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Aerospace — Characteristics of aircraft electrical systems

Aéronautique — Caractéristiques des systèmes électriques à bord des aéronefs

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Foreword

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International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 1540 was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 1, *Aerospace electrical requirements*.

This third edition cancels and replaces the second edition (ISO 1540:1984), which has been technically revised.

Introduction

The purpose of this International Standard is to foster compatibility between the providers, distributors and users of aircraft electrical power. This third edition takes into account several recent trends in aircraft electrical system, including that towards increased nonlinear load content on aircraft. It defines design requirements for electrical equipment that will be verified by the test requirements specified in ISO 7137.

Limits defined in this International Standard are based upon historical as well as near term projected equipment characteristics, including recent trends towards increased nonlinear, electronic user equipment. Since these limits are influenced by the overall combination of source, distribution and user equipment, background to their integration sensitivities is also included herein. The intention is to provide system integrator guidance, without restricting flexibility of means by which the specified interface characteristics are achieved. This revision also addresses several power types not at present common on large transport aircraft, such as variable frequency a.c., 230/400 V a.c. and 42 V d.c.

Also fundamental to the basis of these requirements is the assumption that cost-effective utilization equipment needs to be usable on a wide range of new aircraft. This results in some penalties typically only realized on large aircraft, e.g. those associated with longer distribution feeder voltage drops, being accepted for smaller aircraft equipment. The realities of these situations and recent user equipment trends may likely be the reason for differences between this International Standard and other historical standards.

Aerospace — Characteristics of aircraft electrical systems

1 Scope

This International Standard specifies the characteristics of electrical power supplied to the terminals of electrical utilization equipment installed in an aircraft. It is intended to support the interface definition for user equipment designed to accept electrical power on a variety of new civil aircraft applications, such as those certified via the Technical Standard Order (TSO) certification process. It might not be desirable for equipment targeted to a single application or specific military application to follow this International Standard because of the penalties associated with multi-application.

This document also attempts to provide background to the development of these requirements that may be useful to those designing and/or integrating modern aircraft electrical systems. The delivered quality of this electrical power is a result of the combined characteristics of the electrical power source, distribution and user equipment. While only user equipment restrictions are specifically defined, background to key source and distribution equipment interfaces are identified in order to support development of the overall system.

A wide variety of electrical supply types and distribution parameters have been considered, as may be found on both small and large transport aircraft. Sources considered include physically rotating and static types, provided either on-aircraft, or as part of the ground support equipment. Distribution voltages addressed are

— nominal 14 V, 28 V and 42 V d.c.;

— nominal 26 V a.c., 400 Hz, one-phase;

— nominal 115/200 V rms and 230/400 V rms a.c., both one-phase and three-phase, at either a nominal 400 Hz constant frequency (CF), or over a variable frequency (VF) range which includes 400 Hz.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 6858, *Aircraft — Ground support electrical supplies — General requirements*

ISO 7137:1995, *Aircraft — Environmental conditions and test procedures for airborne equipment* [1)]

1) Endorsement of EUROCAE ED-14C and RTCA/DO-160C.

3 Terms and definitions

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

3.1
abnormal electrical system operation
aircraft operation where a malfunction or failure in the electrical system has taken place and the protective devices of the system are operating to remove the malfunction or failure from the rest of the system before the limits for abnormal power quality are exceeded

NOTE Once initiated, abnormal operation may continue for the remainder of a flight with the power quality delivered to users exceeding normal operation limits, but staying within abnormal operation limits.

3.2
abnormal power quality limits
limits provided at user terminals during abnormal operation that take into account the operating tolerances of the system protective devices and any inherently limiting characteristics of the system design

NOTE See also 3.30.

3.3
crest factor
absolute value of the ratio of the peak to the rms value of an a.c. waveform measured under steady-state conditions

NOTE 1 It is unitless and the ratio for a true sine wave is equal to $\sqrt{2}$.

NOTE 2 Written as $| V(\text{pk}) / V(\text{rms}) |$.

3.4
current modulation
difference between the maximum and minimum value of electrical current drawn during conditions of cyclic or randomly repeating current variation

NOTE Measurable current modulation by user equipment can impact the quality and/or stability of the provided electrical power.

3.5
distortion (current or voltage)
rms value of the a.c. waveform exclusive of the fundamental component in an a.c. system, or the rms value of the alternating (ripple) component on the d.c. level in a d.c. system

NOTE a.c. system distortion can include harmonic and non-harmonic components. Harmonics are sinusoidal distortion components which occur at integer multiples of the fundamental frequency. Interharmonics are distortion components which occur at non-integer multiples of the fundamental frequency. These and all other elements of waveform distortion are included in this general definition of distortion. (See also 3.23 and 3.25.)

3.6
displacement factor
⟨a.c. user equipment⟩ cosine of the angle (Φ) between the input current (provided at the fundamental frequency) and the input voltage (provided at the fundamental frequency)

NOTE This value does not include the effect of distortion in the input current (and/or voltage) waveform, and it is therefore not applied in this specification in favour of the more general power factor definition. (See also 3.35.)

3.7
distortion factor (current or voltage)
ratio of the distortion in a waveform to the rms value of the fundamental component of the waveform

NOTE 1 The distortion factor is typically expressed as a percentage:

$$df\ \text{(per cent)} = 100 \times \frac{\sqrt{(X_{\text{rms}}{}^2 - X_1{}^2)}}{X_1}$$

where

X_{rms} is the rms value of the complete (voltage or current) waveform;

X_1 is the rms value of the fundamental frequency component.

NOTE 2 In a d.c. system, this fundamental component is true d.c. (See also 3.5, 3.43.)

3.8
distortion spectrum
itemization of the amplitude of each frequency component found in the a.c. or d.c. distortion

NOTE 1 Its components may be harmonic or non-harmonic multiples of the fundamental frequency, some of which result from amplitude or frequency modulation.

NOTE 2 Only components up to a frequency of 16 kHz (for 400 Hz, CF equipment) and 32 kHz (for VF equipment) are addressed in this International Standard to clearly separate requirements related to electrical power quality from those related to electromagnetic compatibility (EMC).

3.9
distribution system
collection of interconnection and circuit protection equipment between power sources and user equipment

NOTE See Figure 1.

3.10
drift
extremely slow variation in a random manner of a controlled parameter (such as frequency in a CF system) inside of the specification limits from causes such as ageing of components or self-induced temperature changes

3.11
drift rate
speed of variation due to drift of a controlled parameter

NOTE Drift rate is typically expressed in Hz/min or V/min, depending upon the parameter examined.

3.12
electric engine start operation
special case of normal electrical system operation where an extreme demand of electrical power is required to support the starting of a main engine or the auxiliary power unit

NOTE 1 Normal voltage transient limits may be exceeded during this condition with only selected utilization equipment required to operate throughout the event.

NOTE 2 Typical engine start times are between 15 s and 90 s.

3.13
electric power generating system
EPGS
combination of rotating and static electrical power sources and the devices which provide their control and protection

3.14
electric power system
combination of electrical power sources, conversion equipment, control and protective devices and utilization equipment connected via a distribution network

NOTE Also called simply ‘system’.

3.15
emergency electric system operation
electrical system condition during flight when the primary electric power system becomes unable to supply sufficient or proper electrical power, thus requiring the use of independent and potentially limited source(s) to power a reduced complement of distribution and utilization equipment selected to maintain safe flight and personnel safety

3.16
emergency power source
generator, power conversion device (or a combination thereof not involving part of utilization equipment) or battery installed to provide independent electrical power for essential purposes during conditions of electrical emergency in flight

3.17
external power unit
ground power unit
GPU
rotating or static source (or combination thereof) supplied by the maintenance facility to source electrical power demands while the aircraft is not in flight

NOTE It may be either a point-of-use or centrally located ground power electrical supply in land-based facilities, or a shipboard power supply in marine applications.

3.18
frequency
reciprocal of the period of the a.c. waveform

NOTE 1 Frequency is measured in hertz (Hz).

NOTE 2 Steady-state frequency is the time average of the frequency over a period not to exceed one second. Instantaneous frequency is the frequency of a single cycle.

3.19
frequency modulation
cyclic and/or random variation of instantaneous frequency about a mean frequency during steady-state conditions

NOTE Amplitude of the frequency modulation is equal to the difference found between the maximum and minimum frequency measured over a one minute interval.

3.20
frequency modulation rate
rate of change of frequency due to frequency modulation

NOTE Frequency modulation rate is measured in hertz per second (Hz/s).

3.21
fundamental frequency
frequency of the primary power producing component of a periodic waveform supplied by the generation system (component of order 1 of the waveform’s Fourier series representation)

3.22
ground
point along a conductive structure or cable which serves as an essentially zero potential reference for a.c. and/or d.c. voltages

3.23
harmonics
sinusoidal voltage or current components (distortion) of a periodic waveform which occur at a frequency that is an integer multiple of the fundamental frequency

NOTE 1 Most nonlinear loads generate odd-numbered harmonics; for example, as a result of full wave rectification of the input power.

NOTE 2 The frequencies at which these ‘characteristic harmonics’ are produced by a user with a diode-type input rectifier are determined by the following equation:

$$f_H = (k \times q \pm 1) \times f_1$$

where

H is the number of the harmonic;

k is an integer, beginning with 1;

q is an integer, representing the number of rectifier commutations per cycle;

f_1 is the fundamental frequency.

NOTE 3 Half wave rectification produces even-numbered harmonics, which cause very undesirable results (e.g. d.c. content) in the a.c. power system. Full wave rectification at the input of single-phase power users results in ‘triplen’ harmonics at odd multiples of three times the fundamental frequency. These are also very undesirable given the potential quantity of single-phase users and the fact that these harmonics interact with the distribution system’s normally high (zero sequence) impedance to this frequency. User distortion current requirements are therefore intentionally restrictive for even and triplen harmonics. (See also 3.5, 3.39.)

3.24
impedance
complex electrical characteristic of a device or group of devices which relates the ratio of the phasor steady-state voltage to the phasor steady-state current

3.25
individual frequency component of distortion
ratio of the rms value of the waveform distortion at one specific frequency to the rms value of the fundamental component of the waveform

NOTE 1 See also 3.8.

NOTE 2 The individual frequency components of voltage distortion are expressed as

$$D_{vn} = 100 \times (V_n / V_1)$$

where

V_n is the rms value of an individual, non-fundamental frequency component;

V_1 is the rms value of the fundamental frequency component.

3.26
linear load
user of electrical power whose total impedance is constant despite variations in applied voltage and whose current spectrum matches that of the applied voltage

NOTE Conversely, nonlinear loads may have changing impedance with applied voltage and a different spectral content from that of the applied voltage source.

3.27
load unbalance
difference between the highest phase power draw and lowest phase power draw in volt-amperes for a three-phase a.c. power user

3.28
momentary power interruptions
short term power interruptions during which time the supplied voltage will decay at a rate dependent upon bus and load characteristics, as is typical during transfer of power sources

3.29
normal electrical system operation
conditions which include all intended modes of aircraft ground and flight operation during which no electrical system faults or malfunctions occur, except instances of propulsion engine or auxiliary power unit electric starting

NOTE 1 It assumes proper functioning of all equipment within defined operating procedures and limits. Examples of such operation are switching of utilization equipment loads, engine speed changes, source switching and synchronization, and the intended paralleling of power sources.

NOTE 2 Normal operation also includes momentary power interruptions, transients and spikes. (See also 3.1.)

3.30
normal power quality limits
limits which should be maintained during periods of normal electrical system operation

NOTE See also 3.2.

3.31
per unit
PU
standardized quantity in a system where various parameters are quantified with respect to a base value

NOTE 1 The base value is generally the rated value.

NOTE 2 For power systems this is typically applied to the powers, voltages, currents, or impedances where ‘per unit’ numbers equal the actual parameter value divided by the base values.

EXAMPLE In a 115/200 V rms, 3-phase, 120 kVA system: 1 PU power is 120 kVA; 1 PU voltage is equal to 115 V rms; 1 PU phase current is equal to 348 A rms; and 1 PU impedance is equal to 0,33 ohms. A three-phase load on this system that consumes 52 A rms per phase would be considered as drawing 0,15 PU power.

3.32
phase voltage
phase-to-neutral voltages supplied to single-phase or three-phase utilization equipment

NOTE All a.c. voltage values defined in this International Standard are rms, line-to-neutral quantities unless otherwise specified.

3.33
phase voltage displacement
maximum angular separation (about a nominal 120 degrees) between the zero voltage points of any two of the three voltage waveforms in a three-phase a.c. system during steady-state conditions

3.34
phase voltage unbalance
maximum difference between rms phase voltage amplitudes during steady-state conditions

NOTE $V_{\text{UNB}} = \text{max.}\{V_{\text{AN}}, V_{\text{BN}}, V_{\text{CN}}\} - \text{min.}\{V_{\text{AN}}, V_{\text{BN}}, V_{\text{CN}}\}$

where

V_{AN}, V_{BN}, V_{CN} are the phase voltage magnitudes.

3.35
power factor
a.c. user equipment feature determined by the ratio of the real, or active, power consumed in watts to the apparent power drawn in volt-amperes, with

NOTE 1 $PF = P / S$

where

P is the real power in watts;

S is the apparent power, product of rms voltage and current, in volt-amperes.

NOTE 2 This definition of power factor includes the effect of distortion in the input current (and/or voltage) waveform.

NOTE 3 When the fundamental current waveform drawn by a user electrically lags the fundamental voltage waveform (as is typical in inductive loads), it is considered a ‘lagging’ power factor. Likewise if the current waveform electrically leads the voltage waveform (as expected for capacitive loads), it is considered a ‘leading’ power factor. When the user only draws real power (no reactive power) and its input current is exactly in phase with the supplied voltage, it is termed a ‘unity’ power factor load ($PF = 1$). (See also 3.6.)

3.36
primary power source
generator, usually driven by one of the aircraft propulsion engines, and any associated power conditioning equipment (not forming part of the utilization equipment) installed to provide electrical power during all phases of aircraft operation

3.37
ripple
cyclic variation about the mean level of the d.c. current or voltage value during steady-state electrical system operation

NOTE Since it is not always a symmetrical quantity, the difference between upper and lower peak values is measured instead of the mean value of voltage or current.

3.38
rms value (voltage or current)
value of voltage or current based upon the equivalence to the d.c. value that would yield the same power transfer in a d.c. circuit

NOTE The rms voltage value can be computed as

$$V_{rms} = \sqrt{\frac{1}{T} \int_0^T v^2(t)\, dt}$$

where

T is the waveform time period;

$v(t)$ is the instantaneous voltage at time t.

3.39
sequence impedances (/harmonics)
positive, negative and zero sequence impedances, determined from a mathematical analysis method termed ‘Symmetrical Components’ which breaks the quite difficult problem of analysing a three-phase unbalanced system into a study of two balanced three-phase circuits and one zero-phased circuit

NOTE The practical application of these characteristic impedances allows for more complex power system analysis, including the effects of harmonic currents to produce harmonic voltages. Positive and negative sequence impedances are determined by the resistance and reactance of the generating power source and the distribution network. In a.c. electrical systems, therefore, these impedances increase with increasing source (generator) frequency. For passive elements such as distribution feeders, the positive and negative sequence impedances are identical; this is not true for electrical machines.

Zero sequence impedances strongly relate to the impedance of the system to current flow through the power system neutral. Therefore this impedance is heavily influenced by the application of a wired or structure return path, and for the latter case, the exact three-phase wire bundle configuration and its distance from the return path structure. Unbalanced currents and fault currents flow through this impedance.

While positive, negative and zero sequence impedances or currents are traditionally associated with particular harmonic multiples, the harmonics present in a three-phase power system can also be characterized as having positive, negative and zero sequence components. Positive sequence current harmonics consist of three phasors, equal in magnitude and separated from each other by 120° phase displacement, with the same phase sequence as phasors representing the fundamental bus current.

Negative sequence current harmonics also consist of three phasors, equal in magnitude and separated from each other by 120° phase displacement, but with a phase sequence which is opposite to that of phasors representing the fundamental bus current. Whereas positive sequence harmonics provide for positive torque contribution to an a.c. bus fed synchronous motor, negative sequence harmonics negate torque in a.c. bus fed synchronous motors.

Zero sequence harmonics consist of three phasors which are likewise equal in magnitude, but with identical phase angles, and are therefore described as being ‘in phase’ with each other. Whereas balanced positive and negative sequence harmonics do not result in any neutral conductor current, balanced zero sequence harmonics, such as those from single-phase to neutral nonlinear loads, result in three times the harmonic current in the neutral conductor than is present in any phase. The third harmonics of fundamental phase A, B and C currents, termed ‘triplen’ harmonics, have identical phase angles and therefore act with a magnitude which is triple that of any one phasor. (See 3.25.)

3.40
spike
variation from the controlled steady state or transient level of a characteristic that occurs for an extremely short duration (microseconds)

NOTE 1 Spikes generally produce a voltage peak and/or wave train, the characteristics of which are dependent on relative impedances of the source, the line, and of the utilization equipment, as well as the manner in which the event occurs.

NOTE 2 Typical voltage spikes result from the switching of inductive or capacitive load elements.

3.41
steady state
operating condition of the system when only negligible changes in electrical parameters appear

3.42
system stability
aspect of system dynamic compatibility associated with certain system performance criteria defined at the power system interfaces

NOTE 1 For aircraft power systems the primary interface is the electrical bus.

NOTE 2 The key performance criteria are therefore associated with the maintenance of voltage and current values, and spectral content thereof, at various points on that bus within the limits defined by this International Standard in the presence of both internal and external stimuli.

3.43
total harmonic distortion (current or voltage)
ratio of the rms value of a waveform's harmonics to the rms value of its fundamental component

NOTE 1 See also 3.7, 3.8.

NOTE 2 The total harmonic distortion may be defined by the following equation:

$$THD_X \text{(per cent)} = 100 \times \frac{\sqrt[2]{\sum_{2}^{n} X_n^{\,2}}}{X_1}$$

where

X_1 is the fundamental value of current or voltage;

X_n is the nth harmonic value of current or voltage.

3.44
transient
momentary variation of a characteristic from its steady-state limits, and back to its steady-state limits, as a result of a system disturbance

NOTE 1 Rapid load or engine speed changes followed by the conditioned response of the generating system, as well as brief voltage variations or interruptions due to normal source or load switching are considered normal transients.

NOTE 2 Transients which exceed normal transient limits as a result of an abnormal disturbance and eventually return to steady-state limits are defined as abnormal transients.

3.45
uninterruptible power
power (typically d.c.) delivered to essential and/or voltage transient sensitive users in such a manner that normal power interruptions are either eliminated or reduced in severity and probability

3.46
utilization equipment
unit or functional group of units which receives electrical power on the aircraft

NOTE Sometimes referred to as 'load equipment'.

3.47
utilization equipment rating
maximum power a user can be expected to continually consume over a time period which is not less than 200 ms

3.48
voltage modulation
⟨a.c. voltage⟩ cyclic and/or random variation of the a.c. peak voltage around a mean value during steady-state conditions

NOTE 1 Voltage modulation amplitude is the difference between the maximum and minimum peak voltage values that occur in a one second period during steady-state operating conditions. (See 3.27.)

NOTE 2 Frequency characteristics of voltage modulation are the components at individual frequencies that together make up the voltage modulation envelope waveform.

NOTE 3 For d.c. power, see **ripple** (3.37).

3.49
voltage regulation
result of action by a voltage control mechanism and the source being controlled over the normal operating range of the equipment

NOTE 1 d.c. voltages used herein are defined by the mean value measured between the positive terminal and ground.

NOTE 2 Steady-state d.c. voltages are the time average of the respective voltage values over a time period of between 0,2 s and 1 s.

4 Requirements applicable to all systems

4.1 General

Electrical power quality characteristics described in this document apply at the electrical input terminals of utilization equipment. These characteristics include both normal and abnormal operating conditions of the aircraft electrical power system during all phases of flight and ground operation. They have specifically been examined to include realistic operating conditions for a large variety of aircraft.

All of the power system equipment should therefore be designed so that normal service maintenance will ensure the retention of these specified characteristics throughout the full range of operational and environmental conditions likely to be encountered in the aircraft, or support facility, in which they are installed.

In order to provide the necessary compatibility among electric power source, distribution and utilization equipment to ensure these characteristics, constraints applicable to each of these, at the subsystem and equipment level, are required.

General requirements found in this clause are intended for incorporation into source and utilization equipment specifications. They relate to functional aspects of the power system interface. Detailed requirements for user equipment, intended to be verified by test, are found in Clause 10. Detailed requirements for external and on-board electrical power source equipment are found in related standards and specifications. Typical subsystem level aspects, such as adequate control over the load balance, or the aggregate effects of nonlinear load, are not easily addressed by an industry standard. It is the airframer’s and/or the subsystem integrator’s responsibility to ensure that adequate measures are taken in the definition and application of these subsystems such that the essential coordination occurs. Clause 11 includes applicable background in this area.

Compatibility also involves topics that are outside of the scope of this document, including the topic of electromagnetic compatibility (EMC). Specific aircraft electronic equipment requirements related to EMC and other environmental effects are defined in ISO 7137.

4.2 On-aircraft power sources

4.2.1 Alternating current (a.c.) power sources

Primary a.c. power generation shall be three-phase, four-wire, wye-connected supplying a nominal voltage of either 115/200 (line-to-neutral/line-to-line) V rms or 230/400 V rms and an A-B-C phase sequence (see Figure 2). The nominal frequency for constant frequency sources shall be 400 Hz. Variable frequency sources shall provide for a minimum generator frequency that is not less than 360 Hz. Where an auxiliary single-phase supply is provided, it shall meet the line-to-neutral requirements stated herein.

The neutral point of each source of power is normally connected to vehicle structure, which shall then be considered the fourth wire. If vehicle structure is used as the fourth wire, it may be preferable to make this connection close to the point of power distribution in order to minimize the distortion of the supplied a.c. voltage by single-phase rectifier type loads. In the case of aircraft with substantial composite structure, an alternative grounding scheme that carries a neutral return wire to the utilization equipment may be preferred.

Performance of a.c. source equipment at its specific point of regulation (POR) shall be as specified in the applicable specification for that source equipment.

4.2.2 Direct current (d.c.) power sources

Direct current power sources shall provide for a two-wire system having a nominal voltage of 14 V, 28 V or 42 V d.c. Performance of the d.c. source equipment at its specific point of regulation (POR) shall be as specified in the applicable specification for that source equipment.

The negative of each power source is normally connected to vehicle structure, which shall then be considered the second wire. If vehicle structure is used as the second wire, it is preferable, especially in the case of aircraft with considerable composite structure, to make this connection close to the point of power distribution to utilization equipment. An alternative grounding scheme that carries a neutral return wire through to the utilization equipment may also be applied.

4.3 External power sources

External power sources shall conform to the requirements identified in Clause 3.2 in all areas regarding output of power to the aircraft. Specific requirements for external power sources shall be as specified in ISO 6858. In addition, external power sources may have environmental and/or safety requirements imposed upon them due to local regulations and codes to which they must adhere.

4.4 Source/distribution system coordination

Necessary coordination between the design and control of the electrical power sources and the distribution system, including all of the involved protective devices, shall be such as to ensure that the characteristics of electrical power at the utilization equipment terminals are in accordance with this International Standard. In addition, they shall specifically coordinate to ensure that the failure of any power source and its disconnection from the system does not result in subsequent impaired performance or loss of the remaining power sources.

4.5 Utilization equipment

4.5.1 Equipment operation and performance

Utilization equipment shall maintain its specified performance when supplied with power having the ranges of characteristics detailed herein and shall not degrade the power characteristics beyond their allowed limits. This shall include potential failure modes of the utilization equipment.

When use is required of power having other characteristics, or closer tolerances than are specified herein, the conversion to other characteristics or closer tolerances shall be accomplished as part of the utilization equipment.

The individual specification for the utilization equipment shall state the degrees of degradation of performance, if any, permitted in specific regions of normal, abnormal, emergency system or engine starting operation. Utilization equipment shall not suffer damage or cause an unsafe condition and shall automatically resume specified performance following the return to normal operating conditions from any of these regions of operation.

In the case where equipment would require previous energizing to ensure its operation (pre-heating or storing), its consumption in the waiting period shall be maintained at the minimum value.

4.5.2 Power type

Use of the primary power type generated shall be maximized, and where there are alternatives, due consideration shall be given to the power type requiring the lightest weight distribution cable. Single-phase supplied equipment should be connected between phase and neutral. All equipment for which power consumption exceeds 500 VA should be supplied from a three-phase power source.

These requirements may be disregarded where

- 28 V d.c. is the only supply available;
- emergency operation is required; or
- interrupt-free supplies are required (unless no break power transfer is available on the a.c. supply bus).

Utilization equipment shall preferably use only one power type (a.c. or d.c.). Equipment that uses multiple power types shall provide its specified performance when subjected to simultaneous variations and singular interruptions of each power input within the limits described in this International Standard.

The wiring of return currents shall be carried out as follows:

- no point of equipment internal wiring shall be bonded to its casing; and
- all connections to neutral or negative (d.c.) shall be separately brought out from the equipment before being connected to the structure or ground.

The casing shall be bonded to the aircraft structure by an independent connection. The details of application shall be in accordance with the applicable standards in the areas of interference elimination and bonding.

4.5.3 Power supply interruptions

The loss of power (a.c. or d.c.) or the loss of one or more phases of a.c. power to any utilization equipment terminal, however repetitive, shall not result in an unsafe condition or damage to utilization equipment. Equipment performance in these events shall be as defined in the applicable utilization equipment specification for abnormal operation. Allowances for equipment re-initialization are expected in these circumstances.

In the case of power supply interruptions, the voltage loss may be progressive; so-called transients of normal operation may follow the recovery voltage.

Micro-interruptions or under voltages of variable duration may be seen as interruptions of supply by certain components. In this case, equipment comprising digital circuits and/or memory or sequential circuits shall be the subject of a self-test. (See ISO 7137.)

4.5.4 Power supply input polarity

User equipment is not required to operate, but shall not be damaged when the polarity of the input power it receives is incorrect. Direct current or single phase a.c. user equipment shall accept reversal of power and return inputs without damage. Three-phase user equipment shall accept either incorrect phase sequence (A-B-C) or a momentary condition of a missing phase without damage.

5 Constant frequency (CF) a.c. power system characteristics

5.1 General characteristics

The characteristics below apply to the power at the utilization equipment terminals unless otherwise stated. They have been determined to be suitable for general application. Equipment designed to these characteristics should therefore find ease of compatibility with a wide variety of power sources and aircraft. These characteristics apply to 26 V, 115/200 V and 230/400 V a.c. systems that utilize nominal 400 Hz power generated by rotating or static sources. Voltage differences between the various systems are accommodated within Table 1.

The voltage characteristics apply to line-to-neutral (L-N) quantities; line-to-line (L-L) characteristics should be as a result of the L-N values being as shown.

NOTE All a.c. voltage values are rms values unless otherwise stated. Steady-state a.c. voltages are the time average of the respective voltage values over a time period of between 0,2 s and 1 s. Peak voltages are the maximum instantaneous value of the voltage waveform.

5.2 Steady-state characteristics

5.2.1 Applicability

The characteristics specified in 5.2.2 to 5.2.8 are applicable to the entire range of steady-state operating conditions.

5.2.2 Phase voltage

The individual phase voltages and average of the three phase voltages shall remain within the limits of Table 1.

5.2.3 Phase voltage unbalance

The maximum difference between any two phase voltages shall not exceed the limits of Table 1.

5.2.4 Phase voltage displacement

The angular displacement between any two of the three phase voltages shall not exceed the limits of Table 1.

5.2.5 Voltage modulation

The modulation of phase voltages shall not exceed the limits of Table 1 when measured as the peak-to-valley difference between the maximum and minimum peak voltages reached on the modulation envelope over a period of at least one second. Frequency components of the modulation shall be within the limits of Figure 3.

5.2.6 Voltage waveform characteristics

The voltage supplied to utilization equipment shall maintain the following waveform characteristics for any phase voltage:

— the crest factor is within the limits of Table 1;

— the voltage distortion factor does not exceed the limit specified in Table 1;

— individual frequency components of distortion, which do not include the fundamental, do not exceed the limits of Figure 4;

— the d.c. content of the voltage waveform is within the limits of Table 1.

5.2.7 Frequency

The frequency of the power supplied shall be within the limits defined in Table 1.

5.2.8 Frequency modulation

Frequency variations due to modulation shall be such that the departure from the average frequency lies within the limits defined in Figure 5.

5.3 Transient characteristics

5.3.1 Voltage transients

Transient voltages shall remain with the limits of Figure 6 for normal operating conditions, which includes normal power transfers between sources and changes in load demand such as motor starts. Transient voltages shall remain within the limits of Figure 7 for abnormal operating conditions that include the response of the power system because of system faults.

Table 1 — Limits for 400 Hz, 115/200 V a.c. three-phase power at user terminals

Steady-state characteristics	Normal	Abnormal	Emergency
Phase voltages:			
Three-phase average (V rms)	104,0 – 120,5	95,5 – 132,5	104,0 – 120,5
Individual phase (V rms)	100 – 122	94 – 134	100 – 122
Max. unbalance (V rms)	6		8
Displacement (degrees)	116 – 124		
Voltage modulation:			
Max. peak-valley amplitude (V pk)	4,0		
Frequency components	Figure 3		
Voltage waveform:			
Crest factor	1,26 – 1,56		
Distortion factor	8 % total		10 % total
Individual comp. of distortion	6 % max. according to Figure 4		7,5 % max. according to Figure 4
D.C. component (V d.c.)	−0,1 – +0,1		
Frequency:			
Frequency (Hz)	390 – 410	360 – 440	360 – 440
Frequency modulation	Figure 5		
Transient characteristics	**Normal**	**Abnormal**	**Emergency**
Voltage transients	Figure 6	Figure 7	Figure 6
Voltage spikes	Figure 9		
D.C. content		Figure 10	
Frequency transients	Figure 11	Figure 11	
Maximum power interrupt	200 ms	7 s	N/A

NOTE 1 All values shown are measured at utilization equipment input terminals.

NOTE 2 Limits for single-phase systems are as shown for single-phase quantities of three-phase systems.

NOTE 3 Limits for systems of alternative voltage follow those above, except voltage values are 26/115 of those shown for 26 V a.c. systems and 230/115 times those shown for 230 V a.c. systems.

NOTE 4 Unless otherwise stated, limits for abnormal and emergency operating conditions equal those for normal operating conditions.

5.3.2 Voltage spikes

The generation of spike voltage transients due to load switching as seen at the input to utilization equipment shall be within the limits specified in Figure 9. This effect may be imposed upon other system voltage waveforms.

5.3.3 D.C. content transient

The generation of d.c. content transients during abnormal operating conditions shall result in the d.c. content on the a.c. waveform being within the limits specified in Figure 10.

5.3.4 Frequency transients

Normal and abnormal frequency transients shall be within their respective limits of Figure 11.

5.3.5 Simultaneous voltage and frequency transients

Simultaneous voltage and frequency transients shall remain within the respective limits of 5.3.1 and 5.3.4.

5.3.6 Power interruptions

CF a.c. power systems are designed such that in normal operation they either have an interruption in power prior to source power transfers (break power transfers), or they will have a continuous flow of power during the power transfer (no-break power transfers, NBPT). In the latter case, there may be rare circumstances that do not allow NBPT operation, and the utilization equipment will experience an interruption in power. Therefore, all systems shall consider the potential for interruptions in power. The duration of these normal power interruptions shall not exceed the limits of Table 1.

During abnormal operation the CF power source can be interrupted for longer durations to allow time for system fault clearing and reconfiguration. The duration of these abnormal power interruptions shall not exceed the limits of Table 1.

6 Variable frequency (VF) a.c. power system characteristics

6.1 General characteristics

The characteristics below apply to the power at the utilization equipment terminals unless otherwise stated. Equipment designed to these characteristics should therefore find ease of compatibility with a wide variety of power sources and aircraft. Equipment that has lesser needs for frequency range, power quality and/or inter-compatibility of equipment between applications should follow the unique requirements developed for those individual applications.

These characteristics apply to 26 V a.c., 115/200 V a.c. and 230/400 V a.c. systems that utilize VF power. Voltage characteristics for 26 V a.c. and 230 V a.c. L-N systems are simply scaled from the 115 V a.c. L-N values listed in Table 2.

Two VF ranges are considered herein:

a) narrow range, between 360 Hz and 650 Hz;

b) wide range, between 360 Hz and 800 Hz.

The voltage characteristics apply to L-N quantities; L-L characteristics should be as a result of the L-N values being as shown.

NOTE All a.c. voltage values are rms values unless otherwise stated. Steady-state a.c. voltages are the time average of the respective voltage values over a time period of between 0,2 s and 1 s. Peak voltages are the maximum instantaneous value of the voltage waveform.

6.2 Consideration of CF power characteristics

Utilization equipment designed for application with VF electrical power shall also function when provided power from a CF electrical system, as defined by the input characteristics specified in Clause 5. This is necessary since aircraft with VF-type main power sources are likely to also receive power from CF-type auxiliary or external power sources when the engines are not operating.

6.3 Steady-state characteristics

6.3.1 Applicability

The characteristics specified in 6.3.2 to 6.3.7 are applicable to the entire range of steady-state operating conditions.

6.3.2 Phase voltage

The individual phase voltages and average of the three phase voltages shall remain within the limits of Table 2 for narrow-range VF and Table 3 for wide-range VF.

6.3.3 Phase voltage unbalance

The maximum difference between any two of the phase voltages shall not exceed the limits of Table 2 for narrow-range VF and Table 3 for wide-range VF.

6.3.4 Phase displacement

The angular displacement between any two of the three phase voltages shall not exceed the limits of Table 2 for narrow-range VF and Table 3 for wide-range VF.

6.3.5 Voltage modulation

The modulation of phase voltages shall not exceed the limits of Table 2 (narrow-range VF) or Table 3 (wide-range VF) when measured as the peak-to-valley difference between the maximum and minimum peak voltages reached on the modulation envelope over a period of at least one second. Frequency components of modulation shall be within the limits of Figure 3.

6.3.6 Voltage waveform characteristics

The voltage supplied to utilization equipment shall maintain the following waveform characteristics for any phase voltage:

— the crest factor is within the limits of Table 2 for narrow-range VF and Table 3 for wide-range VF;

— the voltage distortion factor does not exceed the limit specified in Table 2 for narrow-range VF and Table 3 for wide-range VF;

— the individual frequency components of distortion, which do not include the fundamental, do not exceed the limits of Figure 4;

— the d.c. content of the voltage waveform is within the limits of Table 2 for narrow-range VF and Table 3 for wide-range VF.

6.3.7 Frequency

In VF systems, the main, engine-driven generators of the primary power system do not regulate the frequency of the a.c. voltage; instead, this frequency varies while tracking (through a ratio) the engine speed. Since the selected frequency range overlaps that expected of external and auxiliary power sources, all VF system frequency requirements are a direct result of the predicted engine speed performance.

Therefore, the steady-state frequency characteristics of the power supplied to VF equipment shall be within the limits defined in Table 2 for narrow-range VF and Table 3 for wide-range VF.

6.4 Transient characteristics

6.4.1 Voltage transients

Transient voltages shall remain with the limits of Figure 8 for normal operating conditions, which includes normal power transfers between sources and changes in load demand such as motor starts. Transient voltages shall remain within the limits of Figure 7 during abnormal operating conditions, which include the response of the power system because of system faults.

6.4.2 Voltage spikes

The generation of spike voltage transients due to load switching shall be held within the limits specified in Figure 9. This effect may be imposed upon other system voltage waveforms.

Table 2 — Limits for narrow-range variable frequency, 115/200 V a.c. three-phase power at user terminals

Steady-state characteristics	Normal	Abnormal	Emergency
Phase voltages:			
Three-phase average (V rms)	104,0 – 120,5	98,5 – 132,5	104,0 – 120,5
Individual phase (V rms)	100 – 122	97 – 134	100 – 122
Max. unbalance (V rms)	6		8
Displacement (degrees)	116 – 124		
Voltage modulation:			
Max. peak-valley amplitude (V pk)	4,0		
Frequency components	Figure 3		
Voltage waveform:			
Crest factor	1,26 – 1,56		
Distortion factor	8 % total		10 % total
Individual component of distortion	6 % max. according to Figure 4		7,5 % max. according to Figure 4
D.C. component (V d.c.)	−0,1 – +0,1		
Frequency variation	360 – 650 (Hz)		
Transient characteristics	**Normal**	**Abnormal**	**Emergency**
Voltage transients	Figure 6	Figure 7	Figure 6
Voltage spikes	Figure 9		
D.C. content		Figure 10	
Frequency:			
Max. step change (Hz)	290		
Max. accel./decel. (Hz/s)	100/200		200/200
Max. power interrupt	200 ms	7 s	N/A

NOTE 1 All values shown are measured at utilization equipment input terminals.

NOTE 2 Limits for single-phase systems are as shown for single-phase quantities of three-phase systems.

NOTE 3 Limits for systems of alternative voltage follow those above except voltage values are 26/115 of those shown for 26 V a.c. systems and 230/115 times those shown for 230 V a.c. systems.

NOTE 4 Unless otherwise stated, limits for abnormal and emergency operating conditions equal those for normal operating conditions.

6.4.3 D.C. content transients

The generation of d.c. content transients during abnormal operating conditions (failures of the source or user of power) shall result in the d.c. content on the a.c. waveform to be within the limits specified in Figure 10.

6.4.4 Frequency transients

Since frequency is not a controlled quantity in a VF system, frequency transients supplied by these systems relate directly to

— the engine speed characteristic of the driving engines throughout the flight envelope (VF generator frequency tracks engine speed through an application-specific ratio);

— the relative differences found between the electrical frequencies of concurrently operating generators.

The first influence results in continuous frequency changes as a result of varying demand, as well as abrupt changes associated with failures in the engine and its fuel or speed control mechanisms. The second influence also results in abrupt frequency transients as part of break-before-make load transfers involving at least one VF generator. Normal in-flight transfers include those between a VF source and an APU or other constant-speed driven 400 Hz source.

Table 3 — Limits for wide-range variable frequency, 115/200 V a.c. three-phase power at user terminals

Steady-state characteristics	Normal	Abnormal	Emergency
Phase voltages:			
Three-phase average (V rms)	101,5 – 120,5	98,5 – 132,5	101,5 – 120,5
Individual phase (V rms)	100 – 122	97 – 134	100 – 122
Max. unbalance (V rms)	9		12
Displacement (degrees)	114 – 126		
Voltage modulation:			
Max. peak-valley amplitude (V pk)	5,6		
Frequency components	Figure 3		
Voltage waveform:			
Crest factor	1,26 – 1,56		
Distortion factor	10 % total		12 % total
Individual component of distortion	7,5 % max. according to Figure 4		9 % max. according to Figure 4
D.C. component (V d.c.)	−0,1 – +0,1		
Frequency variation	360 – 800 (Hz)		
Transient characteristics	**Normal**	**Abnormal**	**Emergency**
Voltage transients	Figure 8	Figure 7	Figure 8
Voltage spikes	Figure 9		
D.C. content		Figure 10	
Frequency:			
Max. step change (Hz)	440		
Max. accel./decel. (Hz/s)	100/200		500/200
Max. power interrupt	200 ms	7 s	N/A

NOTE 1 All values shown are measured at utilization equipment input terminals.

NOTE 2 Limits for single-phase systems are as shown for single-phase quantities of three-phase systems.

NOTE 3 Limits for systems of alternative voltage follow those above except voltage values are 26/115 of those shown for 26 V a.c. systems and 230/115 times those shown for 230 V a.c. systems.

NOTE 4 Unless otherwise stated, limits for abnormal and emergency operating conditions equal those for normal operating conditions.

6.4.5 Frequency step changes

Power transfers between source generators, as previously described, will provide step changes in system frequency. The initial and final frequency will lie within the steady-state limits specified in 6.3.7. The maximum magnitude of these transients, as a result of normal and abnormal power transfers, shall be within the limits of Table 2 for narrow-range VF and Table 3 for wide-range VF.

User equipment shall also satisfy performance requirements when un-powered and subsequently energized with a.c. power anywhere within the steady-state frequency range.

6.4.6 Rate of change of frequency

The rate of change of frequency due to engine speed acceleration/deceleration as seen by user equipment shall remain within the limits defined in Table 2 for narrow-range VF and Table 3 for wide-range VF.

6.4.7 Power interruptions

VF power systems shall be designed such that in normal operation they will have an interruption in power prior to source power transfers (break power transfers). The duration of these normal power interruptions shall not exceed the limits of Table 2 for narrow-range VF and Table 3 for wide-range VF.

During abnormal operation, VF power can be interrupted for longer durations to allow time for system fault clearing and reconfiguration. The duration of these abnormal power interruptions shall not exceed the limits of Table 2.

7 D.C. power system characteristics

7.1 General characteristics

The characteristics below apply to the power at the utilization equipment terminals unless otherwise stated. They have been determined to be suitable for general application. Equipment designed to these characteristics should therefore find ease of compatibility amongst power sources, users of power and aircraft. All d.c. voltages are mean values unless otherwise stated. These characteristics apply to 14 V d.c., 28 V d.c. and 42 V d.c. equipment receiving d.c. power from the following sources:

— 28 V d.c. transformer rectifier unit (TRU) produced unregulated d.c. and d.c. ground power supplies [ISO 7137:1995 (EUROCAE/ED-14 and RTCA/DO-160, Section 18, Category A)];

— 14/28 V d.c. engine driven d.c. generators and d.c. ground power supplies [ISO 7137:1995 (EUROCAE/ED-14 and RTCA/DO-160, Section 18, Category B)];

— 28/42 V d.c. regulated d.c. power from active power converters (herein titled Category R).

7.2 Steady-state characteristics

7.2.1 Applicability

The characteristics specified in 7.2.2 and 7.2.3 are applicable to the entire range of steady-state operating conditions.

7.2.2 Input voltage

The d.c. voltage shall remain within the limits of Table 4.

NOTE 1 Aircraft employing d.c. electric engine starters normally experience low d.c. system voltages during the starting cycle; equipment that is required to operate or be left switched on during this cycle should be so identified in the individual specification which should also define the appropriate voltage characteristics.

NOTE 2 Equipment operated from a battery system with an integral battery charger may be subjected to voltages in excess of the values in Table 4. In these cases, appropriate voltage levels should be specified in the individual equipment specifications.

7.2.3 Voltage ripple

7.2.3.1 Maximum voltage ripple

Ripple on the d.c. supply shall be within the peak-to-peak limits shown in Table 4.

7.2.3.2 Individual frequency components of ripple

Individual frequency components of the voltage ripple shall not exceed the limits of Table 4. This characteristic may also be described as the distortion spectrum of the d.c. voltage.

Table 4 — Steady-state limits for d.c. power at user terminals

	Normal	Abnormal	Emergency
Direct current voltages (V d.c.):			
28 V, Cat. A, B	22,0 – 30,0	20,5 – 32,2	18,0 – 32,2
14 V, Cat. B	11,0 – 15.0	10,25 – 16,0	
28 V, Cat. R	26,5 – 28,5	22,0 – 30,5	
42 V, Cat. R	40,0 – 45.5	33,0 – 48,0	
Voltage ripple:			
28 V, Cat. A, B (V pk–pk)	4,0	6,0	
28 V, Cat. R (V pk–pk)	1,0	2,0	
14 V, Cat. B (V pk–pk)	2,0	3,0	
42 V,Cat. R (V pk–pk)	2,0		
Individual components:			
28 V, Cat. A	Figure 12		
14/28 V, Cat. B	Figure 13		
28/42 V, Cat. R	Figure 14		
Distortion factor (%)	5,5		

NOTE 1 All values shown are measured at utilization equipment input terminals.

NOTE 2 Category 'R' has been created herein to illustrate a locally regulated supply of d.c. power, not at present recognized in ISO 7137:1995 (EUROCAE/ED-14 and RTCA/DO-160, Sections 16 or 18).

NOTE 3 Unless otherwise stated, limits for emergency operating conditions equal those for abnormal operating conditions and limits for abnormal operating conditions equal those shown for normal operating conditions.

7.3 Transient characteristics

7.3.1 Voltage transients

Voltage transients shall remain with the limits of Table 5 for all operating conditions and equipment categories identified.

7.3.2 Voltage spikes

Voltage spikes, due to inductive or capacitive load switching, shall be held within the limits specified in Figure 20. This effect may be imposed upon other system voltage waveforms.

7.3.3 Power interruptions

The duration of normal and abnormal power interruptions shall not exceed the limits of Table 4 for all operating conditions and equipment categories identified.

NOTE The power system can be operated in a manner that minimizes power interruptions to all or preferred utilization equipment. Equipment designed for normally very short or no interruption of power shall be as provided in the specific equipment procurement specification.

Table 5 — Transient limits for d.c. power at user terminals

	Normal	Abnormal	Emergency
Voltage transients:			
28 V d.c. Cat. A	Figure 15	Figure 16	
14/28 V d.c., Cat. B	Figure 17	Figure 18	
28/42 V d.c., Cat. R	Figure 19	Figure 20	
Voltage spikes	Figure 21		
Max. power interrupt:			
28 V, Cat. A	200 ms	7 s	
14/28 V, Cat. B	50 ms	7 s	
28/42 V, Cat. R	5 ms	1 s	

NOTE 1 All values are measured at utilization equipment input terminals.

NOTE 2 Category 'R' has been created herein to illustrate a locally regulated supply of d.c. power, not at present recognized in ISO 7137:1995 (EUROCAE/ED-14 and RTCA/DO-160, Sections 16 or 18).

NOTE 3 Unless otherwise stated, limits for emergency operating conditions equal those for abnormal operating conditions and limits for abnormal operating conditions equal those shown for normal operating conditions.

8 Requirements allocation

Clauses 5 to 7 describe, in effect, the net result of power system interactions between the electrical power source, distribution and utilization equipment. In order for these power quality results and specific system stability considerations to be attained, certain restrictions shall be coordinated and allocated between the individual characteristics of the source and user equipment subsystems. Clause 9 defines equipment restrictions for standard user equipment, and Clause 10 provides general guidance and assumptions regarding both the source (including distribution) subsystem and the composite load configuration which the system integrator can control on an application-specific basis.

9 Utilization equipment restrictions

9.1 General

The following requirements are imposed on the utilization equipment to help ensure that the combined effects of any item of utilization equipment and the aircraft source and distribution equipment, operating as a system, will not result in power characteristics deviating beyond the limits of Clauses 6 to 8 at the input terminals of any other utilization equipment.

NOTE As defined in Clause 3, the term 'utilization equipment' can apply to a functional group of equipment. Compliance with any of the following requirements, therefore, may be provided whereby some of the components in this group specifically act to provide the (inrush current, distortion, etc.) limiting functions required for the group.

9.2 A.C. power utilization

Utilization equipment that requires more than 0,5 kVA of a.c. power shall be configured to utilize three-phase power, balanced amongst the three phases. The apparent (volt-amperes), real (watts) and reactive (vars) demands for any phase of a three-phase load shall not differ from similar power demands of any other phase, during any normal operating mode, by more than the limits of Figure 22.

9.3 Power factor

With the increasing tendency to place more electronic type utilization equipment (nonlinear loads) onto the aircraft's distribution buses, certain interface issues require much more attention than previously applied in order to ensure overall stable operation of the aircraft electrical system. A.C. synchronous generators have a characteristic that would allow for the loss of control of their output voltage during occurrences of extremely high demand of leading power factor current. This phenomenon is called generator self-excitation.

In order to prevent self-excitation of any (main engine, APU or GPU) a.c. synchronous generator due to unusually high demand for leading power factor a.c. current, the leading current associated with each item of utilization equipment shall be limited. This phenomenon is strongly influenced by generator frequency; therefore more severe restrictions are necessary for operation at higher frequencies, e.g. 800 Hz.

Under steady-state conditions, the power factor in each phase of a load shall be as near unity as practical, but shall be within the limits of Figure 23 for all normal steady-state operating conditions. Limits are adjusted for both load power consumption and, in the case of leading power factor limits, for source frequency. The power factor of motors rated over 1 500 V·A shall not be less than 0,40 lagging during starting.

NOTE The load power limits of Figure 23 apply to unique, individual power consumers as well as to the total power consumption of all identical pieces of equipment on the aircraft.

9.4 Load switching transients

The generation of spike voltage transients due to load switching shall be within the limits specified in Figure 9 (a.c.) or Figure 20 (d.c.) when measured at the input terminals of utilization equipment. Load equipment shall be designed to operate under the specified transient voltage input conditions irrespective of the source of the transient.

9.5 Inrush current

All utilization equipment, other than incandescent lamp loads, shall limit its maximum current demand, including inrush, such that with nominal voltage applied at the equipment terminals, the instantaneous peak current does not exceed the limits of Figure 24.

D.C. utilization equipment shall also limit the rate of change in direct current for power initialization or other modes of operation. This rate of change limit prevents wide voltage excursions outside the transient limit curve. The rate of current increase shall be less than five times the rated steady-state current in 1 ms.

9.6 Input current modulation

9.6.1 CF or VF range a.c. equipment

A.C. user equipment whose instantaneous input current during steady-state conditions (beyond 200 ms) is cyclic in nature may cause excess voltage modulation in the a.c. supply to other users. Universal limits for this parameter have not been determined. Therefore, any a.c. user equipment expected to have more than 15 % modulation in its input current during any envisioned steady-state operating mode should be examined for compatibility with the rate/magnitude limits allowable for its intended application.

9.6.2 D.C. equipment

D.C. user equipment whose instantaneous input current during steady-state conditions (beyond 200 ms for Category A equipment, 50 ms for Category B equipment or 5 ms for Category R equipment) is cyclic in nature may cause excess voltage modulation in the d.c. supply to other users. Universal limits for this parameter have not been determined. Therefore, any d.c. user equipment expected to have more than 15 % modulation in its input current during any envisioned steady-state operating mode should be examined for compatibility with the rate/magnitude limits allowable for its intended application.

9.7 Input current distortion

9.7.1 General

Voltage distortion in the a.c. waveform delivered to user equipment can be heavily affected by the non-sinusoidal current draw of some of this equipment. To limit this source of waveform degradation, the input current distortion by the electrical power users shall be limited. User equipment input current distortion requirements however, do not guarantee that the bus level voltage distortion requirements will be met. It remains the responsibility of the subsystems integrator to ensure that source, distribution and utilization equipment designs do not interact under normal and rated load conditions to collectively cause the bus voltage distortion to go beyond its applicable limits, i.e. Figure 4 (CF or VF) and Figures 12 through 14 (d.c.).

To support this coordination, user limits on current distortion are provided which scale or pro-rate the allowed distortion current spectrum according to each individual load's maximum current draw at the fundamental frequency of the source. A.C. current limits are identified which apply at harmonic multiples of the source frequency, as well as at non-harmonic frequencies (as may arise from the use of controlled a.c. rectifiers). Since the purpose of user input current limits is to support the desired bus voltage distortion limits, the level of current distortion allowed is inversely proportional to the typical network impedance at the distortion frequency.

9.7.2 CF equipment allowed distortion current

9.7.2.1 Requirements

Each item of CF electrical utilization equipment shall meet the following requirements when provided electrical power from a low impedance source (as defined in ISO 7137) at 400 Hz.

9.7.2.2 Individual frequency components of distortion

The individual frequency components of the line current shall not exceed the limits of Table 5 (single-phase equipment) or Table 6 (three-phase equipment) as adjusted for the maximum fundamental current of the load being considered.

9.7.2.3 D.C. component of distortion

The steady-state d.c. component of the line current shall not exceed 0,020 of the maximum fundamental rms current.

9.7.3 VF equipment allowed distortion current

9.7.3.1 Requirements

Each item of VF electrical utilization equipment shall meet the following requirements when provided electrical power from a low impedance source (as defined in ISO 7137) at 360 Hz and at 800 Hz.

9.7.3.2 Individual frequency components of distortion

The individual frequency components of the line current shall not exceed the limits of Table 5 (single-phase equipment) or Table 6 (three-phase equipment) as adjusted for the rating of the load.

9.7.3.3 D.C. component of distortion

The steady-state d.c. component of the line current shall not exceed 0,020 of the maximum fundamental rms current.

9.8 Maximum input capacitance

9.8.1 General

Input capacitance of user equipment is an important power quality parameter with different implications to a.c. and d.c. electrical systems. Their draw of leading power factor current can destabilize a synchronous electrical machine source. The key characteristic here, leading power factor current, is specified elsewhere in this International Standard. High power d.c. user equipment with large input capacitance has the ability to present an effective short circuit to d.c. generators during start-up. An appropriate limit for higher voltage d.c. systems will need to be specified when (and if) those systems are included in this International Standard. Classical 28 V d.c. systems do not present similar problems given their reduced maximum user equipment ratings. As a result, no limits are necessary at this time for input capacitance.

Table 6 — Limits for single-phase equipment allowed distortion current

Harmonic order	Limits
Odd triplen harmonics (h = 3, 9, 15, 21, ..., 39)	$I_h = 0{,}15 \times I_1/h$
Odd non-triplen harmonics (h = 5, 7, 11, 13, ..., 37)	$I_h = 0{,}3 \times I_1/h$
Even harmonics 2 and 4	$I_h = 0{,}01 \times I_1/h$
Even harmonics > 4 (h = 6, 8, 10, ..., 40)	$I_h = 0{,}002\,5 \times I_1$
Non-harmonics	$I_h = 0{,}001 \times I_1$

NOTE 1 I_h is the harmonic current of order h.

NOTE 2 I_1 is the maximum fundamental current draw (steady-state conditions).

Table 7 — Limits for three-phase equipment allowed distortion current

Harmonic order	Limits
3rd, 5th, 7th	$0{,}02 \times I_1$
Odd triplen harmonics (h = 9, 15, 21, ..., 39)	$I_h = 0{,}1 \times I_1/h$
11th	$0{,}1 \times I_1$
13th	$0{,}08 \times I_1$
Odd non-triplen harmonics 17, 19	$0{,}04 \times I_1$
Odd non-triplen harmonics 23, 25	$0{,}03 \times I_1$
Odd non-triplen harmonics 29, 31, 35, 37	$I_h = 0{,}3 \times I_1/h$
Even harmonics 2 and 4	$I_h = 0{,}01 \times I_1/h$
Even harmonics > 4 (h = 6, 8, 10, ..., 40)	$I_h = 0{,}002\,5 \times I_1$
Non-harmonics	$I_h = 0{,}001 \times I_1$

NOTE 1 I_h is the harmonic current of order h.

NOTE 2 I_1 is the maximum fundamental current draw (steady-state conditions).

10 Power quality associated assumptions and background

10.1 General

The need for this revision of ISO 1540:1984 arose from the fact that many traditional “rules of thumb” concerning the integration of aircraft electrical systems were becoming no longer valid in the early 1990s. Performance of the electrical generating system in the laboratory can be a poor predictor of performance in the aircraft depending on a number of distribution system and user equipment factors. This is especially true for large civil aircraft with much larger distribution network impedances and a greater amount of nonlinear loads than were traditionally present. The combination of these effects and interactions amongst the various items of equipment has become increasingly difficult to analyse. These and other related areas brought about the need for a cooperative activity amongst those in the power system industry.

Following some preparatory work, a working group of airframers, electrical power system suppliers and some representative utilization equipment manufacturers participated in dedicated working sessions in order to establish the baseline requirements found in this International Standard in the mid-to-late 1990s. A large portion of this work involved analysing variable frequency power application to large civil aircraft. A major goal was to set power quality limits that reduced the difficulty of integrating the electrical system while allowing for user equipment standardization at a reasonable cost. Since the cost of making totally foolproof requirements is prohibitive, this clause was created to retain some of the background generated in this process, to assist those developing new electric power systems.

10.2 Background to the document scope

This is a guidance document to support the electrical system integration process and definition of design and test requirement for generation, distribution and user equipment. It supports international dialogue on these requirements and should provide input into the one regulatory approved document for commercial user equipment testing (ISO 7137). Greater evaluation of the limits proposed herein by the user equipment manufacturers is expected through the RTCA and EUROCAE working groups which revise this document (DO-160/ED-14).

An attempt has been made to accommodate some of the more recent thinking in terms of aircraft sources: ‘double voltage’ a.c. (230/400 V a.c., a strong candidate in large aircraft), variable frequency a.c. (following traditional turboprop usage along with 28 V d.c., but now with wider speed range turbofan engines and better power quality), and 42 V d.c., a new potential standard for avionics power that might bring with it economics of scale from the automotive industry.

This document attempts to assess the delivered power quality limits for all types of commercial transport aircraft. Military vehicles and helicopters are not specifically excluded; but they tend to have custom specifications and equipment. Here we have pursued a broad application base which causes the summarized power quality to be degraded from what might be possible on a single application, but offers maximum equipment application amongst civil applications. The main power quality degrading effects taken into account here are the following.

— Source impedances (primarily reactances).

— High distribution network impedances [generator-to-POR (point of regulation) and POR-to-user equipment].

— Wide input speed range resulting from multiple engine suppliers for a single application. As some engines and gearboxes may be derived from other applications, they tend not to perfectly overlap and cause a wider overall speed ratio for the generator that must work with them all.

— Measurable amount of single-phase loads (specific assumed values follow).

— Measurable amount of rectifier-type nonlinear loads (as might result from a variety of equipment types).

While these effects are considered, no aircraft system level requirements are set to afford the system integrator the opportunity to most cost effectively balance various influences, i.e. source impedance and total user equipment distortion current.

10.3 A.C. power system assumptions

10.3.1 Steady-state a.c. voltage regulation (discussion based on 115/200 V rms systems)

Assumptions considered in determining the CF/VF three-phase average steady-state voltage limits provided in this International Standard include the following.

— Aircraft (main/APU) generating system voltage regulation at its POR of between 112 and 118 three-phase average V rms for all normal load conditions. This includes steady-state conditions as well as transient overload recoveries at a point 200 ms or later from the transient offset (phase voltage limits prior to the 200 ms point are governed by the transient voltage figures).

— External power unit output terminal voltage regulation, combined with its line drop compensation circuit (to reduce the effects of GPU to aircraft feeders), provides a similar 112 to 118 three-phase average voltage range at approximately the same primary distribution point (near a main system channel's POR).

— A maximum of 2 V rms drop is allowed between points of primary and secondary distribution (from the POR to the circuit protection element output).

— Distribution feeder cables are primarily selected to provide minimum weight within thermal limitations. Maximum voltage drop is also considered with a maximum of 6 V rms allowed for CF distribution cable drop (circuit breaker or SSPC to user terminals, worst case normal, after 200 ms of any transient occurrence).

— Distribution feeder cables to VF user terminals are likely to allow a greater voltage drop than for comparable CF equipment owing to increases in feeder impedance with generator frequency. (While feeder resistance decreases with increasing wire gauge, feeder inductance is fairly constant.). This is not an issue for small loads since the resistance in these cables is dominant. For high current VF loads however, larger cables provide diminishing returns and the voltage drop due to feeder reactance ($2 \times \pi \times$ frequency $\times$ inductance) increases linearly with frequency. For this reason this International Standard assumes a maximum voltage drop for VF distribution cables of 8,5 V rms. Large aircraft applications for VF power were, however, in the early design process as this International Standard was written. Airframers and system integrators have the opportunity to otherwise mitigate these effects to allow for similar user terminal voltage for VF as for CF equipment.

Assumptions that relate to the individual phase limits provided in this document include the following.

— Both three-wire (with aircraft skin provided neutral) and four-wire (with wired neutral) power distribution from aircraft generators. Limits consider the worst case three-wire system and its higher zero sequence impedance.

— Total a.c. bus phase current unbalance of 1/6 PU maximum during all normal operational modes for aircraft with approximately 100 or more passengers. These unbalances arise mainly due to single-phase passenger entertainment type of loads and have been measured in this range on several aircraft. Unbalances could occur during the full load and power factor range (unity and minimum 0,75 lagging for CF; 0,85 lagging for VF).

— Similarly, aircraft with fewer than 100 passengers have been observed to have up to 1/3 PU a.c. bus unbalance phase current. These higher unbalances arise mainly due to line-to-line loads such as propeller de-ice, but are counteracted by lower feeder impedances due to shorter wire runs on these smaller aircraft.

— Single-phase rectifier loads which result in triplen (3rd harmonic) currents, and have typically made up the imbalance loads, are expected to be reduced in the future due to the new input distortion current limits.

— The zero sequence impedance of VF systems increases with frequency in the same way as the positive sequence impedance mentioned above. It has been assumed, however, that this will be compensated for by system integrators (where needed) in VF systems to limit the resultant voltage unbalance and phase displacement limits to be the same as for CF systems.

Maximum individual phase voltages are controlled by the source system's voltage regulator and are not aircraft condition dependent.

10.3.2 Transient a.c. voltage regulation

Supporting studies have concentrated in the area of aircraft bus voltage transients and examined transient voltage characteristics as a function of the energy storage elements on the bus, feeder lengths and impedances, other loads power demand, particular phase relationships, etc. A variety of situations are possible, providing the rationale behind the many transient test conditions in ISO 7137:1995 (EUROCAE/ED-14 and RTCA/DO-160, Section 16 — Power Input).

Normal transient voltage requirements in this International Standard consider the extremes in aircraft feeder configurations along with no more than 1,5 PU overload removals and 2 PU load applications. Airframers wish to provide near (CF) historical transient voltage performance for even the more difficult voltage regulation problem — aircraft with long feeders and VF sources operating at high speed. As a result, it was assumed that (especially VF) generating systems would be designed to mostly accommodate this through lower source reactances and faster acting voltage regulators. A somewhat higher (10 V rms) maximum transient voltage overshoot was therefore provided for in VF system requirements to account for this extreme condition.

It was also assumed that the combined failures resulting in loss of voltage regulation and overvoltage protection of VF generators operating at high speed were sufficiently improbable not to require inclusion in the user power quality specification. Such an event would provide significantly higher peak a.c. voltages, and likewise d.c. voltage if passive TRUs were used, than specified in the respective transient voltage response figures in this International Standard.

10.3.3 VF a.c. system frequency range

The frequency range(s) for VF systems have been the subject of considerable debate. Among the main factors involved were the following.

- A strong desire to change from the historical unique frequency range for every aircraft to a ‘standard’ one such that common user equipment could be created and more widely applied.
- Though some newer turbofan engines have higher bypass ratios and lower speed ratios than the engines they replace, a variety of practical application issues related to engine speed suggest the need for margin in the frequency range, including
  - a typical mix of new and derivative engines/gearboxes making perfect speed range overlap difficult and/or expensive even on new applications with multiple engine suppliers;
  - possible changes in an engine’s minimum idle speed (causing a lower minimum frequency) or in its single-engine maximum thrust takeoff speed (causing a higher maximum frequency) during aircraft development or in re-application of the engine/gearbox;
  - allowance for engine overspeed conditions that are not extremely improbable.
- Greater penalties for power transmission as frequency is increased due to the feeder reactance, particularly at high phase currents.
- Decreased allowance for capacitive loading (reduced by the square of frequency as the maximum frequency increases), which potentially makes the current and voltage distortion requirements more difficult to achieve.
- Benefits of increased rotating source power density as its minimum speed (and therefore frequency) is increased.
- A strong desire not to require electronic conversion to support on-board user equipment when interfacing with the existing 400 Hz ground power infrastructure (i.e. 400 Hz must be in the frequency range).
- A desire for the minimum frequency to be no less than that provided to CF equipment which receives emergency power (360 Hz) to minimize impact on certain existing user equipment and facilities.
- Benefit to, or no significant impact on, most user equipment when designed for a relatively higher variable frequency range.

Most users have little or no sensitivity to the difference between a 1,65:1 and a 2,25:1 frequency range, with the obvious exception being large motors that might not otherwise require a motor drive. As the frequency range increases, it becomes more difficult to acceptably balance low speed and high speed operation of the motor without the addition of an electronic motor drive. Many motor applications are however finding benefit in the additional features that a motor controller can provide to help offset the negative impact.

While it is expected that, long term, the wider frequency range will dominate due to the economy of scale for manufacturers, this document maintains two frequency ranges, a slightly more extended narrow VF range from that originally proposed (360 Hz to 650 Hz versus 360 Hz to 600 Hz) and the now universally accepted wide (360 Hz to 800 Hz) range. With an assumption of (small aircraft) short wire runs, it appears possible to provide closer to traditional CF (and MIL-STD-704 type) power quality in narrow-range VF applications, and provide alternative solutions for the marketplace.

10.3.4 Items influencing voltage distortion

10.3.4.1 General

The resultant bus voltage distortion specified to users is a combination of the inherent imperfection in the generating system waveform (voltage distortion) and the distortion caused by non-sinusoidal current draw by nonlinear loads (the latter being the bigger influence in modern aircraft). The load equipment contribution results from interaction between the network's effective source impedance and the non-sinusoidal (distorted) current draw by the user equipment. This 'effective' source impedance is influenced by the actual generating source impedance, the distribution network impedance, and the composite effect of the other linear and nonlinear user equipment that is in-circuit. Distortion voltage increases along with feeder reactance between the generator and bus distorting load.

While the influence of a single nonlinear load is fairly easy to predict, the summed effects of multiple nonlinear loads are not. Various harmonics from one load may add or cancel those of another load. Specific relationships in this area are beyond the scope of this International Standard.

The limits of this International Standard assume a sufficient quality waveform from the generating source, such that the major contribution to distortion voltage results from user non-sinusoidal current draw. Historical standards relate a 'sufficient quality waveform' to one where of the order of 2,5 % voltage distortion is present at the POR when the generating system is tested with linear loads. System integrators should compensate accordingly for source waveform quality, expected load current distortion and the effective impedances in the source and distribution system.

10.3.4.2 Total nonlinear load assumptions

The majority of present aircraft experience in this area involves large transports with a measurable, but not a majority amount of single-phase rectifier loads. Distortion currents from these loads provide their greatest impact when there is little if any linear load simultaneously on the same generator and the zero sequence feeder impedance is high. This type of condition with 1/3 of the generator capacity servicing predominantly single-phase rectifier load has been seen on current large aircraft.

Smaller aircraft experience has tended to focus on a different situation whereby a given generator may be supplying a fairly large amount of three-phase rectifier load, along with a lesser amount of single-phase rectifier and linear load. Rectifier load content on these aircraft may be more than 1/2 of the generator capacity. Similar scenarios on large aircraft with their inherent larger distribution impedances could easily exceed the voltage distortion limits specified in this International Standard. In these instances the user equipment restrictions found in this International Standard may not be sufficient to guarantee the desired voltage distortion, and additional measures must be taken.

User equipment which adheres to the current distortion limits in this International Standard and ISO 7137 should, however, cause much less waveform distortion than that of legacy equipment. Simple 6-pulse rectification systems for three-phase users or single-phase, full wave bridge rectifier systems for one-phase users will not meet the input current distortion requirements in this International Standard. Future single-phase users will require some type of controlled rectification and three-phase power users will need to employ at least 12- or 18-pulse systems depending on the application. All of these factors need to be analysed to understand the situation on a given aircraft.

10.3.5 Resonance on the a.c. network

Requirements for a.c. user equipment's current distortion are specified in an earlier clause. Both passive and active filtering methods may be employed in a.c.-to-d.c. power conversion equipment to meet these requirements. The provider of this equipment and system integrators are cautioned to very carefully determine appropriate passive filter corner frequencies, especially with VF equipment, in order not to excite a resonance in the overall electrical system. No further guidance is available at this time.

10.3.6 Voltage modulation

User equipment which draws cyclic current from an a.c. source (such as light beacons or some surface actuators) is capable of inducing a voltage modulation that adds to the source's inherent modulation characteristic. For this reason the voltage modulation levels in this International Standard are slightly higher than those found in traditional specifications, which have tended to ignore any user equipment contribution to this parameter. The levels proposed here are more anticipatory, however, and are not backed up with the same industry experience as are other assumptions in this International Standard. Systems with potential modulating current loads require specific system analysis to determine if they comply with the recommended limits.

10.4 A.C. source equipment assumptions

10.4.1 General

The following source equipment assumptions relate particular contributions of this equipment to the integration of the overall electric power system (source, distribution and utilization equipment).

10.4.2 Ground power source performance

Considerations for ground power have been included in this document along with those of on-board power sources. Present specifications for aircraft ground power must account for similar aircraft effects as presented in this International Standard, though their power quality is typically evaluated at their output terminals. User equipment power quality specifications can not be appropriately applied at the output terminals of ground power equipment, or even at the aircraft power receptacle, if the same power quality is to be expected much further away at the user terminals. Future update of the documents governing this equipment (ISO 6858) will support more updated requirements in this area; however, benefit will not be realized until these updated requirements are accepted in the industry.

Fortunately, initial evaluation of ground power characteristics, as detailed in some of the more recent specifications and manufacturer supplied data, appear to be adequate in most areas.

10.4.3 Source impedance limit to avoid self-excitation

The output voltage of synchronous machines such as employed on aircraft is regulated via the supply of excitation current from the associated voltage regulator. Requirements for this excitation vary with generator load: as it becomes more inductive, more excitation current is required. Conversely the addition of capacitive load allows for less excitation current. At some point with increasing leading PF load, the voltage regulator does not need to provide any excitation and this machine is said to be self-excited, resulting in an uncontrolled machine output voltage which could damage any connected user and/or distribution equipment. This occurs at a point where the leading PF current draw from the machine roughly represents a capacitive reactance of equal magnitude to the inductive reactance of the machine and source feeders.

In order to avoid self-excitation of any aircraft synchronous electrical machine, its source reactance and the capacitive current draw of the loads are limited. This source impedance is equivalent to the machine's synchronous reactance added to the total reactance of the source-to-user feeder network. The following limit has been determined as reasonable for the generator and feeders:

Max. (X_{Source}) < 2 PU reactance at F_{MAX}

where

X_{Source} is the machine synchronous reactance plus the positive sequence reactance of the feeders between the source and its POR.

Though it includes both the generator and feeder reactance, the total value is dominated by the machine reactance. As long as this requirement is applied at the upper frequency limit of operation for each specific source, this relationship is sufficient for both constant and variable frequency systems.

This is discussed in greater detail in 'Rationale behind in-process changes to constant and variable frequency power quality standards', where an equation is presented relating source reactance, user capacitance, source voltage and operating frequency. Results of manipulating this equation are as follows.

System type	**System voltage** V rms	**Maximum frequency** Hz	**Allowed leading power factor at maximum frequency**	**Allowed equivalent capacitance** uF/kVA/phase
CF	115/200	400	0,968	2,51
CF	230/400	400	0,968	0,63
VF	115/200	800	0,968	1,25
VF	230/400	800	0,968	0,31

As one can see from this data, the user equipment power factor limit is convenient in that it does not change as the system type changes. Representative capacitance which alone could cause this amount of leading power factor does change with frequency and voltage. It should be noted that as specified earlier, variable frequency equipment operating at lower than 800 Hz frequency can draw some amount more leading PF current. For example, if supplied power at the absolute minimum frequency of operation, this equipment could have a 0,831 leading PF. Likewise, if customized for a particular maximum frequency between 400 Hz and 800 Hz, additional leading power factor and equivalent capacitance could also be allowed.

10.4.4 A.C. generating system d.c. content

An a.c. bus, steady-state, d.c. content limit of 200 mV has historically been set to allow for potential d.c. generation from solid-state sources (synchronous machines can not theoretically generate d.c.) or user equipment which might be drawing small amounts of d.c. on a continuous basis. Anything more than this value was felt to be overly penalizing on user equipment, especially on any magnetics in their input power circuits. For simplicity, contributors to this document then considered this bus value to be equally contributed to by the a.c. generators and users.

It is assumed that the specification of transient d.c. content in most historical power quality documents is based upon failure modes of solid-state (VSCF) sources. The curve suggested in this document, however, considers both these failures as well as bus voltage characteristics due to failures of input rectifiers in a.c.-to-d.c. conversion equipment. Prediction of the user equipment failure impact is based upon the expected maximum d.c. current draw for a rectifier load with a failed diode, the total source resistance this load might encounter and a practical protective trip which limits the volt-seconds exposure of a.c. users to the resultant d.c. voltage. These types of failure need to be recognized in future specifications due to the rapid increase in rectifier loads (and resultant likelihood of failures). Users should benefit with a much lower maximum voltage as long as sources are likewise restricted from allowing anything greater than this figure to reach user equipment.

10.5 D.C. system assumptions

10.5.1 Power types

Most specifications, such as ISO 7137, have recognized a variety of d.c. power types and their associated characteristics. Main differences have included whether the d.c. power for aircraft users is either generated directly or it is converted from an a.c. source. Other differentiators include the amount of influence a battery on the d.c. bus has. Today there are more d.c. power generation options, including the production of a regulated d.c. bus from either regulated a.c. or unregulated d.c. It was felt in the creation of this International Standard that power quality for the presently identified equipment Category Z, the 'all else' category, could not be defined since its architecture is not defined. Therefore only Category A (a.c. generation, passive d.c. conversion with small battery influence) and Category B (d.c. generation with possible large battery influence) have been retained in this International Standard, while one new category has been added.

Category R for regulated d.c. power is the new category identified in this International Standard. It does not describe what the power source power is (a.c. or d.c.), only the quality of the regulated output. It has been envisioned that this power type could be useful for avionic type loads that may benefit from a reduced transient voltage range and interrupt time period. Both 28 V and 42 V d.c. voltage levels have been identified for this power type. Inclusion of 42 V d.c. allows for potential cost benefit from components, and maybe equipment, from the very high volume automotive industry.

10.5.2 Category A d.c. voltage regulation

Category A d.c. equipment voltage is determined by a.c. source, distribution feeder and passive transformer rectifier unit (TRU) characteristics. The limits assume that a TRU receives either constant or variable frequency a.c. power as specified for all a.c. power users. In addition, the inefficiency of the TRU and effects of the d.c. distribution feeders account for the resultant (unregulated) d.c. voltage characteristics, including the effects of transient a.c. voltages. Limits provided in this document are very close to historical typical values despite taking into account somewhat more degraded input power conditions.

10.5.2.1 Abnormal d.c. voltage transients

As mentioned in the discussion of a.c. voltage transients in VF systems, variable speed machines (a.c. or d.c.) inherently have excessive (greater than abnormal limits) voltage capability at high speed. Failure modes that would allow these voltages to be passed to VF a.c. user equipment would present excessive d.c. voltages to Category A d.c. user equipment that are sourced by a passive TRU. As was decided for the a.c. equipment case, the remote possibility of these events is not sufficient to penalize Category A d.c. equipment designs to anticipate the event. A note to this effect is included, however, in the applicable abnormal transient voltage figure provided in this International Standard.

10.5.2.2 Impact of a.c. distortion on d.c.

The impact of a.c. voltage distortion on the d.c. ripple produced by a.c.-to-d.c. conversion devices is a function of the amount of distortion and the conversion approach used to produce d.c. power. An increase from 5 % to 8 % total harmonic voltage distortion on the input to either passive or active converters is not considered to have a significant effect. Usage of VF power, however, causes a shift of the d.c. ripple content to higher frequencies.

Present practice has been to accommodate the existing specification limits in most current applications since the user equipment does not desire a change. A small change to the existing curve, however, was put into Figure 12 to account for the effects of 18- or 24-pulse count TRU type approaches (which meet the current distortion limits of this International Standard) at high frequencies.

10.5.3 Category B d.c. voltage regulation

Category B d.c. equipment voltage is determined by d.c. source, distribution feeder and user equipment characteristics, along with some influence of a large battery. Source characteristics dominate the resultant user power of this type since the feeder impedances are typically fairly small and user equipment is usually not very impacting. Normal transients are faster than can be guaranteed on large aircraft systems, while abnormal transient voltages are higher in consideration of potential failure modes in the d.c. generation system.

No serious study of this power type was made, so limits for this type of input power are largely unchanged.

10.5.4 Category R d.c. voltage regulation

This category is suggested for possible usage as a high integrity, high power quality local bus for avionic or other special purpose equipment. As stated earlier, it attempts to utilize low cost devices manufactured for more electric type automotive application. Key features and assumptions revolve around the assumption that the voltage is locally regulated. This allowed primarily for much smaller and faster voltage transients than other power types, along with very good steady-state regulation. No specific assumptions were made as to the input power to the converters producing this voltage; this is one reason that a new category was needed.

10.5.5 D.C. distribution feeders

D.C. system parameters in this International Standard consider a typical voltage drop from d.c. generation to user equipment as 1,5 V d.c. during steady-state conditions. That value can be doubled during transient conditions.

10.6 D.C. engine starting power quality

No attempt was made in this International Standard to define power quality on a d.c. network during (main) engine starting events. In the past only a minority of equipment was required to operate during the possible very low voltages present during the early portion of the start event. Characteristics of this voltage have also been very application dependent.

10.7 270 V d.c. input power

While at present part of certain military vehicle development efforts, 270 V d.c. has not gained momentum as a distribution voltage in present or near term civil aircraft. The many technical issues associated with its usage on a large transport aircraft make it quite difficult to provide early specification guidance prior to serious application evaluation by one of the civil airframers. For these reasons it was not otherwise addressed in this International Standard.

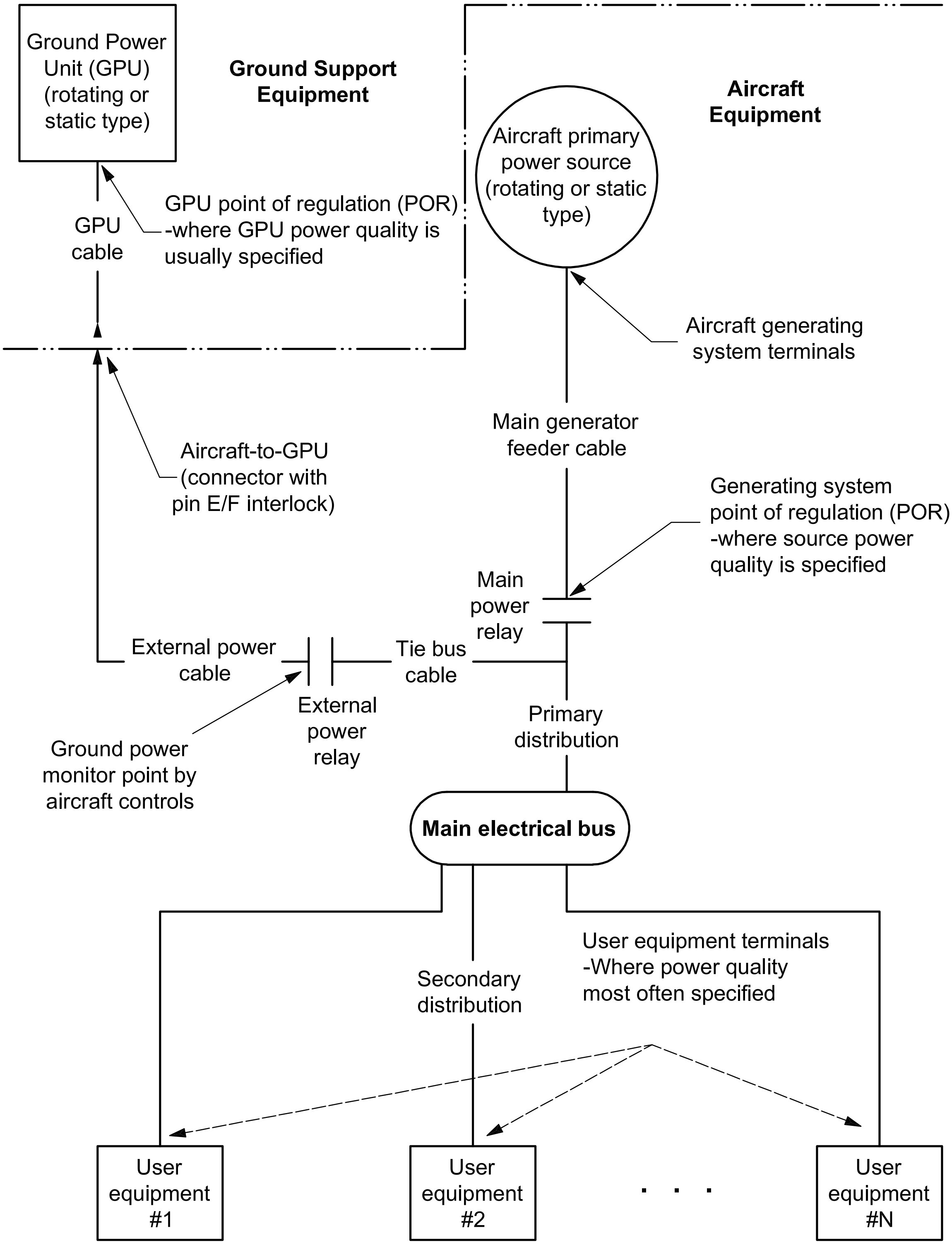
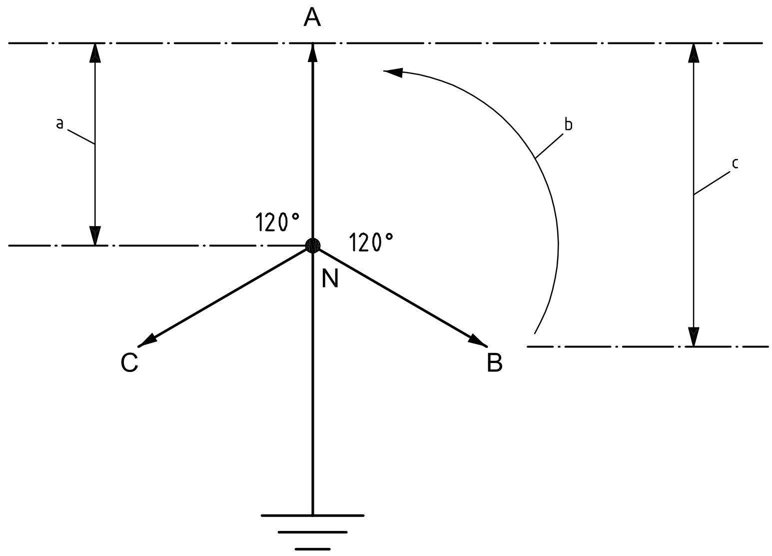


Figure 1 — Strawman electrical system schematic for power quality evaluations



NOTE Displacement factor calculations only examine the phase displacement between the fundamental components of the voltage waveform.

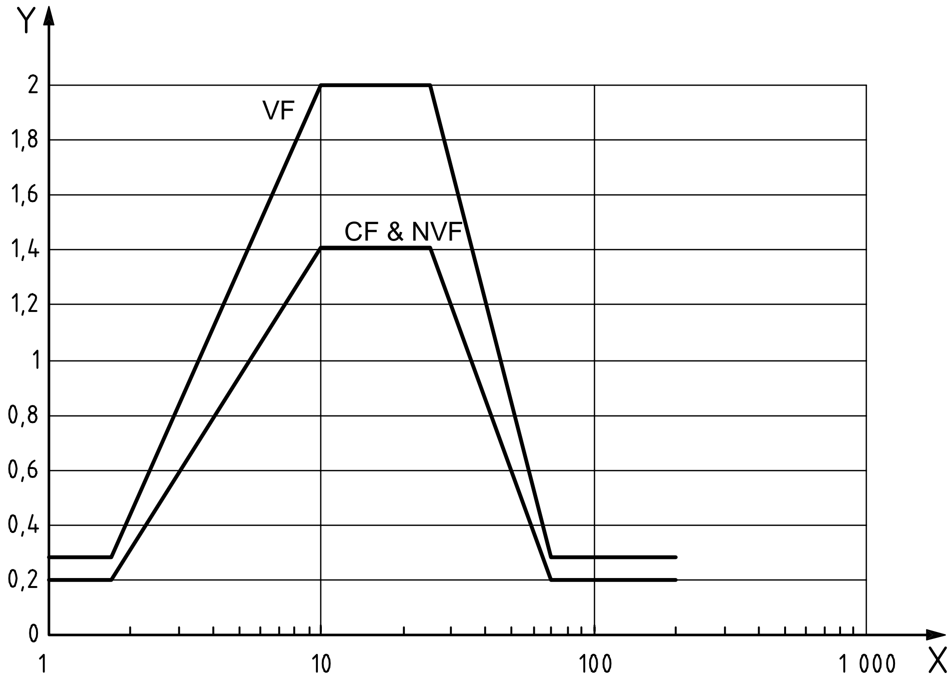
Key

[a] Phase voltage (line to neutral).

[b] Direction of positive phase rotation.

[c] Line voltage (line to line).

Figure 2 — Diagram of line designations and normal (positive) phase sequence



NOTE Multiply V rms values by 26/115 for 26 V a.c. input equipment and 230/115 for 230/400 V a.c. input equipment.

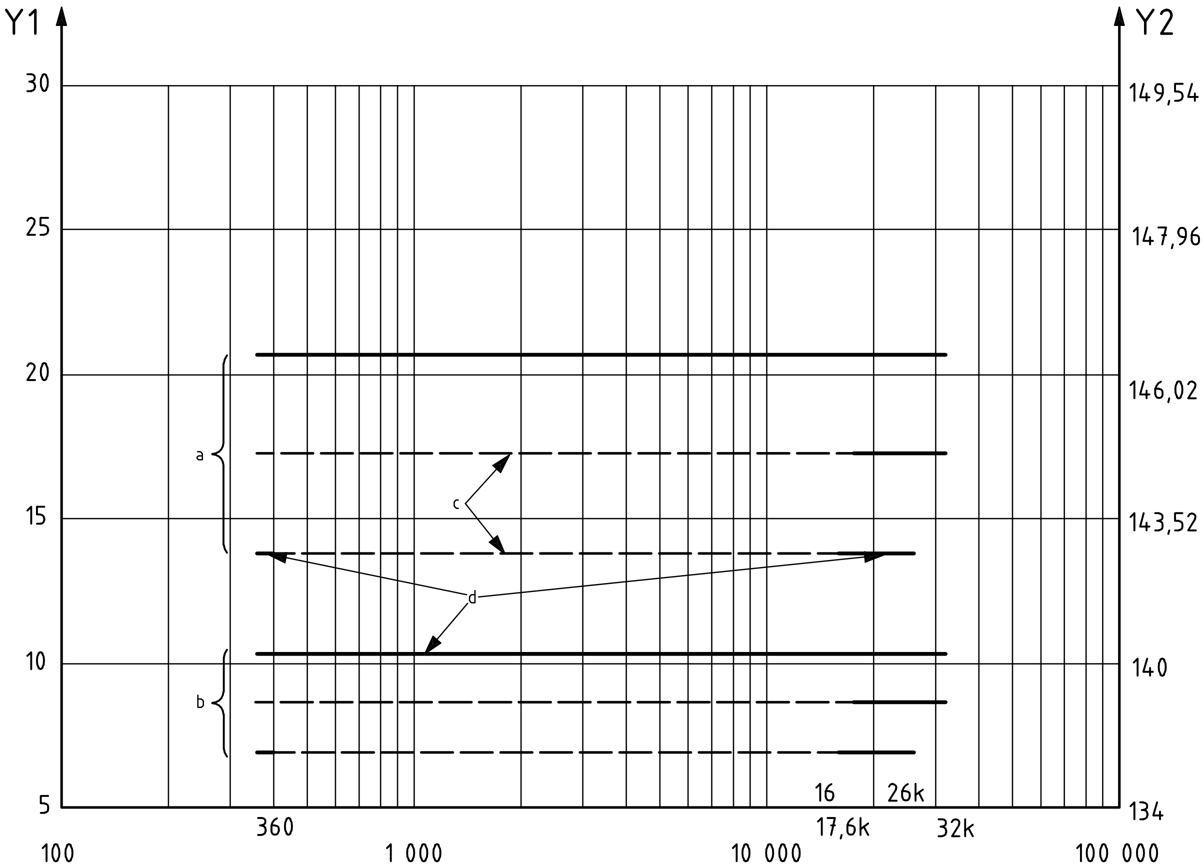
Freq. (Hz)	**CF/NVF** (V rms)	**WVF** (V rms)
1,0	0,20	0,28
1,7	0,20	0,28
10,0	1,41	2,00
25,0	1,41	2,00
70,0	0,20	0,28
200,0	0,20	0,28

Key

X frequency, Hz

Y voltage (V rms)

Figure 3 — Frequency characteristics of constant frequency and variable frequency voltage modulation envelope



Input	F_{min}	F_{max}	V rms	dBuV
115 CF Normal	400 Hz	16,0 kHz	6,90	136,78
115 CF Emerg.	360 Hz	17,6 kHz	8,63	138,72
230 CF Normal	400 Hz	16,0 kHz	13,80	142,80
230 CF Emerg.	360 Hz	17,6 kHz	17,25	144,74
115 NVF Normal	360 Hz	26,0 kHz	6,90	136,78
115 NVF Emerg.	360 Hz	26,0 kHz	8,63	138,72
115 WVF Normal	360 Hz	32,0 kHz	8,63	138,72
115 WVF Emerg.	360 Hz	32,0 kHz	10,35	140,30
230 NVF Normal	360 Hz	26,0 kHz	13,80	142,80
230 NVF Emerg.	360 Hz	26,0 kHz	17,25	144,74
230 WVF Normal	360 Hz	32,0 kHz	17,25	144,74
230 WVF Emerg.	360 Hz	32,0 kHz	20,70	146,32

Key

X frequency (Hz)

Y1 distortion (V rms)

Y2 distortion (dBuV)

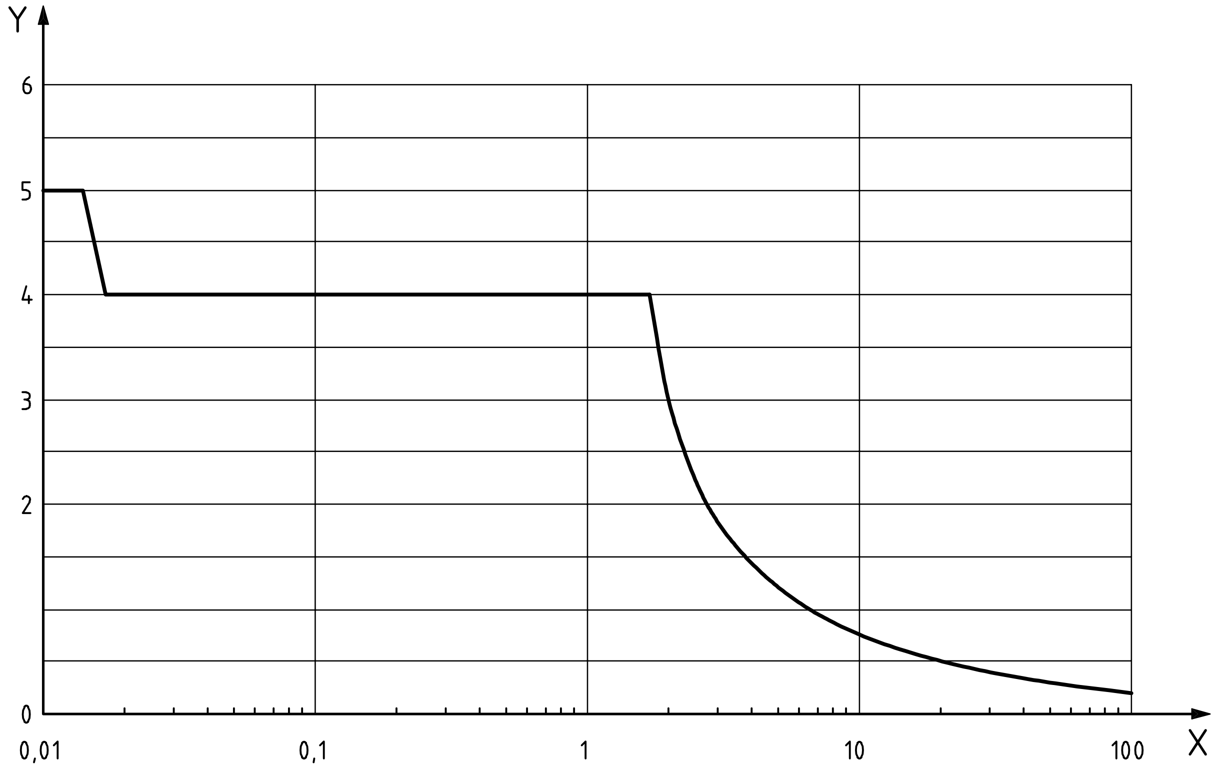
[a] 230 V systems.

[b] 115 V systems.

[c] Constant frequency portions.

[d] Variable frequency portions.

Figure 4 — Voltage distortion spectrum of a.c. input power



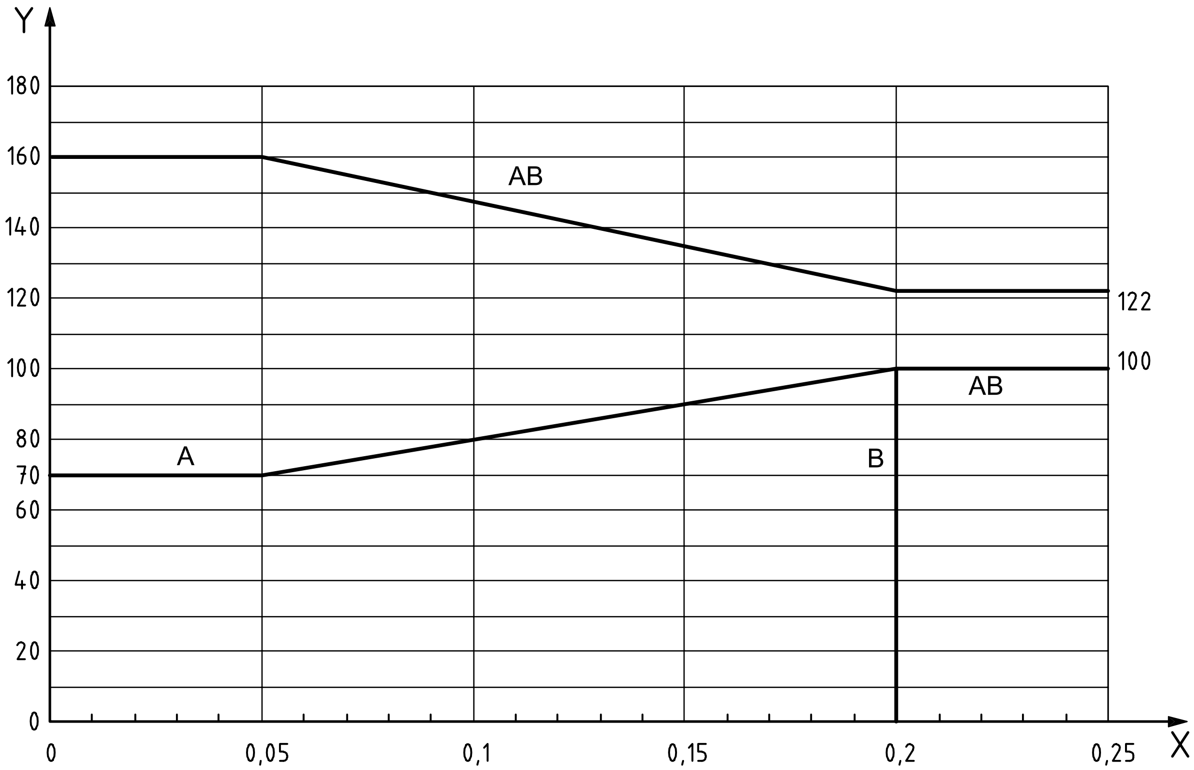
Rate (Hz)	**Modulation amplitude** (± Hz)
0,01	5,0
0,014	5,0
0,017	4,0
1,7	4,0
2,0	3,0
10,0	0,75
100,0	0,2

Key

X repetition rate (Hz)

Y modulation amplitude (± Hz)

Figure 5 — Frequency modulation of constant frequency a.c. input power



Curve A is the normal transient range due to load switching and NBPT; Curve B is the normal transient range due to non-NBPT bus switching.

NOTE 1 Spike voltages and other phenomena of < 1 ms duration are not shown.

NOTE 2 Limits are for rms values of complete a.c. cycles. Peak values are a function of the crest factor limits defined in Table 1 and Table 2 (V pk = crest factor × V rms).

NOTE 3 Multiply V rms values in this figure by 26/115 for 26 V a.c. input equipment and 230/115 for 230 V a.c. input equipment.

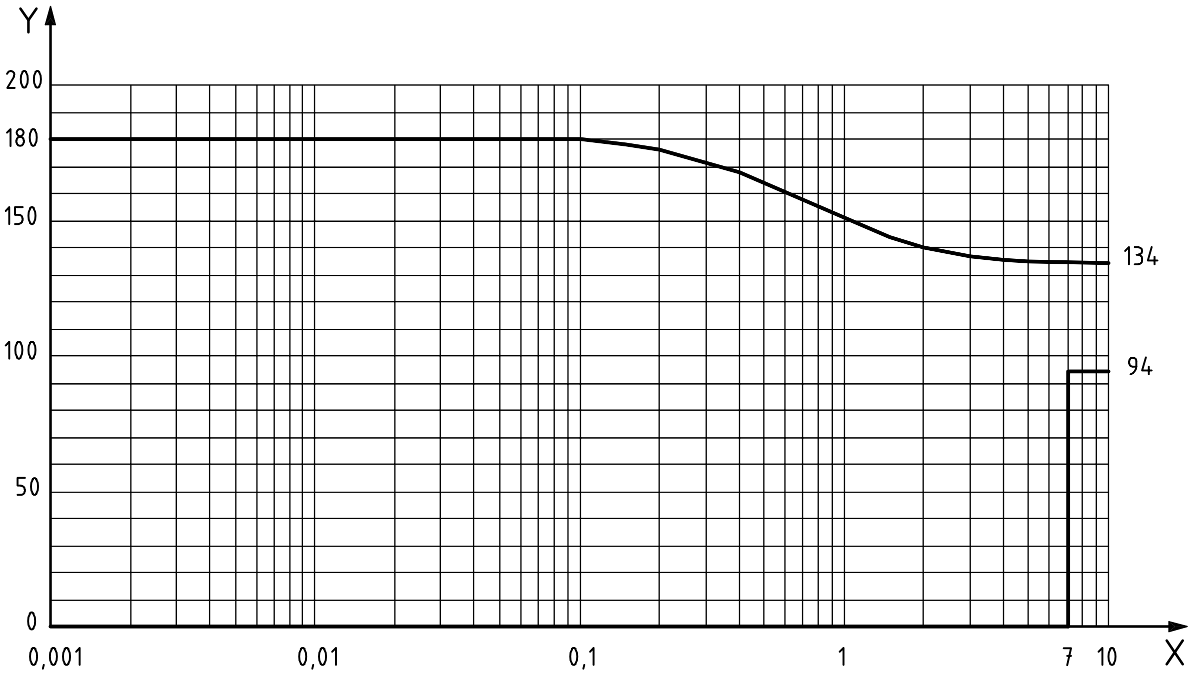
Load switching			**Bus txfr**
Time (s)	V_{min} (V rms)	V_{max} (V rms)	V_{min} (V rms)
0,001	70,0	160,0	0,0
0,050	70,0	160,0	0,0
0,200	100,0	122,0	100,0

Key

X time (s)

Y phase voltage (V rms)

Figure 6 — Normal constant frequency and narrow variable frequency a.c. input power voltage transients



NOTE 1 Spike voltages and other phenomena of < 1 ms duration are not shown.

NOTE 2 Limits are for rms values of complete a.c. cycles. Peak values are a function of the crest factor limits defined in Tables 1 through 3 (V pk = crest factor × V rms).

NOTE 3 Variable frequency equipment may receive a.c. voltage transients which exceed the maximum value shown during extremely rare failure conditions.

NOTE 4 Multiply V rms values in this figure by 26/115 for 26 V a.c. input equipment and 230/115 for 230 V a.c. input equipment.

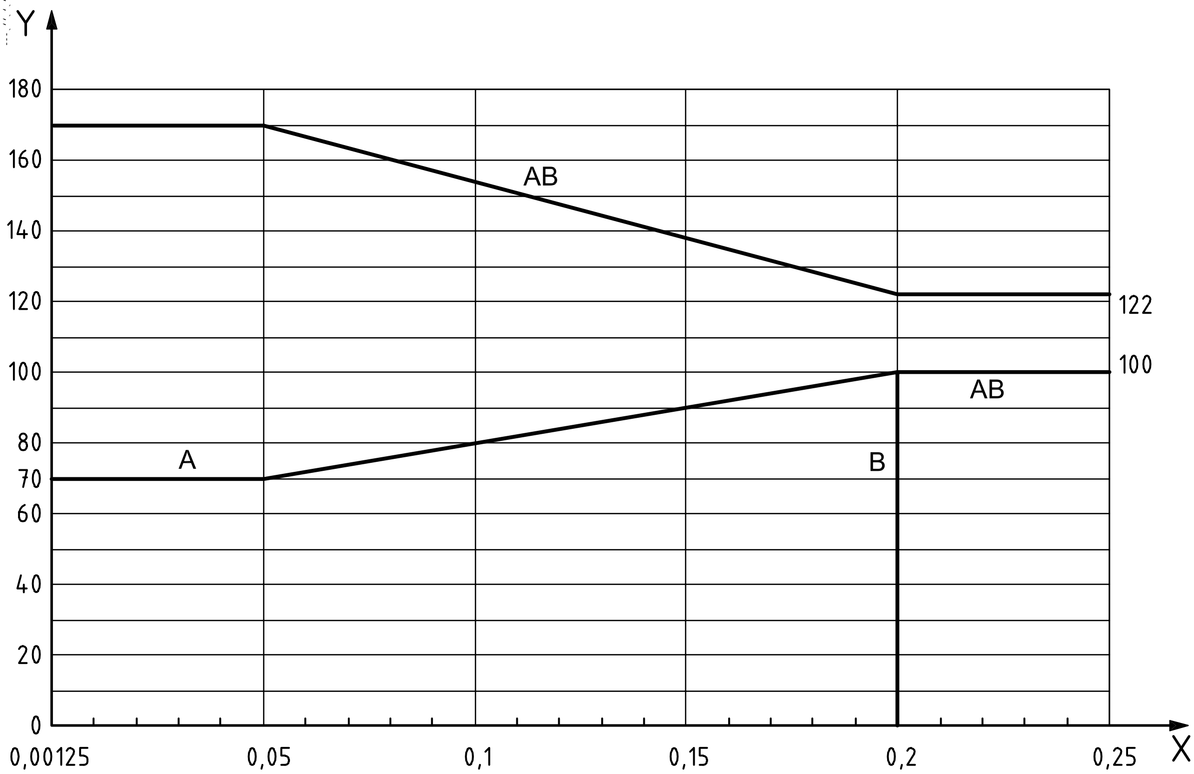
Sec.	V rms
0,001	180
0,2	176
1,0	151
3,0	137
10,0	134

Key

X time (s)

Y phase voltage (V rms)

Figure 7 — Abnormal (constant frequency and variable frequency) a.c. input power voltage transients



Curve A is the normal transient range due to load switching; Curve B is the normal transient range due to bus switching.

NOTE 1 Spike voltages and other phenomena of < 1 ms duration are not shown.

NOTE 2 Limits are for rms values of complete a.c. cycles. Peak values are a function of the crest factor limits defined in Table 3 (V pk = crest factor × V rms).

NOTE 3 Multiply V rms values in this figure by 26/115 for 26 V a.c. input equipment and 230/115 for 230 V a.c. input equipment.

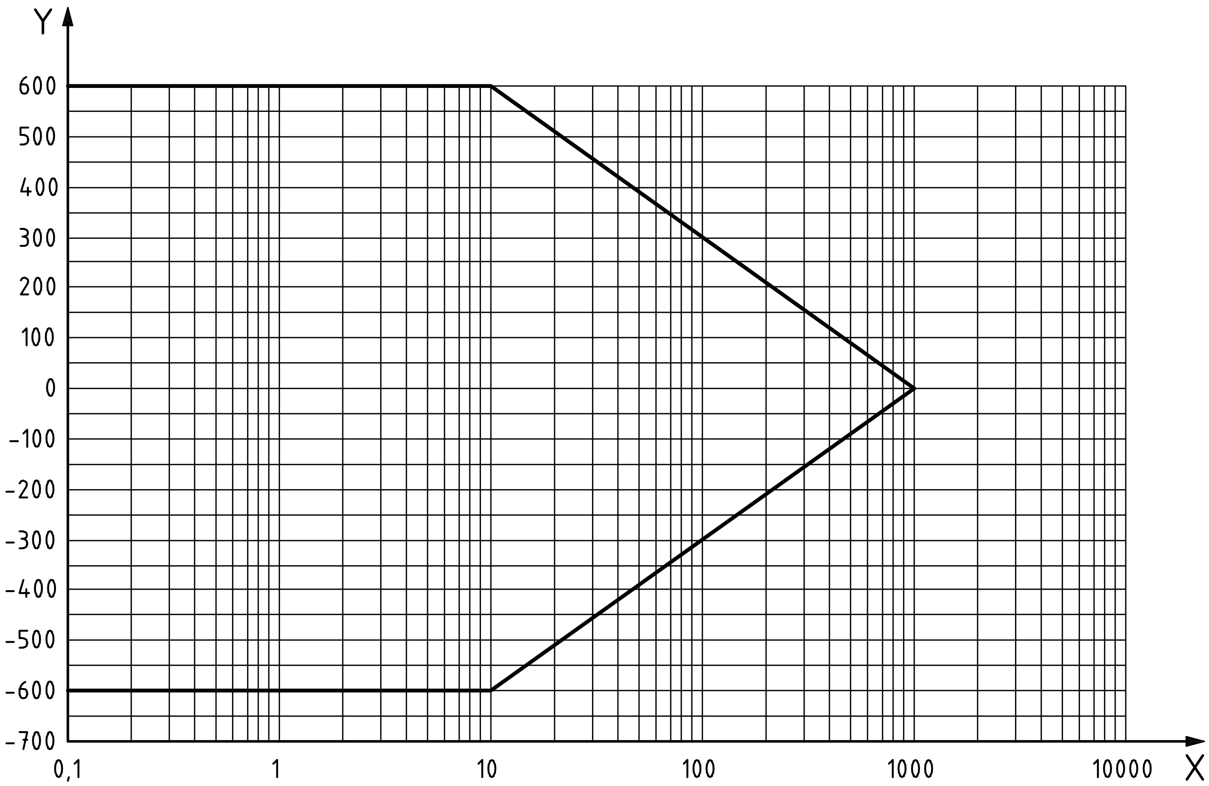
Load switching			**Bus txfr**
Time (s)	V_{min} (V rms)	V_{max} (V rms)	V_{min} (V rms)
0,001	70,0	170,0	0,0
0,050	70,0	170,0	0,0
0,200	104,0	122,0	100,0

Key

X time (s)

Y phase voltage (V rms)

Figure 8 — Normal, wide-range variable frequency a.c. input power voltage transients



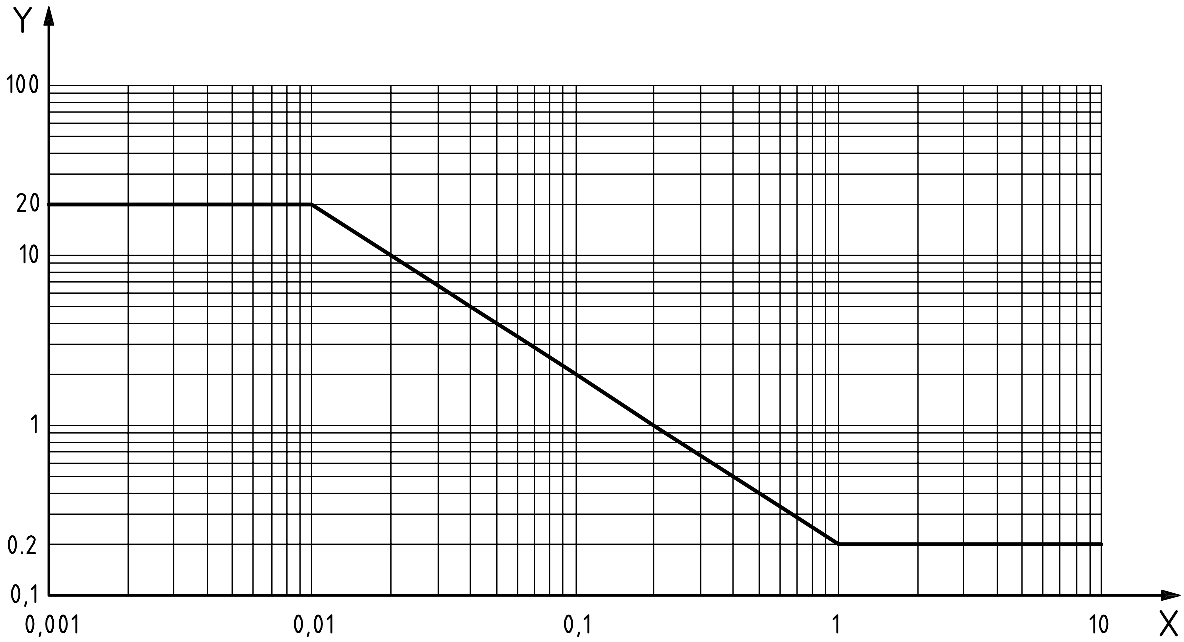
NOTE Multiply V pk values in this figure by 26/115 for 26 V a.c. input equipment and 230/115 for 230 V a.c. input equipment.

Key

X time (µs)

Y voltage (V pk)

Figure 9 — A.C. input power (constant frequency and variable frequency) voltage spike limitations



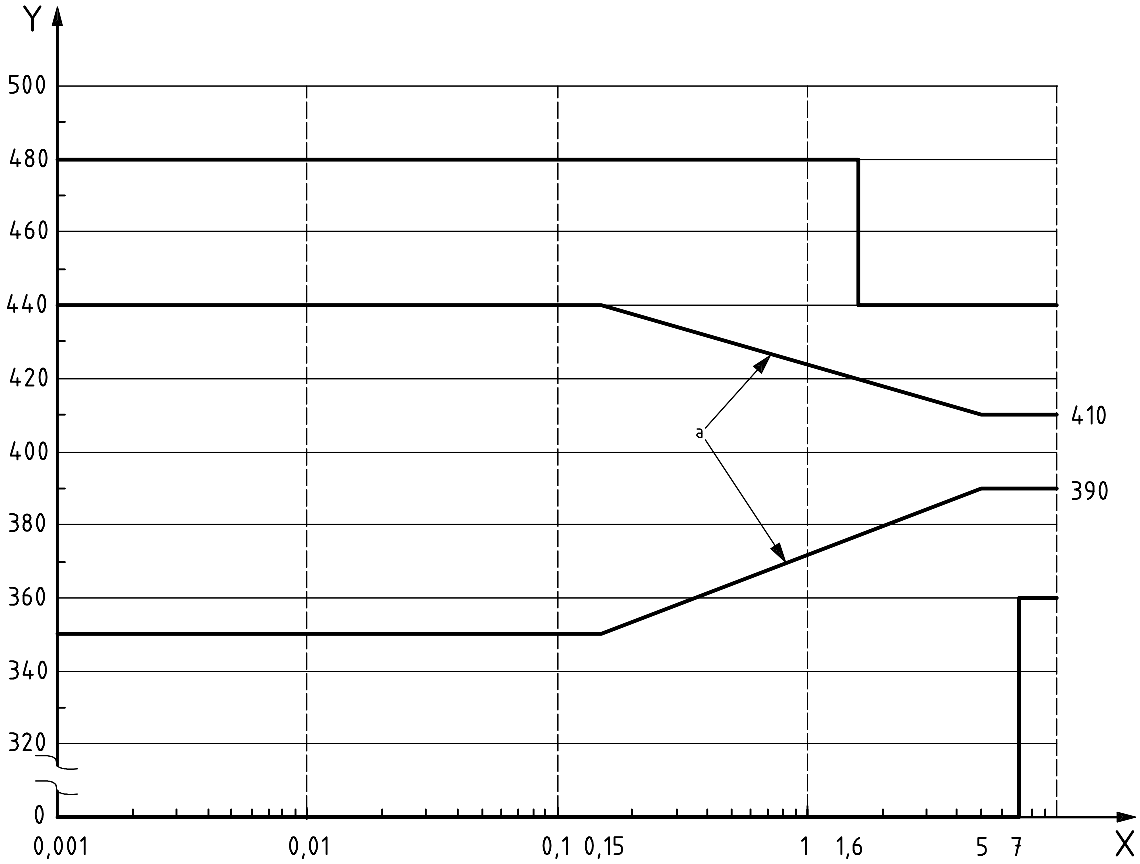
D.C. content	
Time (s)	**Voltage** (V d.c.)
0,001	20,0
0,01	20,0
0,02	10,0
0,10	2,0
0,20	1,0
1,0	0,2
10,0	0,2

Key

X time (s)

Y voltage (V d.c.)

Figure 10 — Abnormal d.c. content transient on a.c. input power (constant frequency and variable frequency)



NOTE Frequency transients of less than the time periods shown are not defined.

Normal transients			**Abnormal transients**		
Time (s)	**Overshoot frequency** Hz	**Undershoot frequency** Hz	**Time** (s)	**Overshoot frequency** Hz	**Undershoot frequency** Hz
0,001	440	350	0,001	480	0
0,15	440	350	1,60	480	0
5,00	410	390	1,60	440	0
10,00	410	390	7,00	440	0
			7,00	440	360
			10,00	440	360

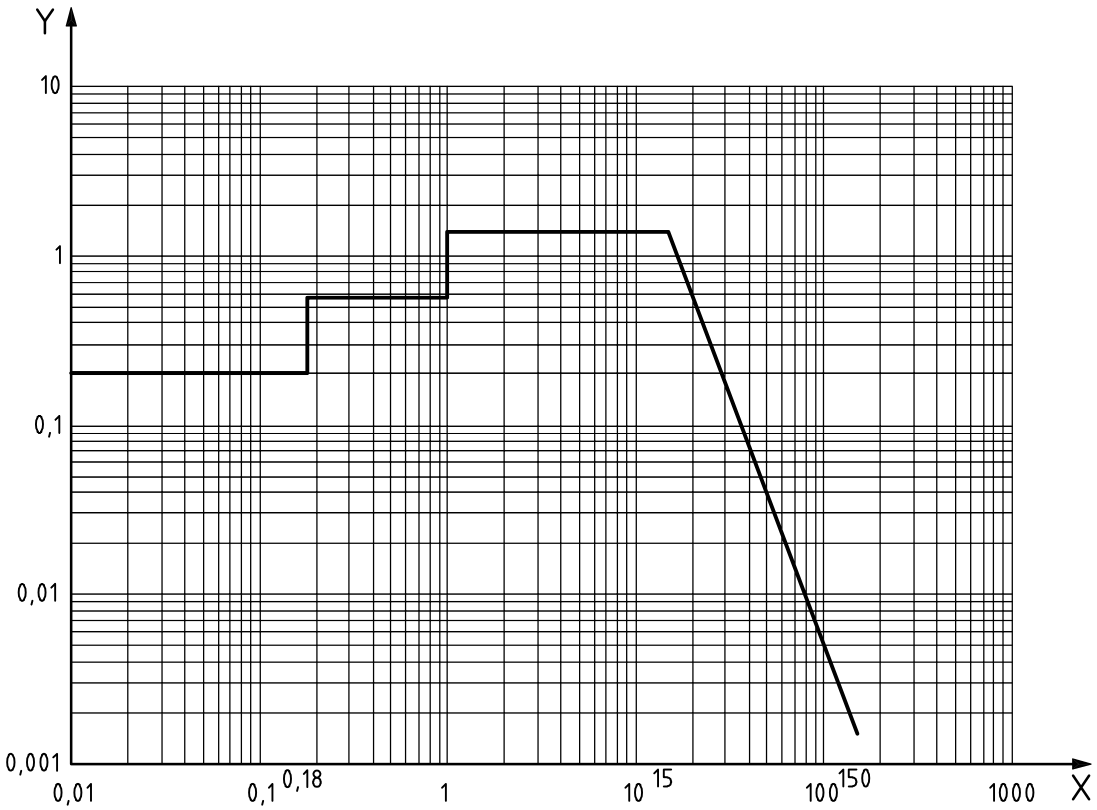
Key

X time (s)

Y frequency (Hz)

[a] Normal transients.

Figure 11 — Constant frequency a.c. input power frequency transients



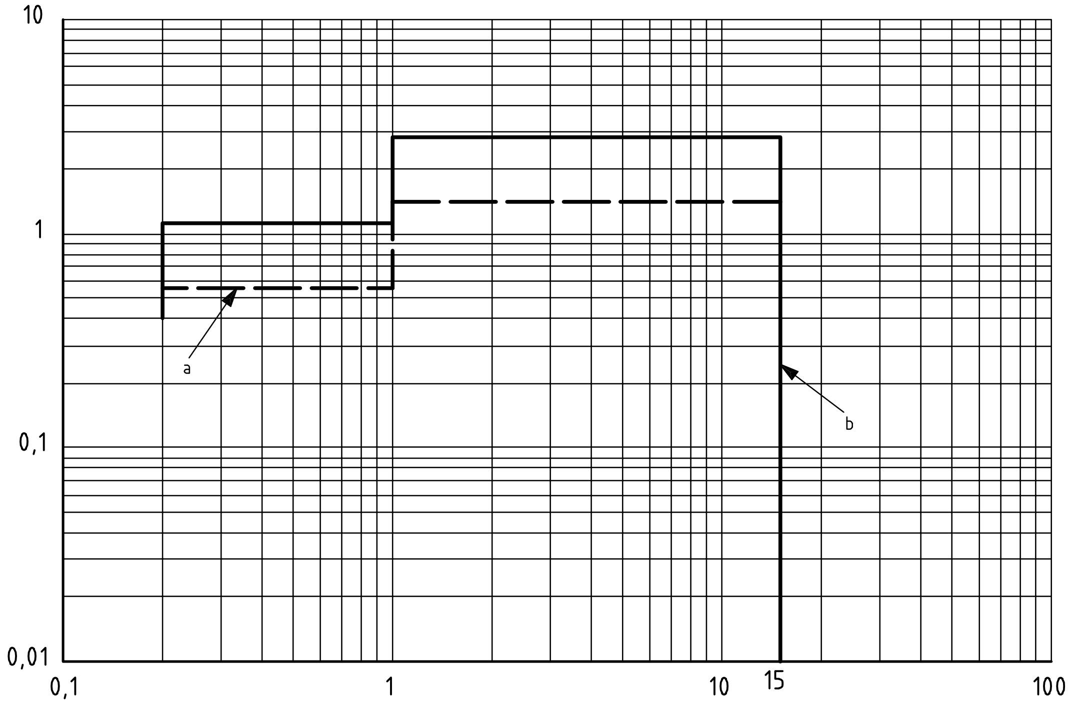
A.C. ripple frequency limits	
Frequency (kHz)	**Component** (V rms)
0,01	0,2
0,18	0,2/0,56
1,0	0,56/1,4
15,0	1,4
150,0	0,001 5

Key

X frequency (kHz)

Y voltage (V rms) of each frequency component

Figure 12 — Frequency characteristics of ripple in Category A 28 V d.c. input power



A.C. ripple frequency limits		
	28 V input	**14 V input**
Frequency (kHz)	**Component** (V rms)	**Component** (V rms)
0,2	1,12	0,56
1,0	1,12/2,8	0,56/1,4
15,0	2,80	1,40

Key

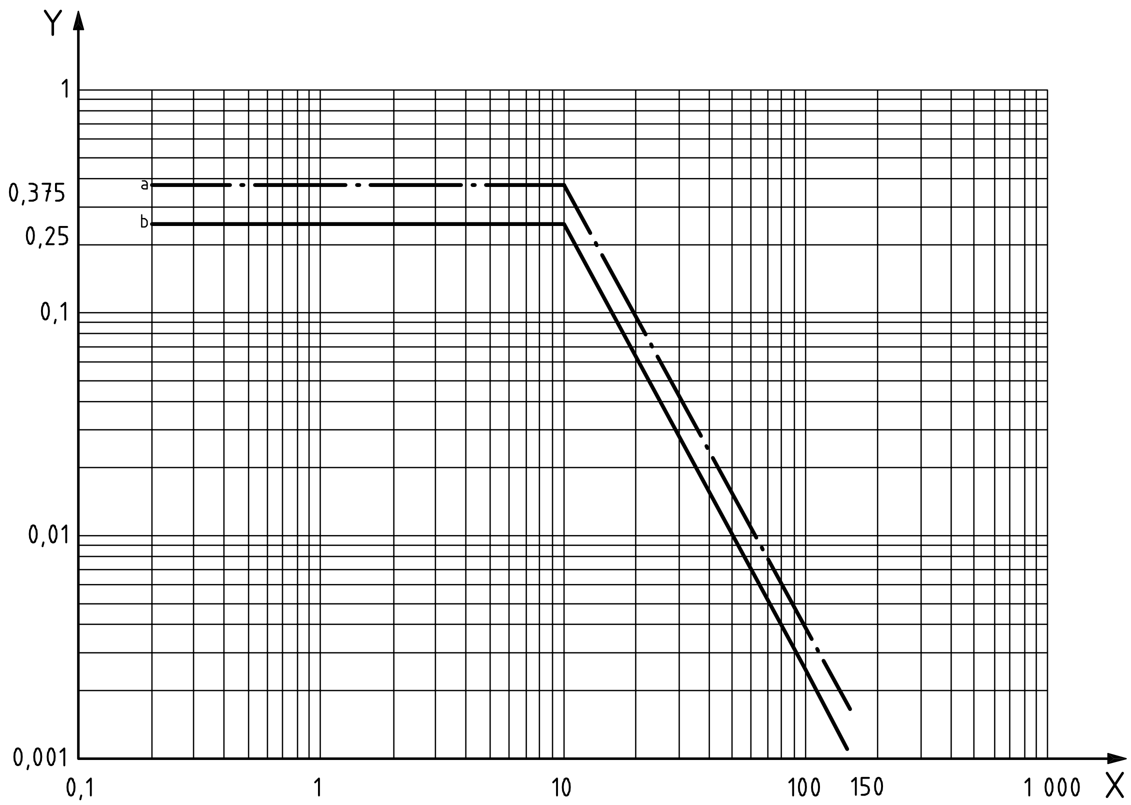
X frequency (kHz)

Y voltage (V rms) of each frequency component

[a] 14 V nominal.

[b] 28 V nominal.

Figure 13 — Frequency characteristics of ripple in Category B 14/28 V d.c. input power



A.C. ripple frequency limits		
	28 V input	**42 V input**
Frequency (kHz)	**Component** (V rms)	**Component** (V rms)
0,2	0,25	0,375
10,0	0,25	0,375
150,0	0,001 1	0,001 7

Key

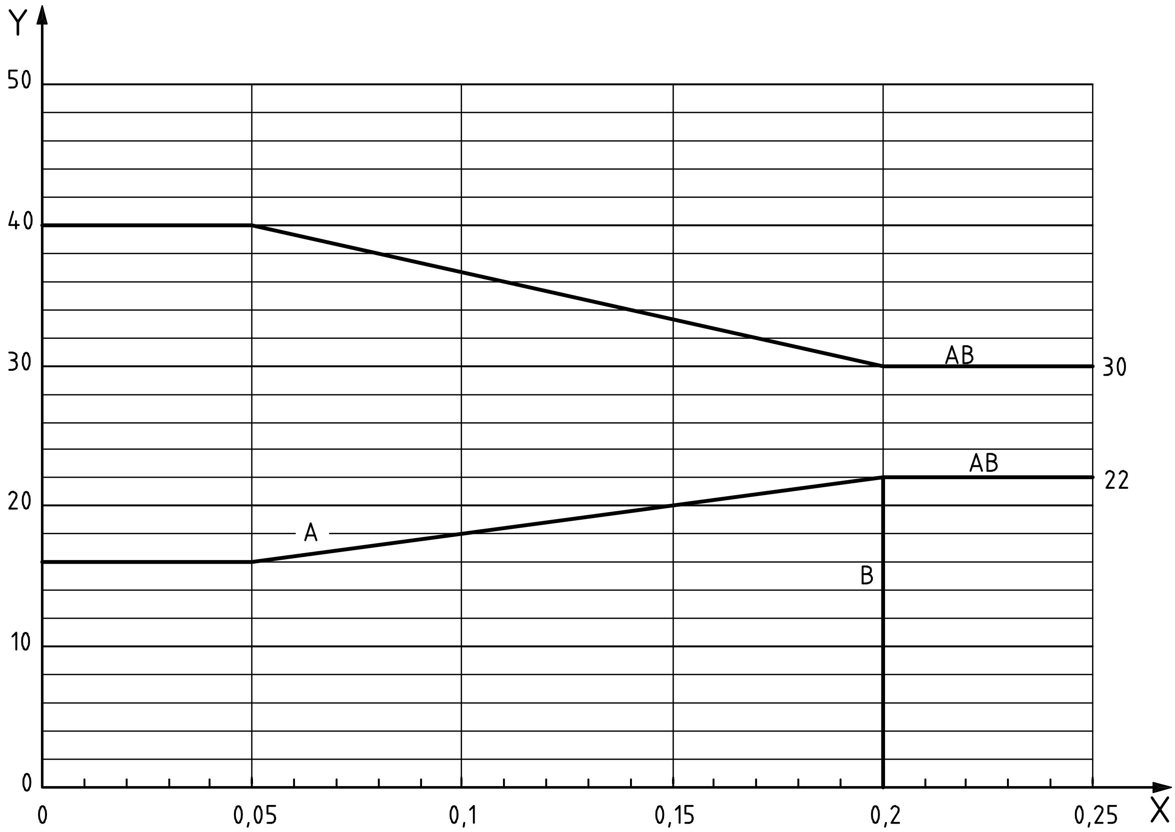
X frequency (kHz)

Y voltage (V rms) of each frequency component

[a] 42 V nominal input.

[b] 28 V nominal input.

Figure 14 — Frequency characteristics of ripple in Category R 28/42 V d.c. input power



Curve A is the normal transient range due to load switching and a.c. or d.c. NBPT; Curve B is the normal transient range due to non-NBPT bus switching.

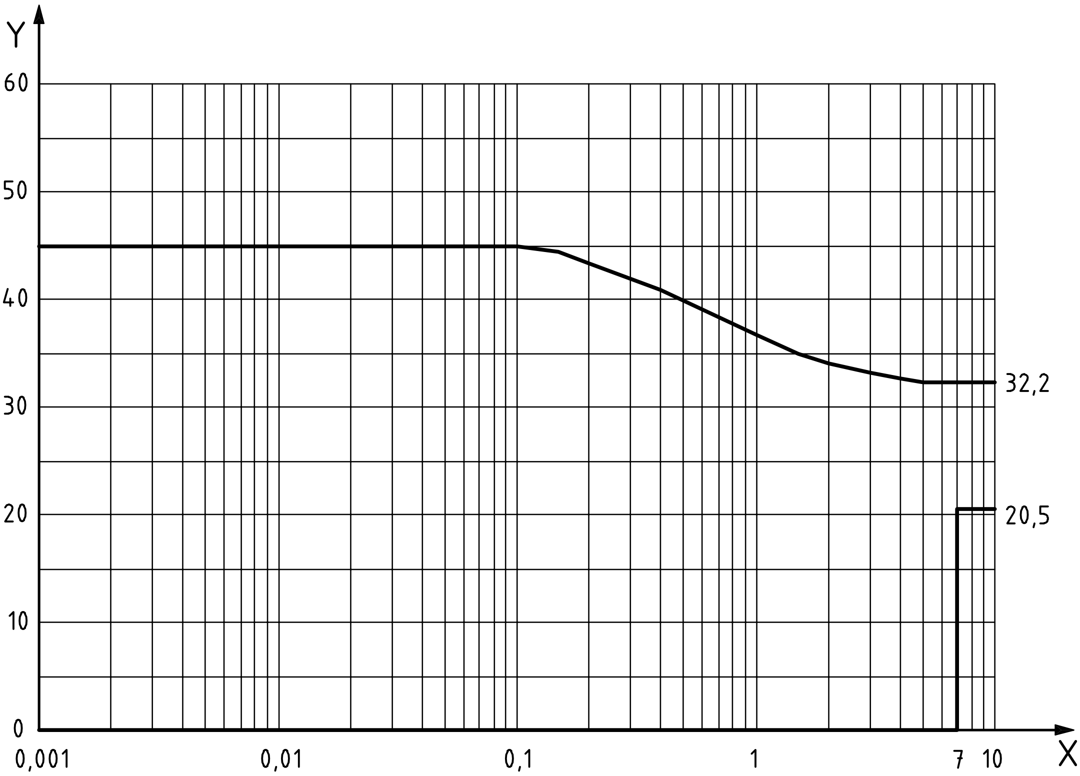
NOTE Spike voltages and other phenomena of < 1 ms duration are not shown.

Key

X time (s)

Y voltage (V d.c.)

Figure 15 — Normal Category A 28 V d.c. input power voltage transients



NOTE 1 Category A user equipment which receives d.c. power from VF sourced TRUs may receive higher transient voltages than those shown here during extremely rare failure conditions (loss of control and protection).

NOTE 2 Spike voltages and other phenomena of < 1 ms duration are not shown.

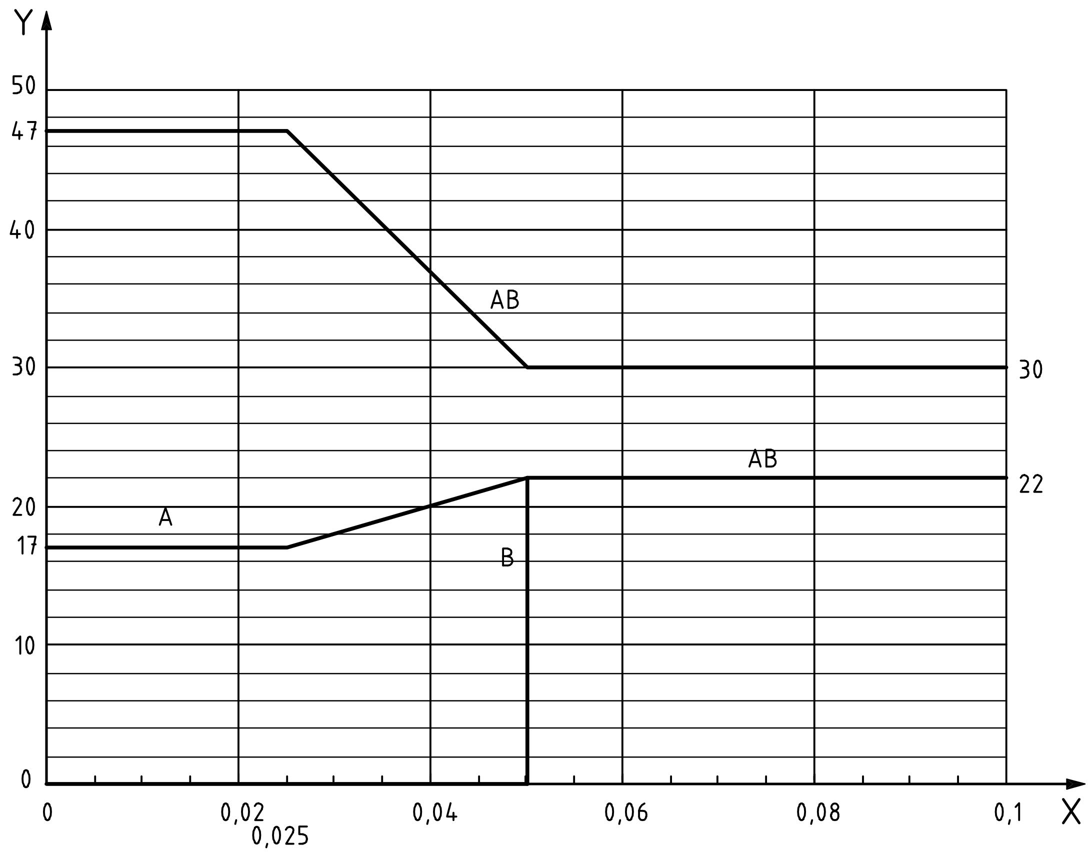
Time (s)	**Voltage** (V d.c.)
0,001	45,0
0,1	45,0
0,2	43,4
0,4	40,8
1,0	36,6
4,0	32,7
10,0	32,7

Key

X time (s)

Y voltage (V d.c.)

Figure 16 — Abnormal Category A 28 V d.c. input power voltage transients



Curve A is the normal transient range due to load switching; Curve B is the normal transient range due to non-NBPT bus switching.

NOTE 1 Spike voltages and other phenomena of < 1 ms duration are not shown.

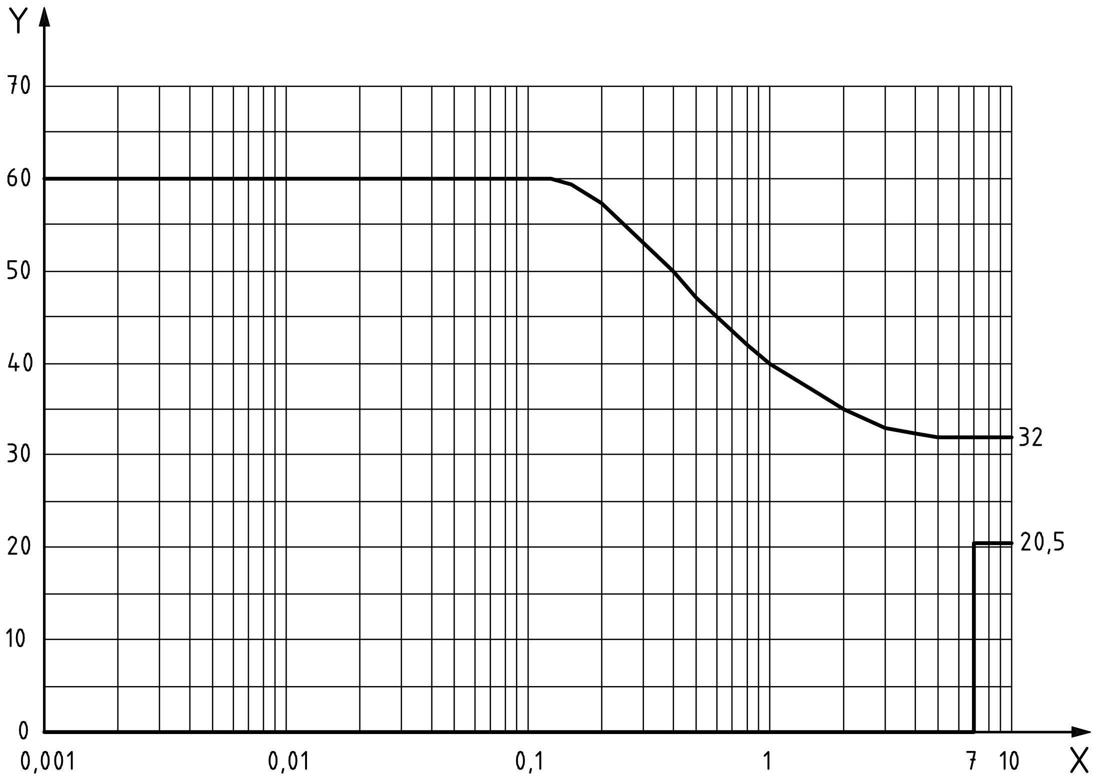
NOTE 2 Multiply 28 V d.c. values by 14/28 for 14 V d.c. input equipment.

Key

X time (s)

Y voltage (V d.c.)

Figure 17 — Normal Category B 14/28 V d.c. input power voltage transients



NOTE 1 Spike voltages and other phenomena of < 1 ms duration are not shown.

NOTE 2 Multiply 28 V d.c. values by 14/28 for 14 V d.c. input equipment.

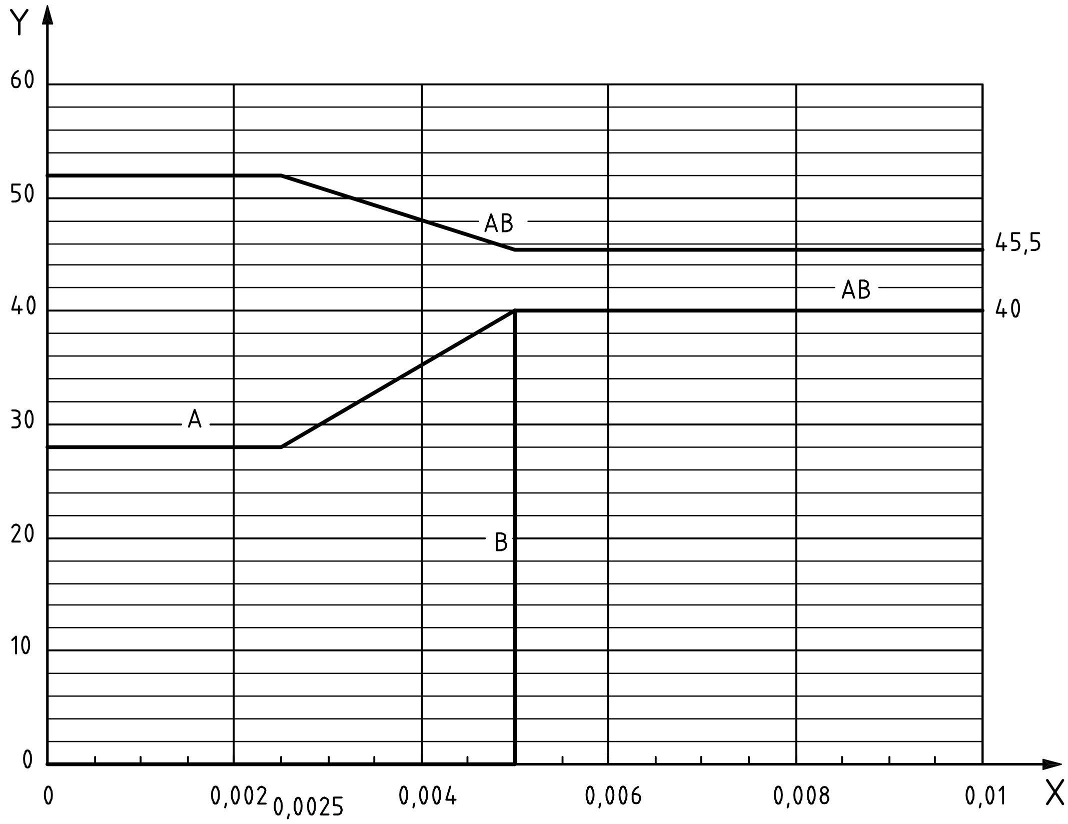
Time (s)	**Voltage** (V d.c.)
0,01	60,0
0,2	57,3
0,5	47,0
1,0	40,0
2,0	35,0
5,0	32,0

Key

X time (s)

Y voltage (V d.c.)

Figure 18 — Abnormal Category B 14/28 V d.c. input power voltage transients



Curve A is the normal transient range due to load switching; Curve B is the normal transient range due to non-NBPT bus switching.

NOTE 1 Spike voltages and other phenomena of < 1 ms duration are not shown.

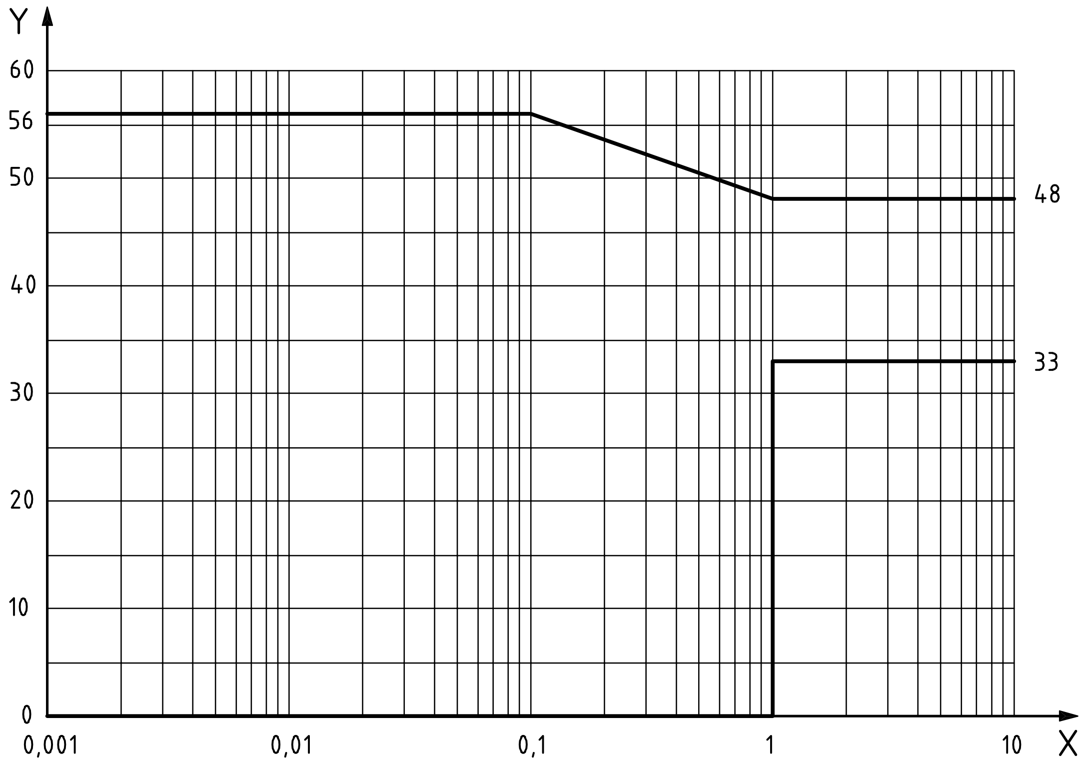
NOTE 2 Multiply 42 V d.c. values by 28/42 for 28 V d.c. input equipment.

Key

X time (s)

Y voltage (V d.c.)

Figure 19 — Normal Category R 28/42 V d.c. input power voltage transients



NOTE 1 Spike voltages and other phenomena of < 1 ms duration are not shown.

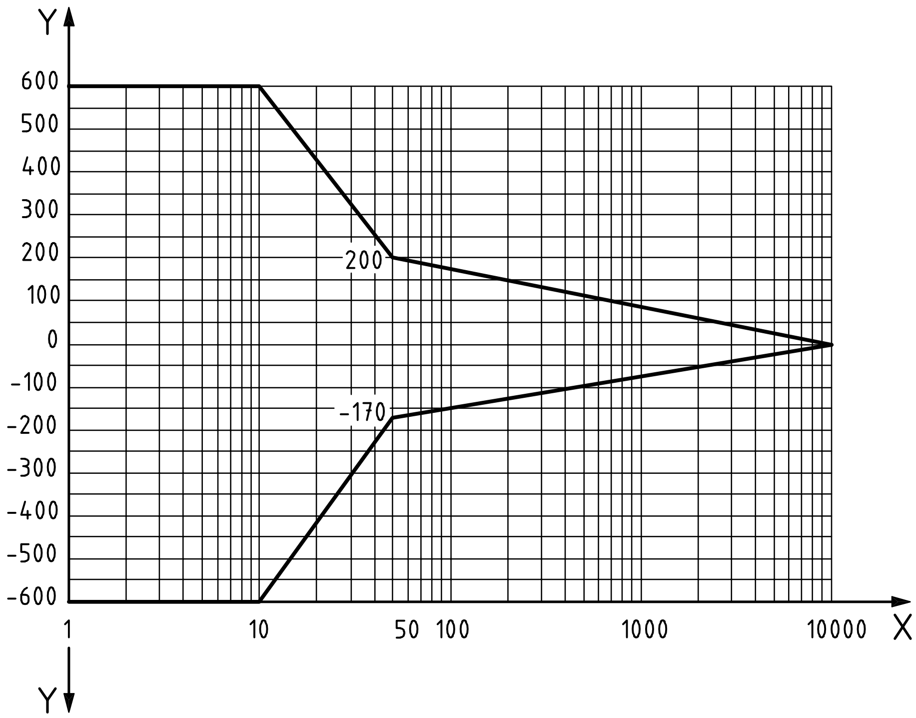
NOTE 2 Multiply 42 V d.c. values by 28/42 for 28 V d.c. input equipment.

Key

X time (s)

Y voltage (V d.c.)

Figure 20 — Abnormal Category B 28/42 V d.c. input power voltage transients



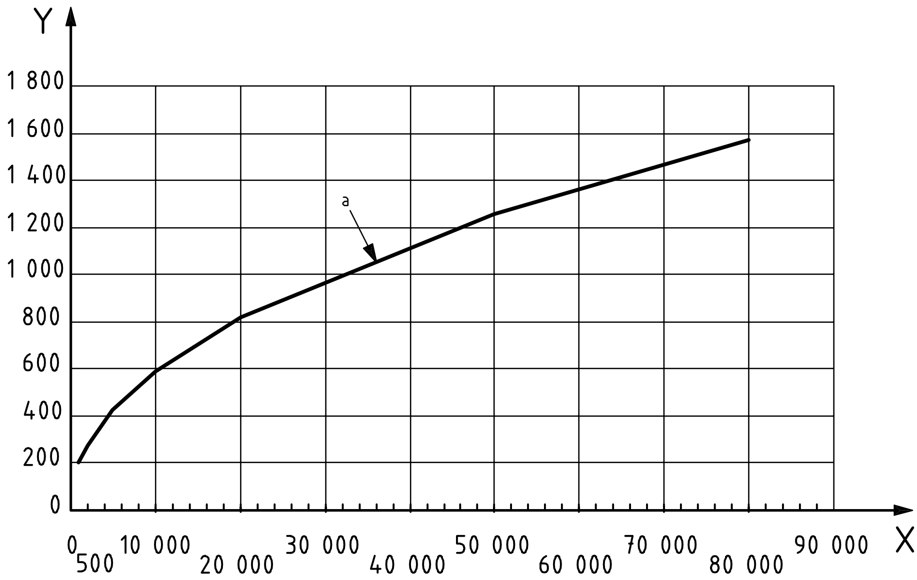
NOTE Voltages shown are for 28 V d.c. input equipment, multiply by 14/28 for 14 V d.c. input equipment.

Key

X time (μs)

Y voltage (V pk)

Figure 21 — D.C. input power voltage spike limitations



Three-phase load (W, V·A or var)	**Max. unbalance** (W, V·A or var)
500	144,4
5 000	426,1
20 000	817,6
80 000	1 568,5

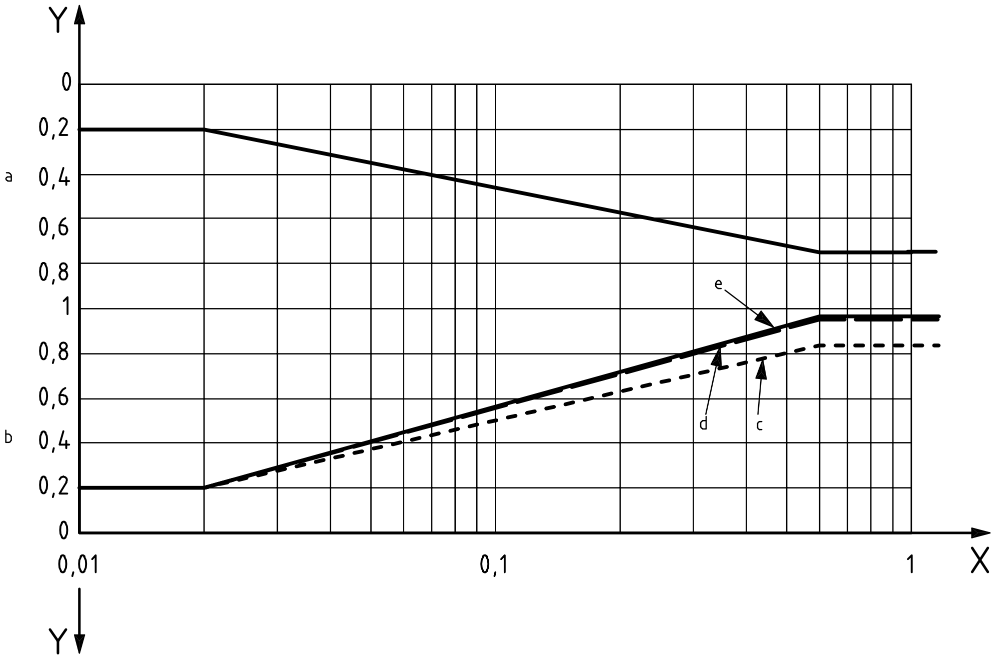
Key

X three-phase load (V, V·A or var)

Y maximum unbalance (V, V·A or var)

a Unbalance = $200 \times (\text{load}/1\ 000)^{0,47}$.

Figure 22 — Three-phase a.c. user equipment phase balance requirements



Total power (kV·A)	Leading power factor limit		
	VF at 360 Hz	**VF** at 650 Hz	**CF/VF** at 800 Hz
0,01	0,2	0,2	0,2
0,02	0,2	0,2	0,2
0,60	0,831	0,951	0,968
⩾ 1,00	0,831	0,951	0,968

Total power (kV·A)	**Lagging power factor limit**
0,01	0,2
0,02	0,2
0,60	0,75
⩾ 1,00	0,75

Key

X total power of identical equipment (kV·A)

Y power factor (V, V·A or var)

[a] Lagging power factor.

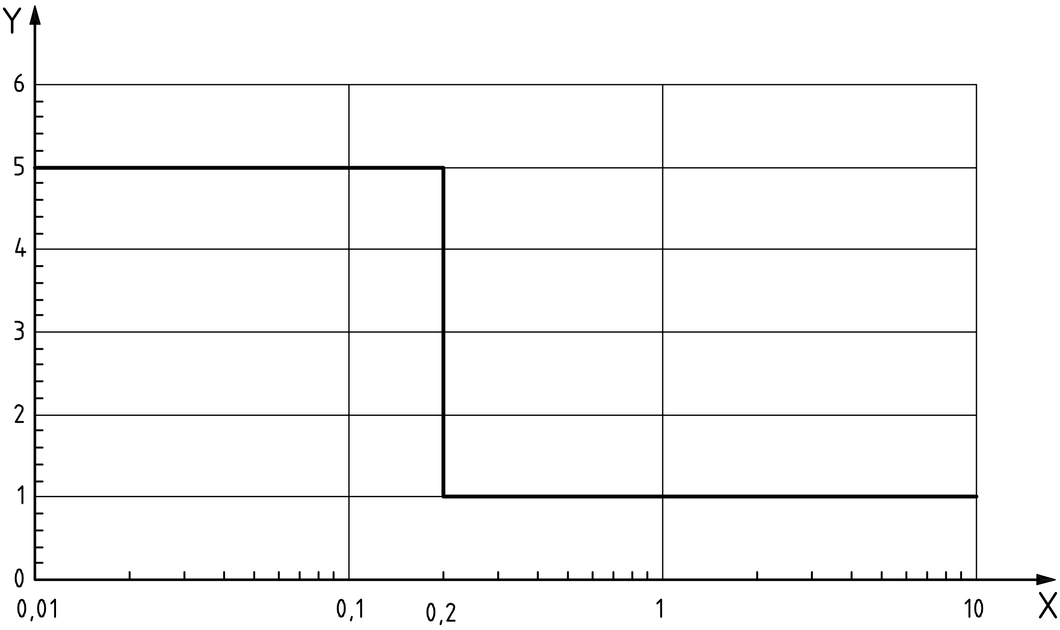
[b] Leading power factor.

[c] Variable frequency at 360 Hz.

[d] Variable frequency at 650 Hz.

[e] Constant frequency/variable frequency at 800 Hz.

Figure 23 — Power factor limits for user equipment and equipment groups



Time (s)	Instantaneous current / rated current
0,01	5,0
0,2	1,0

Key

X time (s)

Y instantaneous current/rated current

Figure 24 — Maximum inrush current for a.c. and d.c. user equipment

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