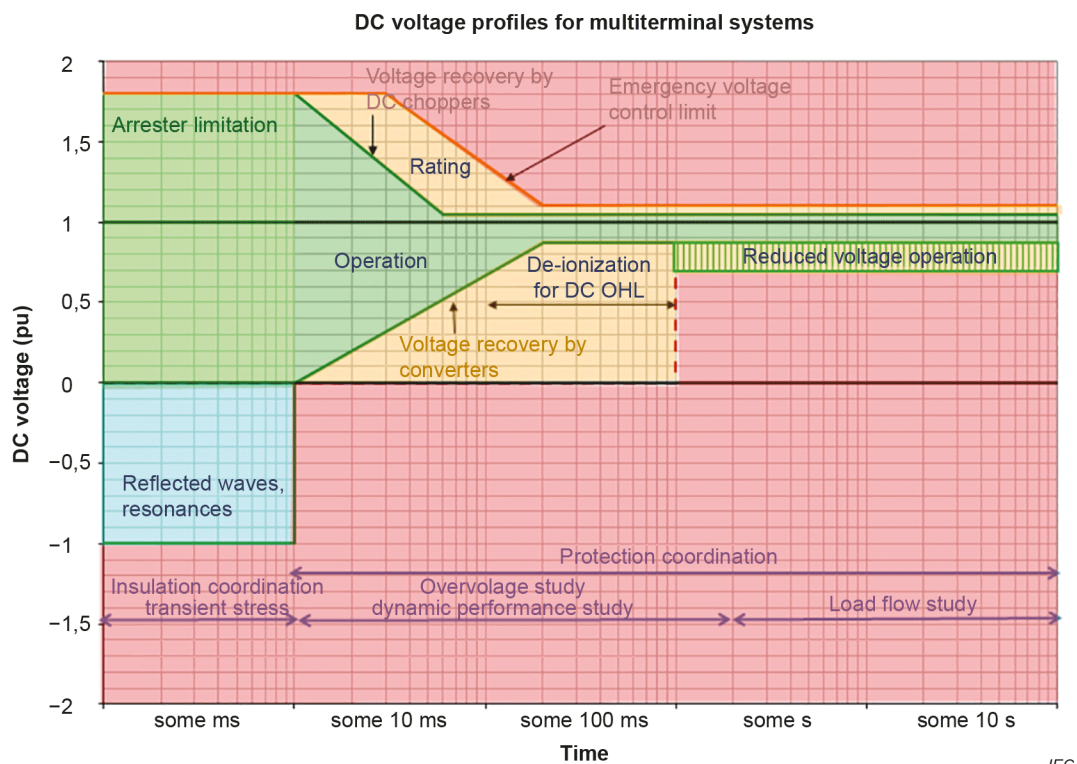
1976
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Annex K (informative)

CIGRE approaches for DC systems

1980 As an example of a temporary voltage profile for the DC voltage, Figure K.1 shows temporary
1981 voltage limits that are considered in DC systems. In order to derive a specific representation,
1982 several aspects are considered. Figure K.1 is a generic representation which is derived from
1983 the following assumptions:

- 1984 a) worst case voltage unbalance for non-solidly grounded DC systems;
1985 b) sections of the DC system which include voltage source converter (VSC), DC breakers with
1986 associated protection and dynamic braking system (DBS);
1987 c) the voltage profile shown applies only for non-faulty sections for which successful fault
1988 clearing is achieved;
1989 d) the DC voltage of plus and minus line can be balanced by appropriate measures (e.g. DBS,
1990 coordinated converter controls);
1991 e) a rating curve can be defined for overvoltage scenarios in order to prevent equipment
1992 failures;
1993 f) in case tripping faulty sections are to be isolated and subsequently grounded at their AC
1994 and DC terminals.



1995

1996 Source: Source: TB 657 Guidelines for the preparation of connection agreements or Grid Codes for multi-terminal
1997 schemes and DC system, CIGRE, 2016.

1998 **Figure K.1 – Temporary DC pole to ground voltage profiles in DC systems**

1999 The time and voltage limits depend on the technology and topology of the DC system. The
2000 scales are used for illustration only.

2001
2002
2003
2004

Annex L (informative)

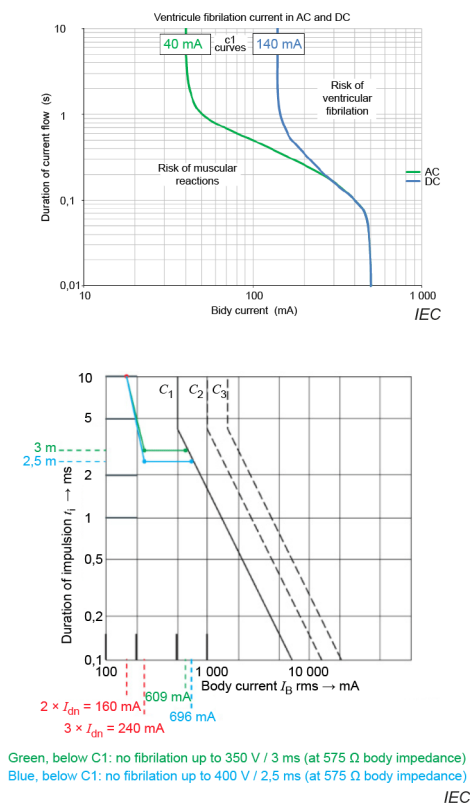
Voltage level in CurrentOS

2005 L.1 Introduction to the organization

2006 CurrentOS is a non-profit, open, independent Foundation for the promotion and adoption of
2007 active DC microgrids. The Foundation was set up to assure the availability of the CurrentOS
2008 Set of Rules to any product manufacturer. It aims to come to a unified standard for DC microgrid
2009 control purposes. The foundation provides to its partners an open set of rules and clear
2010 guidelines on how to manufacture products that work in a CurrentOS based DC environment.

2011 L.2 Voltages used in CurrentOS

2012 To comply with the Low Voltage Directives in Europe (2014/35/EU) and meet the demands of
2013 various stakeholders, there is a growing need for drivers to accept voltage within tighter
2014 tolerances. Specifically, there is a request to reduce the tolerance for the 1 500 V voltage to
2015 10 %, allowing for the highest nominal voltage in multiple use-cases that require additional
2016 protection. See Figure L.1.



- For short duration < 200 ms, the same amplitude of current in AC or in DC gives the same effect (fibrillation).
- The maximum voltage is very similar and the max U_o (400 V) is used, which includes 10 % tolerance. This corresponds to the case that U_4 equals to 440 V, which gives more time to disconnect (important for mechanical devices and arc clearing).
- On new DC applications (sockets, for example), additional protection can be needed.
- Additional protection is still possible for 350 V DC nominal 320 V 380 V including droop with an overshoot to 400 V DC (U_4) (Note: $MT_4 < 3$ mC)

Source: Figure 20 of IEC TS 60479-2:2007.
For duration < 10 ms, body current > 160 mA

2017

Figure L.1 – Threshold of ventricular fibrillation

2018

The voltage is optimized for existing DC equipment such as drives and semiconductors.

2019 To avoid confusion between existing AC labels, the following DC voltage labels in CurrentOS
2020 are used:

2021 – 48 V, 175 V, 350 V, 700 V and 1 400 V for unipolar systems,

2022 – 48 V/96 V, 175/350 V, 350/700 V and 700/1 400 V for bipolar systems.

2023 In pure distribution system with constant voltage operation like public network, the voltage is
2024 set as 750 V and 1 500 V unipolar and 750 V/ 1 500 V bipolar with 10 % tolerances. And the
2025 droop is limited due to the lower tolerance. This ensures compatibility with 700 V and 1 400 V
2026 devices in CurrentOS with wide band tolerances.

2027 350V/700 V is compatible with the voltage definition in DC Industries in Germany.

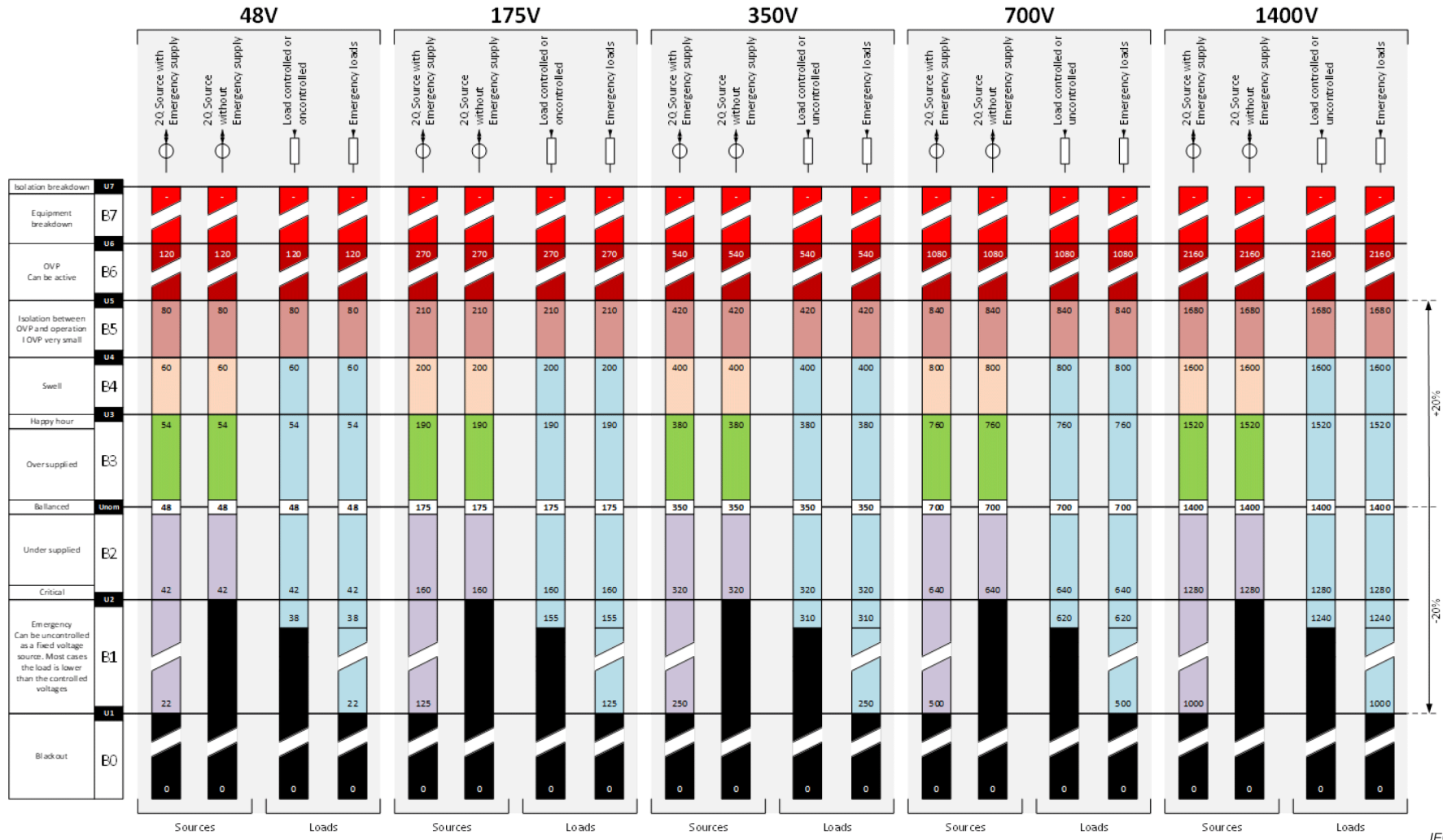
2028 See Figure L.2 and Figure L.3 for more details.

2029

Figure L.2 – Voltage used in CurrentOS

2033

2034



IEC

2035

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2037

Figure L.3 – Voltage bands of different levels

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2041
2042

Annex M (informative)

Voltage level in DC-INDUSTRY and open DC alliance

2043 M.1 General

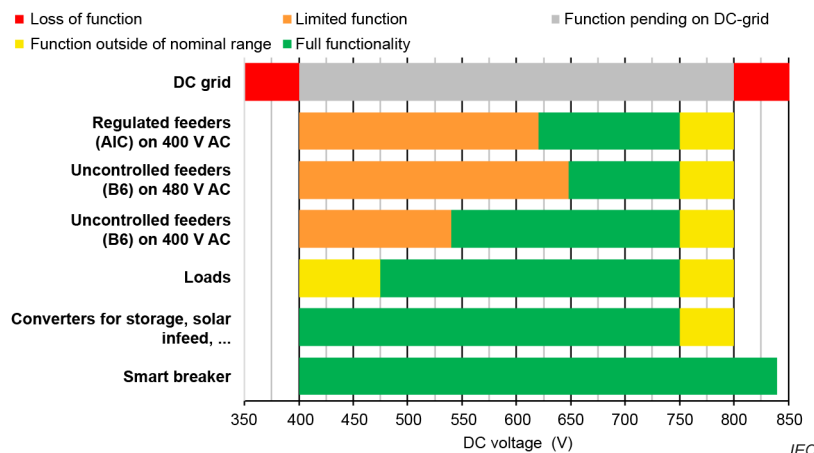
2044 Under the brand DC-INDUSTRIE and DC-INDUSTRIE2 more than 40 industry and research
2045 partners have thoroughly investigated low-voltage DC systems for almost 7 years. The concept
2046 was validated in 10 model applications in industrial (automotive, machine building) as well as
2047 in research settings. Since the project has been completed, the international Open DC Alliance
2048 ODCA, has taken over the concept of establishing a global DC ecosystem and works to
2049 establish DC technology across applications, thereby supporting the goal of resource efficiency
2050 and CO2 neutrality.

2051 This annex describes the voltage between the active poles DC-plus and DC-minus; in no case
2052 does the line-to-ground voltage exceed 400 V under operating conditions.

2053 The DC grid does not have a fixed operating voltage but is rather operated in a voltage band.
2054 This allows for load flow control of the power sources using a voltage-based droop control,
2055 especially in grids with more than one power-supply unit. The operating range of the DC grid is
2056 derived from the operating ranges of the components, especially the active and passive grid
2057 rectifiers.

2058 M.2 Operating range of the components

2059 The components of the DC grid operate in different voltage bands, these are listed in Figure M.1.
2060 The top grey bar indicates the operating range of the DC grid.



2061

2062 Source: ZVEI & consortium DC-INDUSTRIE2, System concept DC-INDUSTRIE2 [Online]. Available at [https://dc-](https://dc-industrie.zvei.org/en/publications/system-concept-for-dc-industrie2)
2063 [industrie.zvei.org/en/publications/system-concept-for-dc-industrie2](https://dc-industrie.zvei.org/en/publications/system-concept-for-dc-industrie2). Reproduced with the permission of DC
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2065 **Figure M.1 – Operating ranges of the components (line-to-line voltage)**

2066 The operating ranges of the components shown in Figure M.1 result in two reasonable voltage
2067 bands:

- 2068 – one band with the nominal voltage 650 V (for AIC on 400 V AC or B6 rectifiers on 480 V AC)
- 2069 and
- 2070 – a band with the nominal voltage 540 V (for B6 rectifiers on 400 V AC).

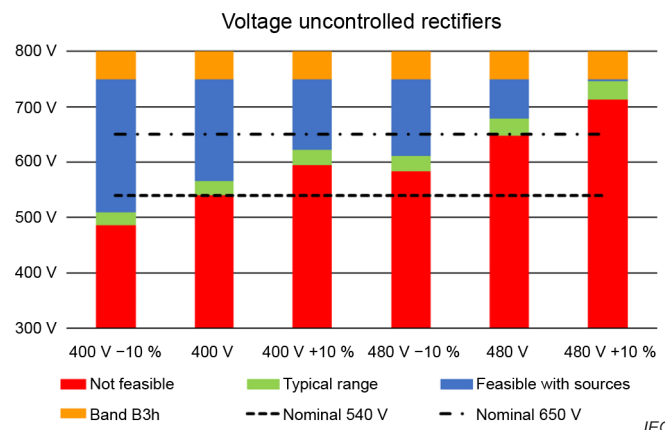
2071 The nominal operating range is based on the AC grids used worldwide, and on the components
 2072 commonly used. This has the advantage that currently available devices and installations are
 2073 suitable for use in the open DC grid without fundamental modifications.

2074 M.3 Regulated feeders

2075 Regulated feeders (AIC) can only generate a DC voltage that is above the rectified AC voltage.
 2076 If the generated DC voltage is also to be smooth to ground (no 150 Hz component), the voltage
 2077 is above twice the peak value of the phase-to-ground voltage. For a 400 V three-phase system,
 2078 this is approximately 650 V. Operation below 600 V can occur if a very large current is drawn
 2079 from the DC mains. The AIC then loses its controllability and acts as an uncontrolled rectifier,
 2080 with the freewheeling diodes acting as rectifier diodes. Due to the high load on the freewheeling
 2081 diodes, this state only lasts a few milliseconds. Upwards, the operating range is limited by the
 2082 voltage stability of the components. In addition, the efficiency decreases with increasing DC
 2083 voltage.

2084 M.4 Uncontrolled feeders

2085 Uncontrolled feeders at 400/480 V AC generate a voltage corresponding to the rectification
 2086 value. This depends on line-side choking, the load and the actual line voltage; a commonly used
 2087 choking of 4 % short-circuit voltage u_k results in a DC voltage of approximately $1,35 \times U_{AC}$.



2088

2089 Source: ZVEI & consortium DC-INDUSTRIE2, System concept DC-INDUSTRIE2 [Online]. Available at [https://dc-](https://dc-industrie.zvei.org/en/publications/system-concept-for-dc-industrie2)
 2090 [industrie.zvei.org/en/publications/system-concept-for-dc-industrie2](https://dc-industrie.zvei.org/en/publications/system-concept-for-dc-industrie2). Reproduced with the permission of DC
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2092 **Figure M.2 – DC voltage of uncontrolled rectifiers (line-to-line)**

2093 Figure M.2 shows in green the typical DC voltage range depending on the mains voltage and
 2094 the permissible tolerances. The lower limit of the green area is $U_{DC} = 1,35 \times U_{AC,eff}$ while the
 2095 upper limit is $U_{DC} = \sqrt{2} \times U_{AC,eff}$. Higher voltages (blue or orange range) can occur when
 2096 sources feed in energy; the orange range corresponds to the voltage band B3.

2097 M.5 Typical DC loads

2098 Typical loads are drive inverters and DC/DC converters. If the supply voltage is too low, the
 2099 specified rated power can no longer be ensured. The upper voltage limit is usually set by semi-
 2100 conductor devices (typically 1 200 V reverse voltage) and electrolytic capacitors (typically
 2101 2×400 V or 2×450 V rated voltage in series).

2102 **M.6 Converters for energy storage or photovoltaic**

2103 Converters for energy storage or PV are always adapted to the conditions of the feeding source,
2104 therefore there are no fundamental restrictions here.

2105 **M.7 DC breakers**

2106 DC breakers are used as protection devices, they also monitor overvoltage and undervoltage.
2107 They are active in voltage bands B2, B3 and B4 and are only switched-off for operational
2108 reasons and in the event of faults.

2109 If the voltage of the DC grid exceeds the value of U_5 (880 V), the DC breaker disconnects the
2110 DC sector not later than after 1 ms.

2111 If the voltage of the DC grid exceeds U_4 (800 V), the DC breaker disconnects after 5 s.

2112 If the voltage of the DC grid dips below U_1 (400 V), the DC breaker disconnects no later than
2113 after 1 ms.

2114 **M.8 Nominal voltage**

2115 The DC grid is operated in a voltage band. The limits of this voltage band depend on the supplier
2116 topology and the supplying AC grid. For regulated feeders and uncontrolled feeders on at least
2117 480 V AC, the nominal voltage is set to 650 V. Uncontrolled feeders on a 400 V AC grid have a
2118 nominal voltage of 540 V. This specification results in the following maximum possible phase-
2119 to-phase voltages on an inverter-supplied motor. See Table M.1.

2120 **Table M.1 – Nominal voltage in DC-INDUSTRY**

	Case 1	Case 2
Nominal DC voltage	540 V	650 V
Maximum motor voltage	$540 \text{ V} \times 0,7 \approx 380 \text{ V}$	$650 \text{ V} \times 0,7 \approx 460 \text{ V}$

2121

2122 At a nominal voltage of 650 V, a standard line motor can therefore be operated at rated power
2123 without any problems. At a nominal voltage of 540 V, standard line motors have a low power
2124 derating, which is, however, usual for inverter-supplied drives.

2125 **M.9 Voltage bands and limits**

2126 Voltage bands and operating statuses are described there; specific values for the voltage limits
2127 and the associated times are not defined in this document. Figure M.3 shows these voltage
2128 limits (the respective upper limit U_X of the voltage in the band BX) and describes the most
2129 important properties; voltage band B3 defines the nominal working range of the DC grid. In this
2130 voltage band (at the terminals of the devices), the grid can permanently operate. The other
2131 voltage bands are avoided, the DC grid only stays temporarily in these other bands.

Band	Nominal voltage: 540 V	Nominal voltage: 650 V
Forbidden band B7 - Damage of devices is very likely		
U6 2 000 V		
Overvoltage protection band B6 - Switching operations can cause this voltage range - Surge protection devices (SPDs) operate and try to protect devices		
U5 800 V		
Temporary overvoltage band B5 - Surge protection devices (SPD) are not active - Breakers disconnect in this band - Insulation and components shall withstand this for up to 5 s - Devices may lose functionality in order to protect themselves		
U4 800 V		
Overvoltage band B4 - Devices may reduce their power - This shall not last longer than 60s - Measures to reduce the voltage must be taken (e.g. charge storage, switch-on power resistors)		
U3 750 V		
Nominal band B3 - Normal operating range - Devices shall be operated permanently - Devices perform with their rated power		
U2 485 V 620 V		
Emergency band B2 - Overload condition - Loads have to be reduced - AIC must only be operated for a few milliseconds		
U1 400 V		
Blackout band B1 - Smart breakers disconnect - Band will be used during pre-charging - Occurs briefly during short-circuit conditions		

IEC

2132

2133 Source: ZVEI & consortium DC-INDUSTRIE2, System concept DC-INDUSTRIE2 [Online]. Available at <https://dc-industrie.zvei.org/en/publications/system-concept-for-dc-industrie2>. Reproduced with the permission of DC
 2134 INDUSTRY.
 2135

2136

2137

Figure M.3 – Voltage bands and limits in DC-INDUSTRY

2138 – B1: Blackout band (< 400 V):

2139 When the voltage falls below U_1 , the DC breakers open. Therefore, the DC grid is only in
 2140 this area for a short time (e.g., in the case of short circuits), except during pre-charging.

2141 – B2: Emergency band (400 V to 620 V, AIC connected to 400 V AC):

2142 This band is characterized by a large overload. The load will be reduced such that the DC
 2143 grid does not reach band B1. Devices will reduce their performance. If B2 is reached by a
 2144 fault in the DC grid and there is still a connection to the AC grid, high balancing currents are
 2145 generated by the power supply units; therefore, in this case, AICs can only be operated for
 2146 a few milliseconds. On the other hand, devices such as drive inverters can also be operated
 2147 in voltage band B2 for a longer period of time if the DC grid is disconnected from the AC
 2148 grid and is supplied from a storage device.

2149 – B3: Nominal band (620 V to 750 V for AIC connected to 400 V AC):

2150 This is the normal working range of the DC grid. It is characterized by a power balance
 2151 between local generation (e.g., of PV systems), feed-in from the AC grid and the
 2152 consumption of the loads. All devices are designed for permanent operation in this voltage
 2153 band.

- 2154 – B4: Overvoltage band (750 V to 800 V):
 2155 In this area, measures will be taken to prevent the shutdown threshold of the devices (800 V)
 2156 from being reached. This can be, for example, feeding back into the AC grid, charging
 2157 energy storage systems, but also switching on opportunity loads. This condition does not
 2158 last longer than 60 s and devices can reduce their performance in this state. In principle,
 2159 however, the function of the grid is retained. The restriction to 60 s is due to increased
 2160 switching losses in the devices.
- 2161 – B5: Temporary overvoltage band (800 V to 880 V):
 2162 Overvoltages can arise due to switching actions, faults and braking of drives. A temporary
 2163 overvoltage of up to 880 V is unproblematic for conventional 400 V electrolytic capacitors
 2164 (two in series connection). With commonly used 1 200 V semiconductors, however, the limit
 2165 of dielectric strength can be reached by internal switching actions; such devices can lose
 2166 their function in this area in order to protect themselves. If the voltage stays in this band for
 2167 longer than 5 s, the upstream DC breaker opens to protect all devices. Overvoltage
 2168 protection devices are not active in this band.
- 2169 – B6: Overvoltage protection band (880 V to 2 000 V):
 2170 Through switching actions, in particular of the overcurrent protection devices, short-term
 2171 overvoltages (in the μs range) can be generated, which lie within this voltage band. If DC
 2172 breakers switch-off an overload or a short circuit, currents flow in the supply lines, which
 2173 are usually a multiple of the operating current. When switching off, the energy stored in the
 2174 parasitic inductance of the cabling will then be dissipated.
 2175 Transient overvoltages up to $U_6 = 2 \text{ kV}$ were observed in existing DC grids, resulting in no
 2176 abnormalities. Devices connected to the DC grid are tested according to IEC 61000-4-5 with
 2177 a 1,2/50 μs pulse and 2 kV anyway. This is the rationale for choosing this voltage level.
- 2178 – B7: Forbidden band:
 2179 In this voltage band, damage to the devices (varistors, semiconductors, capacitors) is
 2180 extremely likely.

2181 **M.10 Operating status of the DC grid**

2182 **M.10.1 General**

2183 Apart from B3, the voltage bands B1 to B6 can only be reached temporarily in normal operation
 2184 mode. Since short-term overvoltage or undervoltage, respectively, is less critical than longer-
 2185 lasting ones, a temporal evaluation can be carried out. An operating status A_x can be
 2186 determined with voltage band B_x and duration S_x . It is assumed here that the duration of the
 2187 transient overvoltage events is so short that it does not significantly affect the service life of the
 2188 equipment. Figure M.4 shows the operating status of the DC grid.

2189 **M.10.2 Duration for the operating statuses**

- 2190 S1: Transient state, typically only a few microseconds
 2191 S2: Error state, for example caused by switching operations; typically lasting up to 1 ms
 2192 S3a/S3b: Voltage control state – active components work against voltage deviations
 2193 S4: Permanent state – regular operation

Upper voltage limit U_x in DC grid for nominal voltage 540 V / 650 V		Voltage band	S1: $t < 50 \mu\text{s}$	S2: $100 \mu\text{s} \leq t \leq 50 \mu\text{s}$	S3a: $1 \text{ ms} \leq t \leq 5 \text{ s}$	S3b: $5 \text{ s} \leq t \leq 60 \text{ s}$	S4: $t > 60 \text{ s}$
Voltage ↑	U6: 2 000 V	B7	A7				
		B7	A6	A7			
	U5: 880 V	B5	A4	A5	A5	A7	A7
		B4	A3	A3	A3	A4	A5
	U4: 800 V	B3	A3	A3	A3	A3	A3
		B2	A4	A4	A2	A2	A2
	U3: 750 V	B2	A4	A4	A2	A2	A2
		B1	A4	A2	A1	A1	
U3: 485 / 620 V	B1	A4	A2	A1	A1		
U1: 400 V	B1	A4	A2	A1	A1		

Time →

2194

IEC

2195 Source: ZVEI & consortium DC-INDUSTRIE2, System concept DC-INDUSTRIE2 [Online]. Available at <https://dc-industrie.zvei.org/en/publications/system-concept-for-dc-industrie2>. Reproduced with the permission of DC
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2198

2199 **Figure M.4 – Operating status depending on voltage and duration**2200 **M.10.3 Examples for the operating statuses**

2201 First example:

- 2202 – Short-term voltage dip, e.g. due to short circuit switched off quickly.
- 2203 – Voltage in band B1 for $t < 100 \mu\text{s} \Rightarrow$ Operating status A4.
- 2204 – A4: Devices can reduce power without affecting continuous operation.

2205 Second example:

- 2206 – Voltage overshoot ($800 \text{ V} < U < 880 \text{ V}$) due to emergency braking of a drive.
- 2207 – Voltage in voltage band B5 for up to 5 s \Rightarrow Operating status A5.
- 2208 – A5: Devices can switch off for self-protection.

2209 **M.10.4 Description of operating statuses**

- 2210 – A7: Prohibited status:
 - 2211 • Damage to equipment is very likely.
 - 2212 • This status is avoided.
- 2213 – A6: Overvoltage protection devices (SPD) active:
 - 2214 • Overvoltage protection devices are engaged and limit the voltage to $\leq U_6$.
 - 2215 • SPDs can only operate for a short time, otherwise overheating is imminent.
 - 2216 • Device can switch off for self-protection.
 - 2217 • Protection of the devices cannot be guaranteed completely.
- 2218 – A5: Overvoltage, SPDs not active
 - 2219 • Voltage is too high but is not clamped by SPDs.
 - 2220 • Devices can switch off for self-protection.
- 2221 – A4: Abnormal status
 - 2222 • Devices endure this condition.
 - 2223 • Devices continue to work.

- 2224 • Devices can reduce power.
- 2225 – A3: Normal working range
- 2226 • Devices provide their rated power.
- 2227 – A2: Acute undervoltage
- 2228 • Sources cannot meet the necessary power demand.
- 2229 • Devices continue to operate.
- 2230 • Devices can reduce power.
- 2231 • Possibly load shedding to stabilize the system.
- 2232 • If power supply units have a connection to the AC grid, they can switch off for self-
- 2233 protection if the currents are too high.
- 2234 – A1: Blackout status
- 2235 • Shut down the devices.
- 2236 • Possibly restart the pre-charging procedure.
- 2237
- 2238

2239

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¹ Withdrawn.

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² Withdrawn.

³ Withdrawn.

⁴ Withdrawn.

⁵ A consolidated version of this document exists, comprising IEC 61000-2-2:2002, IEC 61000-2-2:2002/AMD1:2017 and IEC 61000-2-2:2002/AMD2:2018.

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