International Telecommunication Union

ITU-T

TELECOMMUNICATION
STANDARDIZATION SECTOR
OF ITU

K.147

(01/2022)

SERIES K: PROTECTION AGAINST INTERFERENCE

Protection of networked information technology equipment

Recommendation ITU-T K.147

Recommendation ITU-T K.147

Protection of networked information technology equipment

Summary

Recommendation ITU-T K.147 covers common one, two and four pair link implementations, their configurations, how surges are coupled into a system and what surge mitigation measures are used. Following this overview, the rationale for different surge and power fault test circuit approaches and when they are specified is given.

Networked equipment can be subject to overvoltage and overcurrent transients. Both data and any powering services should be resistant to the expected environmental transients. Where equipment has multiple independent ports, such as central hubs, switches, or repeaters, then testing is required for inter-port resistibility.

Resistibility testing needs to identify lightning transients coupled into a network by magnetic induction, earth potential rise, resistive coupling and transient coupling by a voltage-limiting operation of surge protective functions or flashover. Voltage limitation may convert common-mode surges into differential-mode surges in the signal path. It is also possible for alternating current mains power faults to couple into the network, which can necessitate the use of overcurrent protection.

History

Edition	Recommendation	Approval	Study Group	Unique ID*
1.0	ITU-T K.147	2020-06-29	5	11.1002/1000/14300
1.1	ITU-T K.147 (2020) Cor. 1	2021-01-06	5	11.1002/1000/14575
2.0	ITU-T K.147	2022-01-13	5	11.1002/1000/14726

Keywords

Configurations, Ethernet, K Recommendation applicability, surge coupling, test circuits, test levels, variants.

* To access the Recommendation, type the URL http://handle.itu.int/ in the address field of your web browser, followed by the Recommendation's unique ID. For example, http://handle.itu.int/11.1002/1000/11830-en.

FOREWORD

The International Telecommunication Union (ITU) is the United Nations specialized agency in the field of telecommunications, information and communication technologies (ICTs). The ITU Telecommunication Standardization Sector (ITU-T) is a permanent organ of ITU. ITU-T is responsible for studying technical, operating and tariff questions and issuing Recommendations on them with a view to standardizing telecommunications on a worldwide basis.

The World Telecommunication Standardization Assembly (WTSA), which meets every four years, establishes the topics for study by the ITU-T study groups which, in turn, produce Recommendations on these topics.

The approval of ITU-T Recommendations is covered by the procedure laid down in WTSA Resolution 1.

In some areas of information technology which fall within ITU-T's purview, the necessary standards are prepared on a collaborative basis with ISO and IEC.

NOTE

In this Recommendation, the expression "Administration" is used for conciseness to indicate both a telecommunication administration and a recognized operating agency.

Compliance with this Recommendation is voluntary. However, the Recommendation may contain certain mandatory provisions (to ensure, e.g., interoperability or applicability) and compliance with the Recommendation is achieved when all of these mandatory provisions are met. The words "shall" or some other obligatory language such as "must" and the negative equivalents are used to express requirements. The use of such words does not suggest that compliance with the Recommendation is required of any party.

INTELLECTUAL PROPERTY RIGHTS

ITU draws attention to the possibility that the practice or implementation of this Recommendation may involve the use of a claimed Intellectual Property Right. ITU takes no position concerning the evidence, validity or applicability of claimed Intellectual Property Rights, whether asserted by ITU members or others outside of the Recommendation development process.

As of the date of approval of this Recommendation, ITU had not received notice of intellectual property, protected by patents/software copyrights, which may be required to implement this Recommendation. However, implementers are cautioned that this may not represent the latest information and are therefore strongly urged to consult the appropriate ITU-T databases available via the ITU-T website at http://www.itu.int/ITU-T/ipr/.

Table of Contents

Recommendation ITU-T K.147

Protection of networked information technology equipment

1 Scope

This Recommendation provides a rationale for networked information technology equipment port testing found in [ITU-T K.20], [ITU-T K.21], [ITU-T K.44], [ITU-T K.45] and [ITU-T K.117]. Topics covered are:

- information technology system configurations:
  - data only,
  - provision of network powering,
  - link insulation;
- overvoltage and overcurrent events coupling into the network system;
- lightning surge resistibility test circuit approaches;
- power fault resistibility test circuit approaches;
- resistibility test circuit applicability to [ITU-T K.20], [ITU-T K.21], [ITU-T K.44], [ITU-T K.45] and [ITU-T K.117].

2 References

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Recommendation does not give it, as a stand-alone document, the status of a Recommendation.

[ITU-T K.20] Recommendation ITU-T K.20 (2021), *Resistibility of telecommunication equipment installed in a telecommunication centre to overvoltages and overcurrents*.

[ITU-T K.21] Recommendation ITU-T K.21 (2019), *Resistibility of telecommunication equipment installed in customer premises to overvoltages and overcurrents*.

[ITU-T K.44] Recommendation ITU-T K.44 (2019), *Resistibility tests for telecommunication equipment exposed to overvoltages and overcurrents – Basic recommendation.*

[ITU-T K.45] Recommendation ITU-T K.45 (2019), *Resistibility of telecommunication equipment installed in the access and trunk networks to overvoltages and overcurrents*.

[ITU-T K.117] Recommendation ITU-T K.117 (2016), *Primary protector parameters for the surge protection of equipment Ethernet ports*.

3 Definitions

3.1 Terms defined elsewhere

This Recommendation uses the following terms defined elsewhere:

3.1.1 balanced cable [b-ISO/IEC 1801-1]: Cable consisting of one or more metallic symmetrical cable elements (twisted pairs or quads).

3.1.2 **cable element** [b-ISO/IEC 11801-1]: Smallest construction unit in a cable.

NOTE 1 – Examples are a balanced pair, quad, single fibre, or coaxial pair.

NOTE 2 – A cable element may have a screen.

3.1.3 **cabling** [b-ISO/IEC 11801-1]: System of telecommunications cables, cords and connecting hardware that supports the connection of information technology equipment.

3.1.4 **link** [b-ISO/IEC 11801-1]: Transmission path between two cabling system interfaces, including the connections at each end.

3.1.5 **network powered device (NPD)** [b-ISO/IEC TR 29108]: Device that derives its power from the network.

3.1.6 **power source equipment** [b-ISO/IEC TS 29125]: Equipment that provides power.

3.1.7 **twisted pair** [b-ISO/IEC 11801-1]: Cable element that consists of two insulated conductors twisted together in a determined fashion to form a balanced transmission line.

3.2 Terms defined in this Recommendation

This Recommendation defines the following terms:

3.2.1 **phantom powering**: Transmission of electrical power from power source equipment (PSE) to a network powered device (NPD) using two balanced data pairs; with the power being applied to the pair balance nodes at the PSE link end and extracted from the pair balance nodes at the NPD link end.

NOTE 1 – The data pair balance node is usually the centre tap of the data pair isolating transformer.

NOTE 2 – When all four pairs of an Ethernet link are used, double phantom powering occurs if the two power transmissions are kept separate. Single phantom powering is considered to occur when the NPD combines the two power transmissions into one.

3.2.2 **power over Ethernet (PoE)**: Link phantom powering of a network powered device using two or four balanced data pairs connected to power source equipment.

3.2.3 **single pair power over Ethernet (SPoE)**: Link powering of a network powered device using a balanced data pair connected to power source equipment.

NOTE – Also known as power over data line (PoDL).

3.2.4 **injector power source equipment**: Item, located in a link that provides powering to the link section that connects to a network powered device.

NOTE – The injector can be a single item or consist of a coupling network with a separate power supply.

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

AC Alternating Current

AT Ampere-Turns

AWG American Wire Gauge

DC Direct Current

E-mark Electronically Marked

EMC Electromagnetic Compatibility

EPR Earth Potential Rise

EUT Equipment Under Test

GDT	Gas Discharge Tube
LPS	Lightning Protection System
NAS	Network Attached Storage
NCD	Network Coupler Decoupler
NPD	Network Powered Device
PD	Power Delivery
PE	Protective Earth
PoDL	Power over Data Line
PoE	Power over Ethernet
PSE	Power Source Equipment
SPC	Surge Protective Component
SPD	Surge Protective Device
SPE	Single Pair Ethernet
SPICE	Simulation Program with Integrated Circuit Emphasis
SPoE	Single-pair power over Ethernet
STPE	Screened Twisted Pair Ethernet
USB	Universal Serial Bus

5 Conventions

None.

6 Overview

6.1 General

The use of an equipment link to deliver power and data simplifies system implementation in automotive, industrial, commercial, healthcare, and domestic environments. This Recommendation discusses network configurations where data and direct current (DC) powering can take place over an inter-equipment link. Topics covered are power delivery (PD) levels, system transient overvoltages and possible protective measures against system transients.

6.2 Network power delivery

Figure 1 shows generic examples of network configurations where data and power are transferred over a link. There are three main elements in such systems: hardware capable of supplying DC power, called power source equipment (PSE); a network powered device (NPD); and a twisted pair link section connecting the PSE to the NPD. The upper part of Figure 1 shows a PSE directly connected to a NPD. The middle part of Figure 1 shows how a system based on pure data can be converted to one based on power over Ethernet (PoE) by adding a power injector PSE. The lower part of Figure 1 shows how a combination of an NPD and PSE can be used to daisy chain multiple pieces of equipment to extend the reach or to have several NPDs or both.

Ethernet configurations for two, four and single pair systems can be found in clauses 33, 145 and 104, respectively, of [b-IEEE 802.3].

It is important that the PSE power capability be at least equal to the maximum NPD power demand plus the link losses. The NPD maximum power demand is given by the NPD signature, which can be hardwired or a software-controlled value. Clause 7 lists the PoE and single pair power over Ethernet (SPoE) values defining equipment type, voltage, current and power levels.

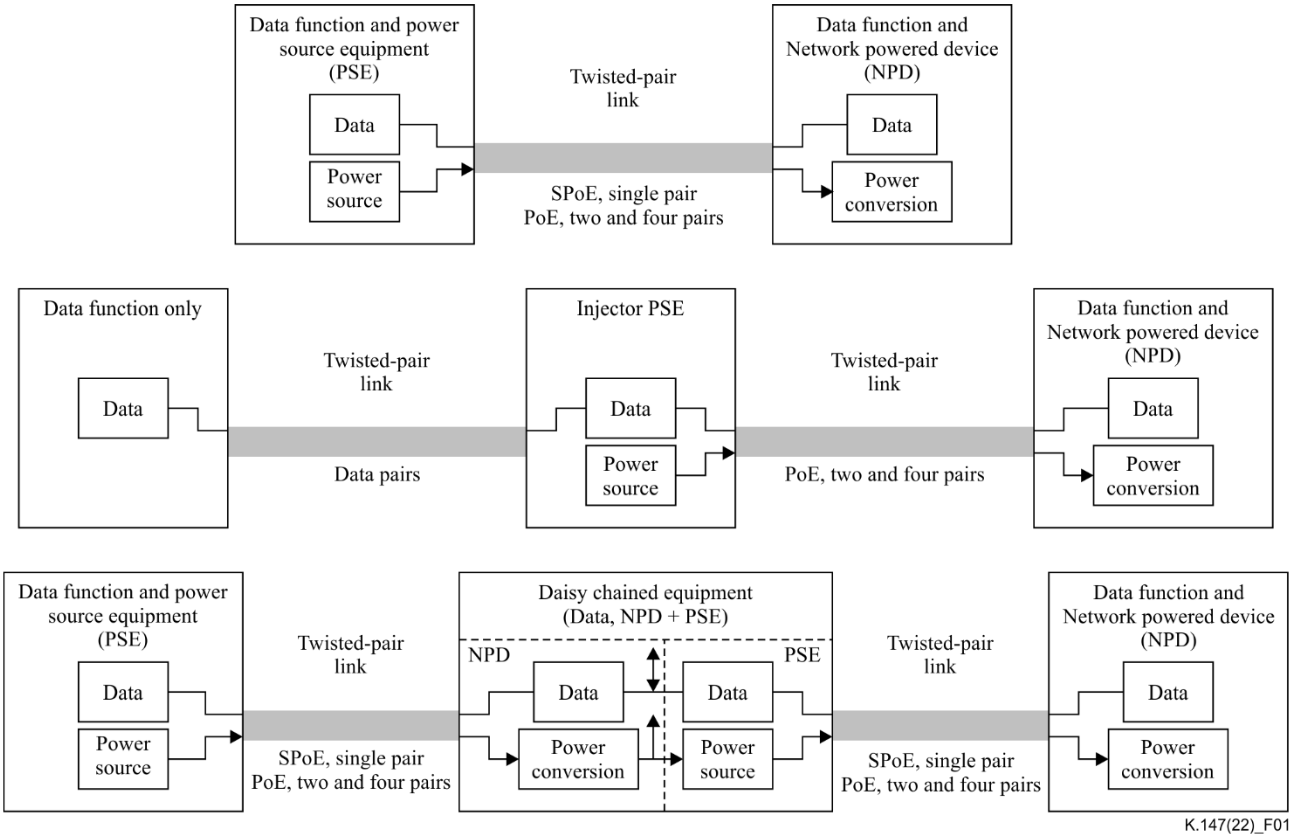


Figure 1 – Generic examples of network configurations where data and power are transferred over a link

6.3 Twisted pair data usage

A twisted pair link can carry the data by one, two or four twisted pairs, see Figure 2. The Ethernet data rate depends on the design link length and the number of twisted pairs. Single pair Ethernet (SPE) can achieve 10 Gb/s over 15 m and 10 Mb/s over 1000 m. Two twisted pairs over 100 m can achieve data rates of 100 Mb/s. Using four twisted pairs can achieve 10 Gb/s over 100 m. At high data rates the protector capacitance loading becomes important both in value and its possible variation with voltage. Protector capacitance values are covered in [b-ITU-T K.12], [b-ITU-T K.96], [b-ITU-T K.99], [b-ITU-T K.103] and [b-ITU-T K.129].

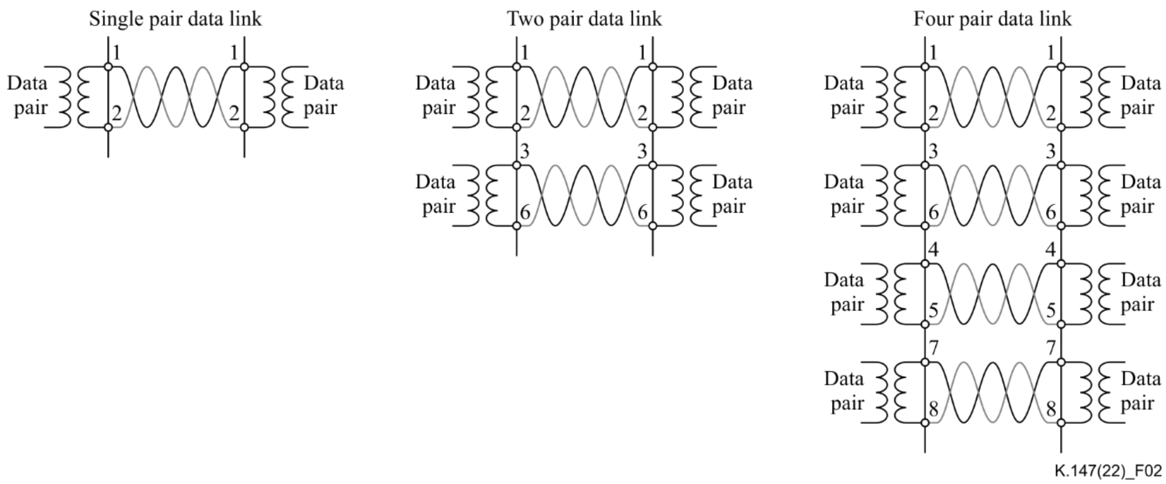


Figure 2 – Twisted pair link data transfer

Protecting an Ethernet transceiver against differential surges is typically done on the isolated secondary side of the transformer by clamping diodes to the transceiver supply rails or by low-capacitance punch-through diodes, see [b-ITU-T K.96]. Typically, the protection threshold voltage levels are between 5 V and 10 V. If the differential surge protection is applied on the link side of the transformer, higher current capability punch-through diodes are required. In the SPE case, the protection should be applied directly to the Ethernet transceiver as it is possible that the link conductors carry both the data signal and a powering voltage, which could be nearly 60 V.

6.4 Twisted pair powering usage

For SPE the powering voltage is differentially applied to the single twisted pair as is the data. Figure 3 shows an example of anSPoE configuration. Data is introduced and extracted from the link by means of alternating current (AC) coupled isolating transformers. Powering is introduced and extracted from the link via a differential-mode choke, which prevents the power source from shunting the data signal.

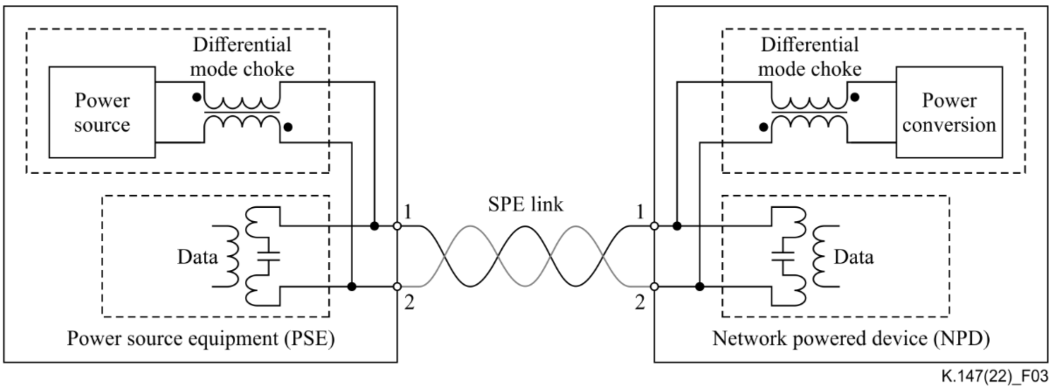


Figure 3 – Example of SPE SPoE using inductive filtering

Protecting the power source and power conversion elements against differential surges is typically done with a PN diode, see [b-ITU-T K.96], as the maximum powering voltage is in the range of 18 V to 60 V.

Phantom powering, which needs at least two independent metallic circuits, is used for two or four twisted pair PoE configurations. Figure 4 shows a phantom powering arrangement. Current I_1 leaving the power source positive terminal enters the PSE data 1 transformer centre tap and splits as currents of $0.5I_1$ in each twisted pair conductor. These currents recombine as I_1 in the NPD data 1 transformer which feeds the power conversion positive terminal. The negative power conversion terminal current return route is similar, feeding the NPD data 2 transformer centre tap. Further examples of different PoE configurations are shown in Figures B.3 to B.7.

As the powering is applied differentially to the two data pairs, differential overvoltage protection should be applied between them. This protection can be applied between the link pairs or at the power source and power conversion functions.

A conventional common-mode choke protecting data and power feeds should not be used in phantom powered systems, as the net DC of I_1 in any pair is likely to saturate the common-mode choke core. As the net DC of the two pairs is zero, a four-winding common-mode choke can be used. Two of the windings would be placed in data pair 1 and the other two in data pair 2.

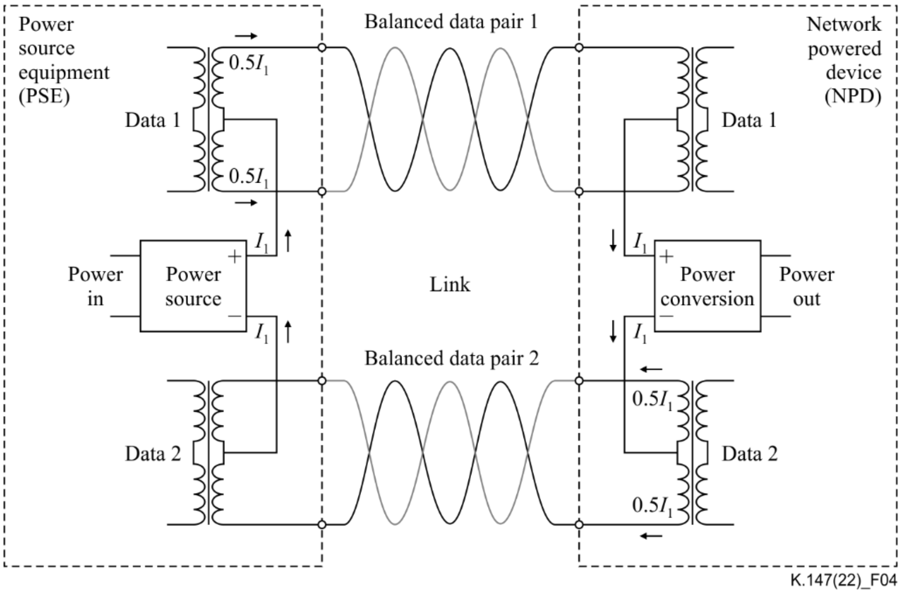


Figure 4 – Example of phantom powering

6.5 Link insulation

It is important that the insulation related to the link not break down. The maximum link withstand voltage can be due to cabling, connectors, data transformers, electromagnetic compatibility (EMC) screen spacing and printed circuit board trace dimensioning. To prevent breakdown, a voltage limiter can be connected in shunt with the insulation. Using only a single shunt voltage limiter, rather than multiple voltage limiters from various circuit nodes, reduces the possibility of common-mode to differential-mode surge conversion.

6.6 Summary of link conductor usage

Figure 5 shows the various data and powering conductor allocations as discussed in clauses 6.1 to 6.5. For further information, see Clauses 33, 104 and 145 of [b-IEEE 802.3].

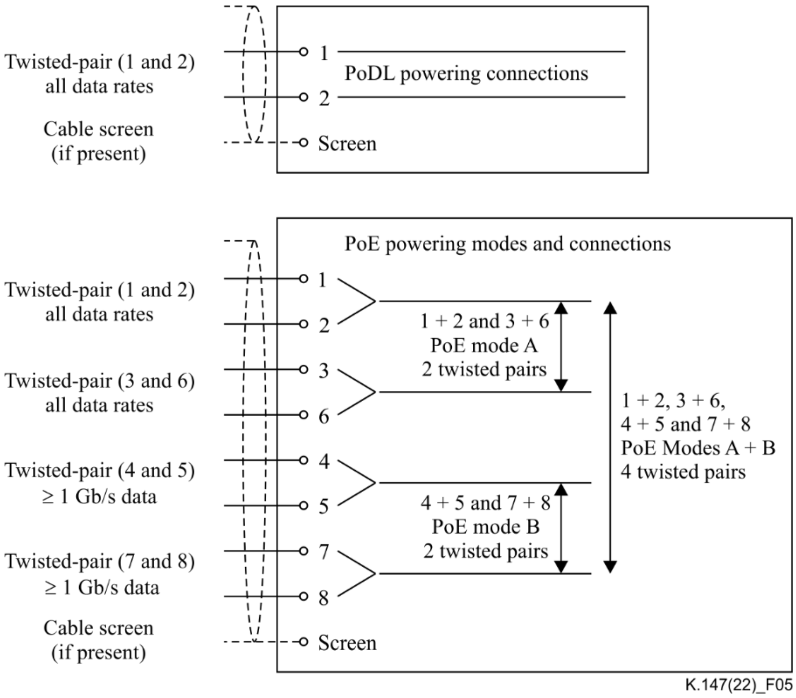


Figure 5 – Summary of typical Ethernet connector conductor usage

7 Link voltage, current and resistance values

7.1 Single balanced pair link SPE

Table 2 references the circuit configurations by the NPD rated power. Over the equipment or device microclimate temperature range any series protection functions must not operate at the link maximum continuous current or, if not automatically resetting, during surge testing. The series protection function resistance should be only a small fraction of the link loop resistance to avoid reducing the configuration reach. Over the equipment or device microclimate temperature range, any shunt voltage limitation protective functions must not have a minimum conduction threshold voltage below the PSE maximum voltage.

Table 2 – Single pair link powering

NPD rated power W	**Link maximum continuous current** mA	**Link loop maximum resistance** Ω	**PSE maximum voltage** V
1.23	92	65	30
3.2	240	25	
8.4	632	9.5	
7.7	231	65	58
20	600	25	
52	1 579	9.5	

Loop resistances for single pair powering systems may be found in Table 104-1 and Table 104-1a of [b-IEEE 802.3]. Also see clause 104 of [b-IEEE 802.3] for further information including powering levels and voltages.

7.2 Two and four balanced pair link

Based on Table 145–26 maximum NPD powers and Table 145–29 minimum NPD voltages of [b-IEEE 802.3], Table 3 shows the calculated maximum total NPD current. Over the equipment or device microclimate temperature range, any series protection functions must not operate at the link maximum continuous current or, if not automatically resettable, during surge testing. The series protection function resistance should be only a small fraction of the link loop resistance to avoid reducing the configuration reach. The 2 × 2 power pair case is for an NPD that requires two different two pair powering feeds. Over the equipment or device microclimate temperature range, any shunt voltage limitation protective functions must not have a minimum conduction threshold voltage below the PSE maximum voltage.

Table 3 – Two and four pair link NPD powering values

Powering pairs	V_{min} V	P_{max} W	I_{max} A
2	42.8	3.84	0.090
2	42	6.49	0.155
2	39.9	13	0.326
2	42.5	25.5	0.600
2 × 2	41.1	35.6	0.866
4	44.3	40	0.903
4	42.5	51	1.20
4	42.9	62	1.45
4	41	71.3	1.74

Loop resistances and powering voltages for two pair powering systems are listed in Tables 33-1 and 33-11 of [b-IEEE 802.3]. Loop resistances and powering voltages for four pair powering systems are listed in Tables 145-1 and 145-16 of [b-IEEE 802.3]. See clause 33 and clause 145 of [b-IEEE 802.3] for further information.

8 Surges on network systems

8.1 Surge coupling mechanisms

[b-ITU-T K.39] states that there are four main coupling mechanisms for surges to couple into networks and equipment:

- direct coupling (permanent or transient);
- magnetic coupling;
- electric coupling;
- electromagnetic coupling.

8.2 Direct coupling – permanent

Resistive coupling may be a permanent coupling like differential earth potential rise (EPR), or transient coupling like the operation of a surge protective device (SPD) or a side flash. Use of inappropriate SPDs can often cause equipment failure through common- to differential-mode surge conversion, see [ITU-T K.117].

Figure 6 depicts a lightning strike to uniform resistivity soil where the lightning current spreads out radially and a series of concentric (dashed) equipotential rings can be mapped. If two earth rods, A and B, are positioned on a strike radial and on different equipotential rings, there will be a difference in EPR between them. Equipment bonded to A and equipment bonded to B will have a differential EPR between them and this is applied to any connecting link between A and B equipment. If the link has a cable screen, a high potential-equalizing current flows in the screen.

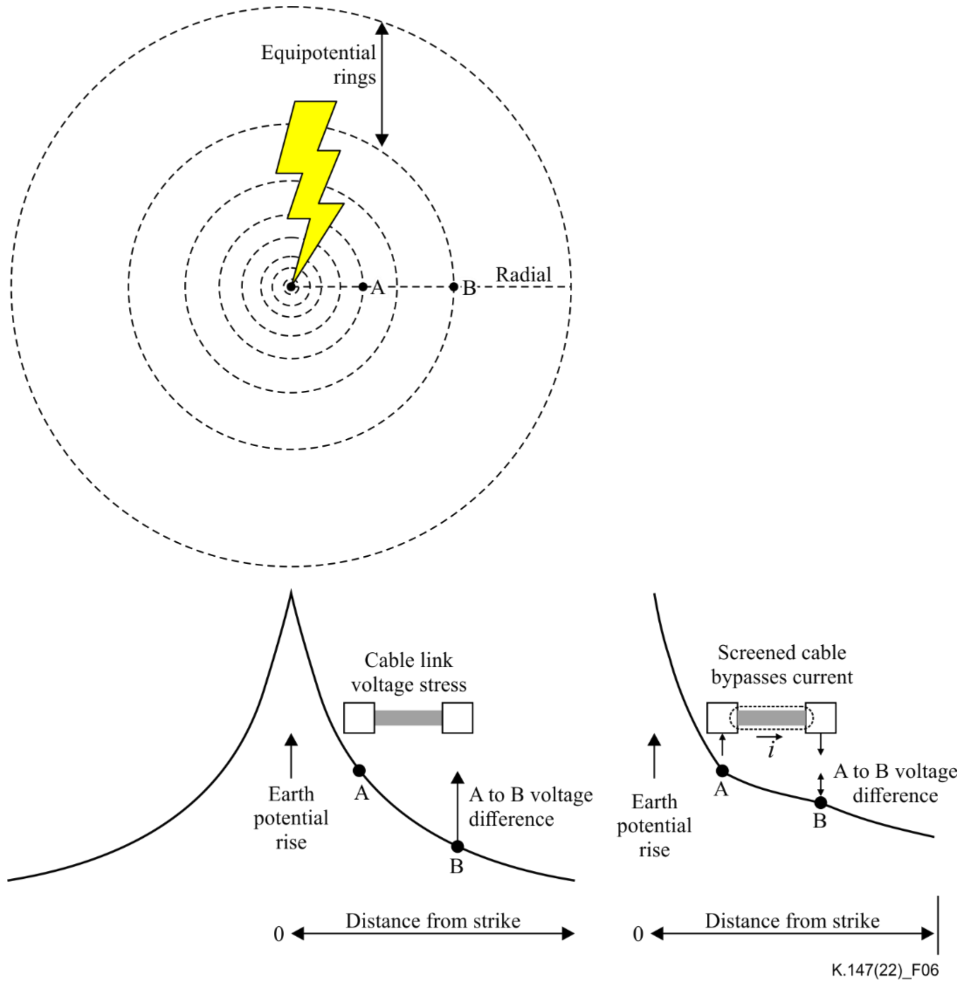


Figure 6 – Lightning EPR example

8.3 Direct coupling – transient

8.3.1 Voltage limiters

Operation of equipment surge protective components (SPCs) or external SPDs can couple transients into a protected service or service transients can be injected into the equipotential bonding network causing localized voltage rise due to bonding conductor inductance.

Voltage limiters are used to protect insulation from breakdown and components from failing. Voltage limitation must not operate under steady state conditions. Depending on the voltage-limitation technology, temporary overvoltage size and duration, the voltage limiter may or may not operate. Under surge conditions, for fast- and slow-front surges, voltage limitation occurs. Should an AC power cross condition occur, the link conductors could have the local AC mains voltage applied to them. To prevent damaging high AC currents to earth, the voltage threshold of link to earth protection must be higher than the local AC mains peak voltage. ITU-T equipment Recommendations such as [ITU-T K.21] verify this by measuring the link to earth insulation resistance at 500 V DC. The measured resistance must be equal to or greater than 2 MΩ. If the measured value is less than 2 MΩ, then an AC mains power cross test is performed to identify any safety hazards. Figure 7 is a simplified version of a [b-IEC 60099-5] diagram illustrating how AC distribution equipment insulation withstands changes with time and how voltage limitation prevents insulation breakdown.

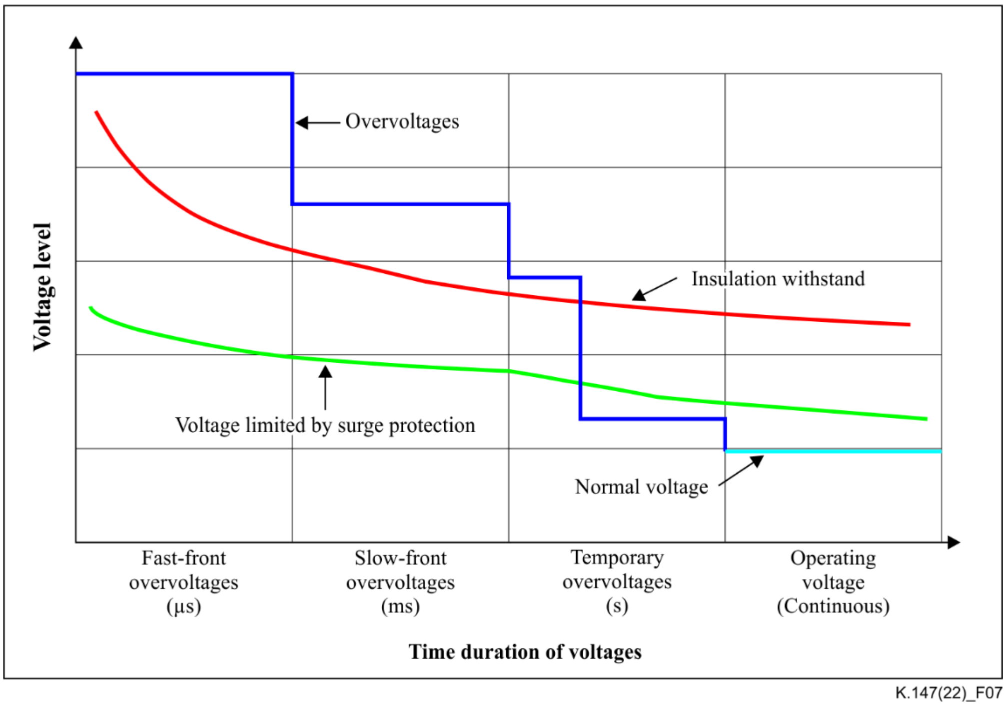


Figure 7 – AC system overvoltage level, insulation withstand and voltage limitation variation with time

Figure 8 shows three undesirable consequences of AC mains service SPD operation. If a large EPR occurs, the SPD can couple that surge on to the protected service as shown by the left circuit of Figure 8. The centre circuit of Figure 8 shows how current surges on the service are diverted by the SPD into the local earthing system causing local protective earth (PE) inductive surge voltages. The right circuit of Figure 8, for three wire (L1, L2 and N) single-phase installations, common in Japan and the USA, shows how SPDs applied to one L-N pair can cause surge voltage differences between equipment connected to L1-N and L2-N. SPDs applied to communication services can cause similar events to the left and centre circuits.

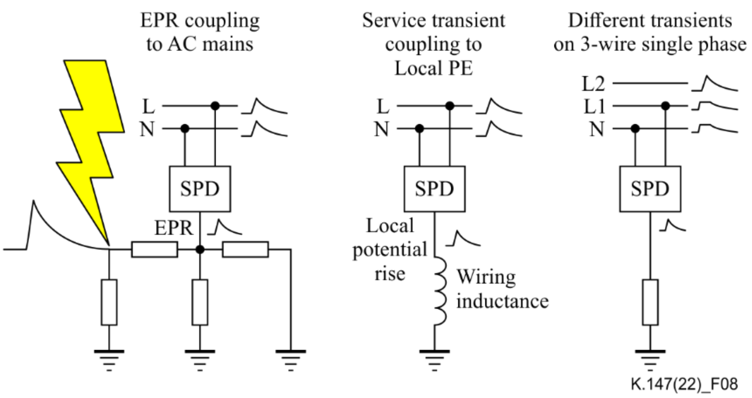


Figure 8 – SPD coupling of EPR voltage (left), injecting surge current into the local earthing system (centre) and causing differential surge on three wire single-phase mains (right)

When a common-mode surge occurs on cable conductors, asynchronous voltage limitation can result in the creation of a large differential surge. Figure 9 shows a circuit that produces common- to differential-mode conversion. Generator G is charged to 2 kV and produces a 5/75 voltage waveshape. Equal value resistors, R1 and R2, feed the common-mode surge to cable conductor A and B. Gas discharge tubes (GDTs), GDTA (520 V sparkover voltage) and GDTB (540 V sparkover voltage), limit the maximum conductor voltages. Resistor R3, between the conductors, represents the port termination and the mutual conductor coupling.

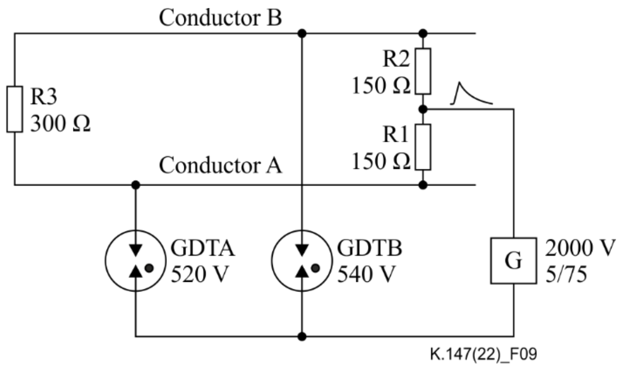


Figure 9 – Example circuit causing common mode to differential-mode surge conversion

Figure 10 shows the common-mode surge voltage (black line) at the junction of R1 and R2 peaks at just over 1500 V. When the surge voltage reaches 520 V, GDTA sparks over, lowering the conductor A voltage to about 10 V (red line). Via resistor R3 the conductor B voltage (red line) is reduced at GDTA sparkover and subsequently the conductor B voltage rises at a slower rate than before. When the conductor B voltage reaches 540 V, GDTB sparks over, lowering the conductor B voltage to about 10 V (red line). During the time between sparkovers there is a large differential voltage of about 450 V for over 1 µs between the conductors (green line, shown inverted for clarity).

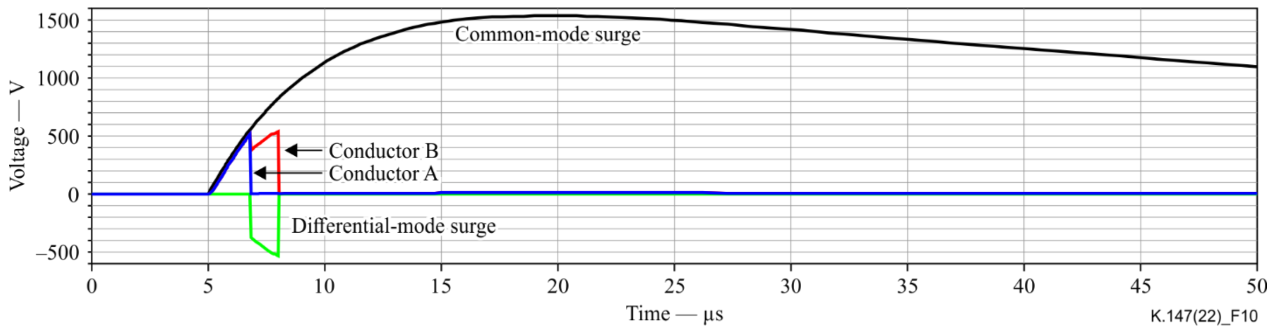


Figure 10 – Surge voltages

Changing the individual two-electrode GDTs for a single chamber three electrode GDT might be expected to fix the asynchronous operation problem, but, because the first part of a three electrode GDT to spark over reduces the voltage on the other part, there is still asynchronous operation as described in [b-Gazivoda-Nikolic].

8.3.2 Capacitance

Surge conditions can result in the charging and discharging of circuit capacitors and these currents may cause disruptions in circuit operation. The inherent capacitance of isolation barriers may need to be considered where they are in series, as shown in Figure 11.

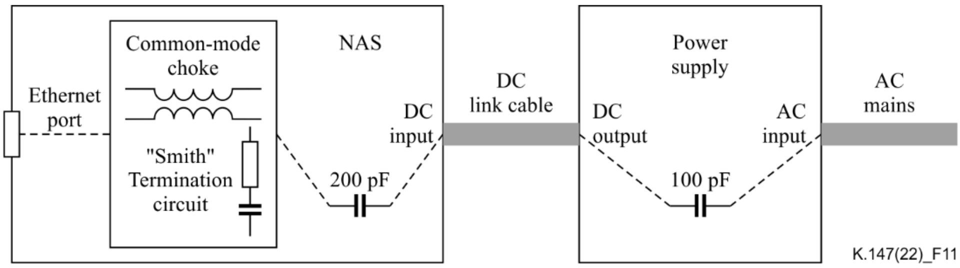


Figure 11 – Example of network attached storage (NAS) and power supply capacitances

If the Ethernet port has a series common-mode choke, then there is no low impedance path for capacitive current flow. If the Ethernet port has a "Smith" termination circuit, then a low impedance path for capacitive current flow exists. In this case, the Ethernet transformer isolation barrier has 100/(200 + 100) = 1/3 of the mains transient voltage across it.

8.4 Magnetic coupling

Transient magnetic fields will induce voltages and, in low impedance circuit loops, currents in the cabling. Transient magnetic fields caused by lightning can be from the lightning itself or the lightning current flowing in the lightning protection system (LPS) down conductor on the side of a building. Inside the building, network cabling can run parallel and quite close to an external LPS down conductor. The down conductor mutual coupling inductance, M, to the network cabling can be several microhenries. Figure 11 shows an example situation where a lightning current or the current in an LPS down conductor radiates a transient magnetic field that couples with open- and short-circuit twisted pair loops. The lightning current is a 100 A peak, 5/75 current impulse coupled to each loop type by a mutual inductance of 5 µH. Figure 12 plots the lightning current (green line), a short-circuit loop conductor current (blue line) and the open-circuit loop end-to-end cable voltage (red line) against time.

In the open-circuit loop, the induced voltage is dependent on 5 µH × (dI/dt), where dI/dt is the lightning rate of current change with time. The time graph green line is the lightning current, the blue line is the current in any loop and the red line is the cable end-to-end voltage. The peak voltage is 110 V indicating an initial lightning current dI/dt of 110/5 = 22 A/µs. After the lightning current peaks, the decreasing current has a negative dI/dt producing a cable voltage about −5 V. Had the lightning current peak been 10 kA, the peak voltage would be 11 kV. The peak cable voltage is balanced, for example, the PSE end would be −5.5 kV and the NPD end would be 5.5 kV. However, if the PSE power source is connected to earth or an SPD is applied at the PSE end, then the other cable end would experience nearly 11 kV as shown in Figure 13.

In the short-circuit loops, the total circuit ampere-turns (AT), try to oppose the lightning current magnetic field AT. The time graph green line is the lightning current and the blue line is a short-circuit loop conductor current. The peak loop current is 46 A, but decays more rapidly than the lighting current.

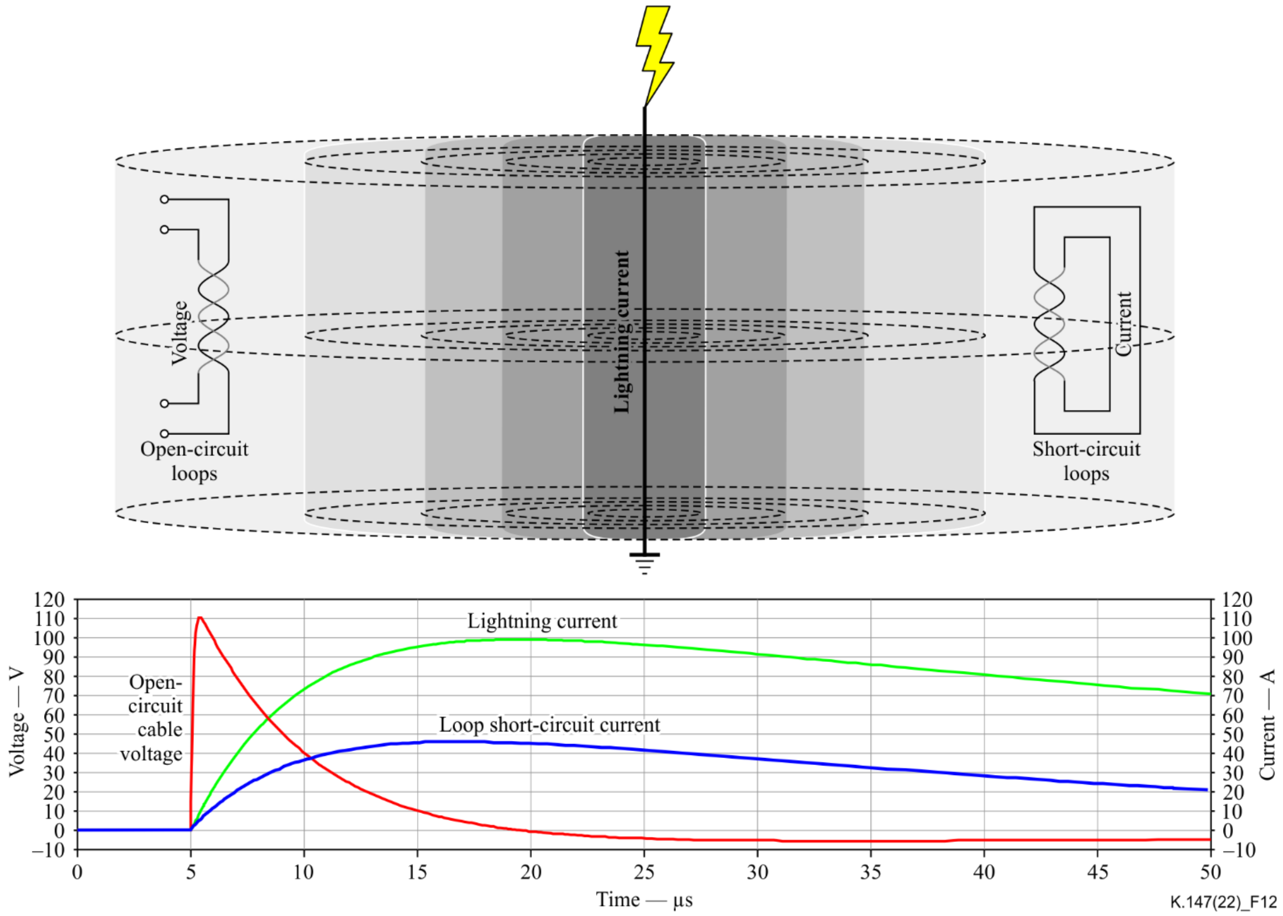


Figure 12 – Magnetically induced cable voltage and current from lightning current

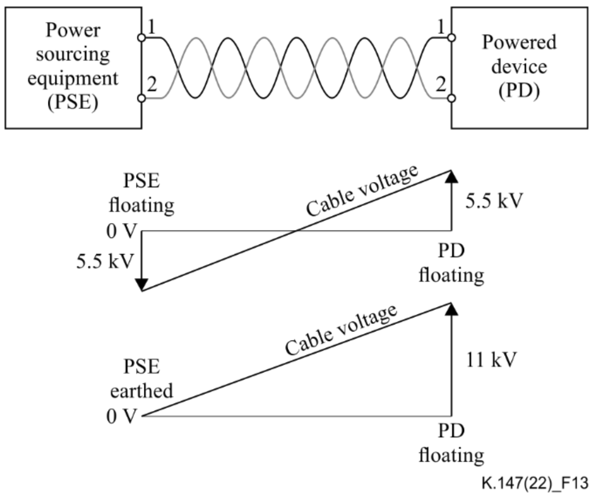


Figure 13 – PSE and NPD port voltages due to magnetic coupling

8.5 Electric and electromagnetic coupling

Transient electric fields can couple into systems possibly causing interference and equipment lock up rather than damage. Electromagnetic fields from transmitting devices can create interference and possibly equipment lock up rather than damage.

8.6 Surge resistibility design approaches

Adequate surge resistibility can be achieved by the use of surge mitigating components having linear or non-linear technology or a combination of both component types. [b-ITU-T K.96] provides an overview of surge mitigation functions and technologies (except for screened cable technology).

Ethernet isolation transformers [b-ITU-T K.126] usually have a withstand voltage rating that will survive the expected common-mode surge voltages. Where the surge voltage levels are unknown or the transformer withstand voltage rating is too low, parallel-connected voltage limiters may be used to prevent transformer insulation breakdown, see Figure 6. Common-mode chokes are also effective means of mitigating common mode surges and reducing EMC problems.

Switching voltage limiters use gas discharge [b-ITU-T K.99] or solid-state thyristor technologies. Clamping voltage limiters use metal oxide varistor [b-ITU-T K.128] or PN junction [b-ITU-T K.103] technologies. All technologies can be used for voltage limitation of the link segment conductors to PE or between conductors. The most appropriate technology depends on the application. For example, in low voltage signal applications, the high capacitance of the metal oxide varistor and the poor fast wave front protection level of 90 V or lower GDTs can result in operational or surge problems.

Overcurrent limiters use either thermal or current level technology. The response of thermal overcurrent protectors is relatively slow, limiting their use to power fault conditions or the short-circuit condition of a DC power supply see [b-ITU-T K.144] (positive temperature coefficient thermistors) and [b-ITU-T K.140] (fuses). Electronic current limiters, which operate on current level, can be used to limit surge currents in signal circuits.

9 Resistibility test circuits

9.1 Lightning resistibility

Table 4 shows the Ethernet test configurations presented in Figures C.1 to C.10 for [ITU-T K.44] for equipment ports and Figures C.11 to C.19 for [ITU-T K.117] for SPDs and PSE devices. Figures C.3 to C.5 and Figures C.8 to C.16 illustrate lightning tests. Figure C.7 shows power cross, Figures C.6, C.17 and C.18 insulation resistance and Figure C.19 voltage drop.

Table 4 – Ethernet tests

Figure	Title	Purpose	Conductors
C.1	Combination wave generator based on clause A.3-5 of [ITU-T K.44]	Impulse	N/A
C.2	Power induction, power contact and rise of neutral potential generator based on clause A.3-6 of [ITU-T K.44]	AC	N/A
C.3	Termination and coupling to earth of untested Ethernet ports based on clause A.6.7-1 of [ITU-T K.44]	Terminations	All
C.4	Ethernet port, including PoE variants, common-mode voltage with stand test circuit based on clause A.6.7-3a of [ITU-T K.44]	Common-mode-current hogging	All
C.5	Ethernet port, including PoE variants, common mode to differential mode conversion surge test circuit based on clause A.6.7-4 of [ITU-T K.44]	Common-mode to differential-mode conversion	All
C.6	Ethernet port, including PoE variants, DC insulation resistance test circuit based on clause A.6.7-3 of [ITU-T K.44]	Insulation	All

Table 4 – Ethernet tests

Figure	Title	Purpose	Conductors
C.7	Ethernet port, including PoE variants, power cross test circuit based on clause A.6.7-7 of [ITU-T K.44]	Power cross	All
C.8	PoE port powering pair transverse/differential surge test circuit based on clause A.6.7-2 of [ITU-T K.44]	Powering differential	Power
C.9	Ethernet port differential-mode surge test circuit including PoE variants based on clause A.6.7-5 of [ITU-T K.44]	Data port differential	Data
C.10	Ethernet screened cable port screen connection high current bonding test based on clause A.6.7-6 of [ITU-T K.44]	High current	Screen
C.11	Impulse limiting voltage under common-mode surge conditions	Common-mode-current hogging	All
C.12	Single twisted pair differential-mode surge test circuit	Differential	Pairs
C.13	Power feed differential-mode surge test circuit	Powering differential-mode	Powering pairs
C.14	Twisted pair common mode to differential-mode voltage surge conversion test circuit	Common-mode to differential-mode conversion	All
C.15	Power feed pair common mode to differential mode surge conversion test circuit	Common-mode to differential-mode conversion	Powering pairs
C.16	Screen bonding test	High current	Screen
C.17	Test circuit to measure the insulation resistance of an SPD with a PE terminal or screen terminals, or both	Insulation	Pairs
C.18	Test circuit to measure the insulation resistance of an isolating transformer SPD without a PE terminal	Insulation	Pairs
C.19	Test circuit to measure the PoE SPD DC input/output voltage drop	Item powering loss	All

9.2 Power fault resistibility

The power cross test shown in Figure C.7 is for direct contact with the local AC mains. As the highest domestic AC mains peak voltage is below 400 V, Ethernet ports passing the 500 V DC insulation test do not require power cross testing.

9.3 SPE link

Standard PoE Ethernet test circuits assume the link connection has four twisted pairs. As SPE only uses a single twisted pair, not all standard PoE Ethernet test circuits are applicable. Some informative references applicable to SPE are given in [b-Maytum] and [b-SPE-R]. Other forms of networking are also likely to need unique tests, for example see [b-USB PD], [b-USB C2.1] and [b-Profinet].

The upper plot in Figure 14 has a maximum PSE voltage of 58 V and the lower 30 V. Horizontal lines show the preferred NPD powers of Table 2. The sloping dashed lines are for different American wire gauge (AWG) values. SPE does not necessarily use standard Ethernet cable conductor sizes, but can be much larger to get lower loop resistance and increased link distance. Figure 14 has been constructed from the spot values found in Table 104–1 and Table 146B–1 of [b-IEEE 802.3].

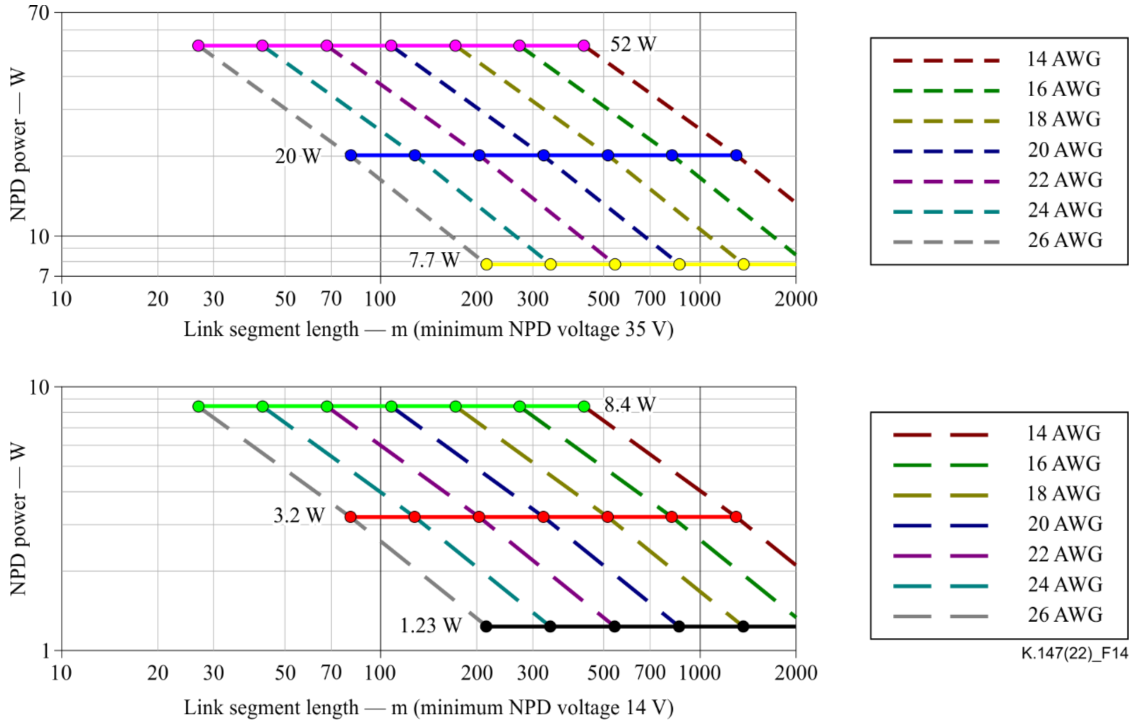


Figure 14 – SPE NPD power-distance capability for link conductor size

Figure 14 shows the trade-off between conductor AWG and distance. For example, on the 20 W blue line the following values can be obtained:

- 14 AWG allows a 1 300 m link section
- 18 AWG allows a 515 m link section
- 22 AWG allows a 200 m link section
- 24 AWG allows a 128 m link section
- 26 AWG allows an 80 m link section

Annex A

Ethernet twisted pair DC power feeds

(This annex forms an integral part of this Recommendation.)

A.1 Introduction

This annex summarizes the DC power feed circuits listed in Table B.1 of [b-IEEE 802.3].

Note that Figures A.1 to A.10 are functionally equivalent to those in [b-IEEE 802.3], but have been redrawn for consistency and alignment with the ISO/IEC JTC1/SC25 vocabulary.

Table A.1 – DC power feed circuits

Figure	Ethernet data rate	Powering pairs	Powering pair configuration	injector
A.1	100 Mb/s to 10 Gb/s	1	C1	
A.2	10 Mb/s	1	C1	
A.3	10 Mb/s & 100 Mb/s	2	C1 or C2	
A.4	≥1000 Mb/s	2	C1	
A.5	10 Mb/s & 100 Mb/s	2	C1 or C2	Yes
A.6	≥1000 Mb/s	2	C1	Yes
A.7	10 Mb/s & 100 Mb/s	4	C1 and C2	
A.8	≥1000 Mb/s	4	C1	
A.9	10 Mb/s & 100 Mb/s	4	C1 and C2	Yes
A.10	≥1000 Mb/s	4	C1	Yes
C1: Power and data on same pair; C2: power and data in separate pairs				

A.2 Powering over one twisted pair

In this case, both power and data share the same twisted pair, see Figures A.1 and A.2.

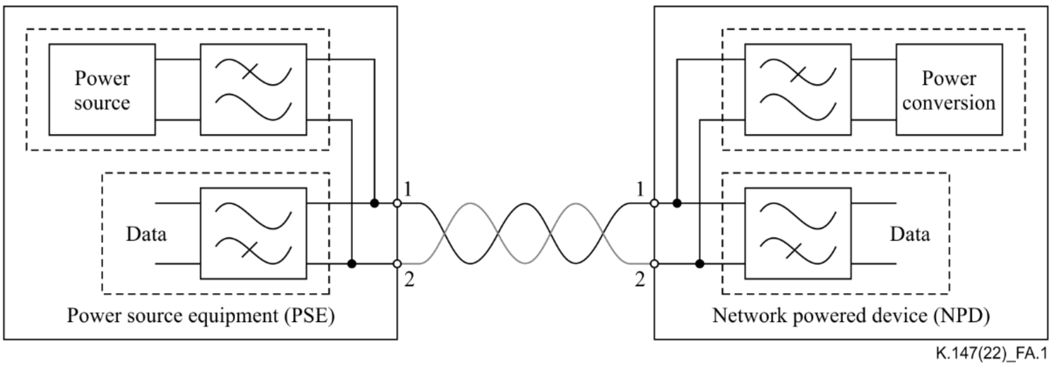


Figure A.1 – Generic SPE system block diagram (based on Figure 104–3 of [b-IEEE 802.3])

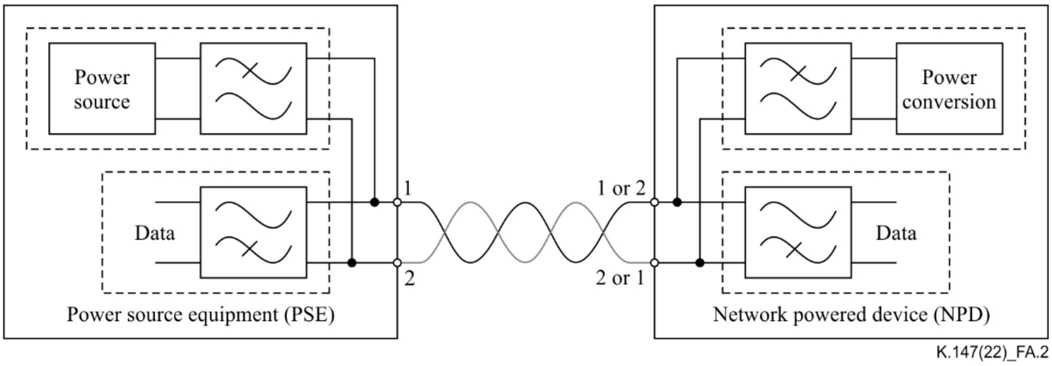


Figure A.2 – 10 Mb/s long reach (1 km or more) SPE system block diagram (based on Figure 104–3 of [b-IEEE 802.3])

A.3 Powering over two twisted pairs

In this case, powering uses two twisted pairs, one for feed and the other for return. These may be shared with data in the alternative A configuration or be separate in the alternative B configuration, see Figures A.3, A.4, A.5 and A.6.

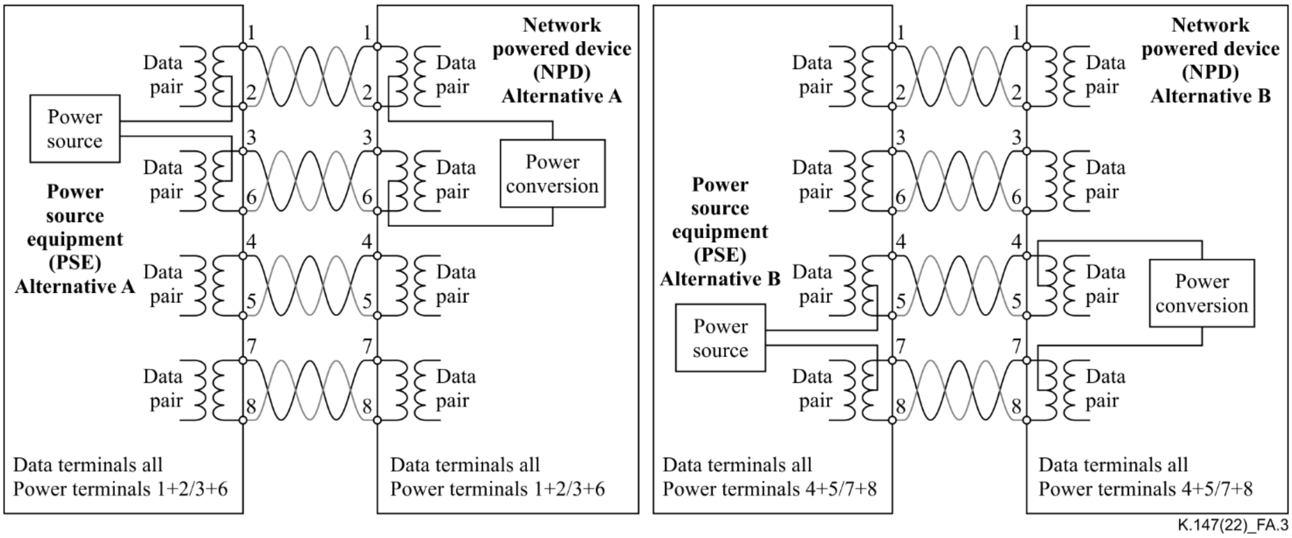


Figure A.3 – 10 Mb/s and 100 Mb/s PoE alternatives A and B (based on Figure 33–4 and Figure 145–4 of [b-IEEE 802.3]

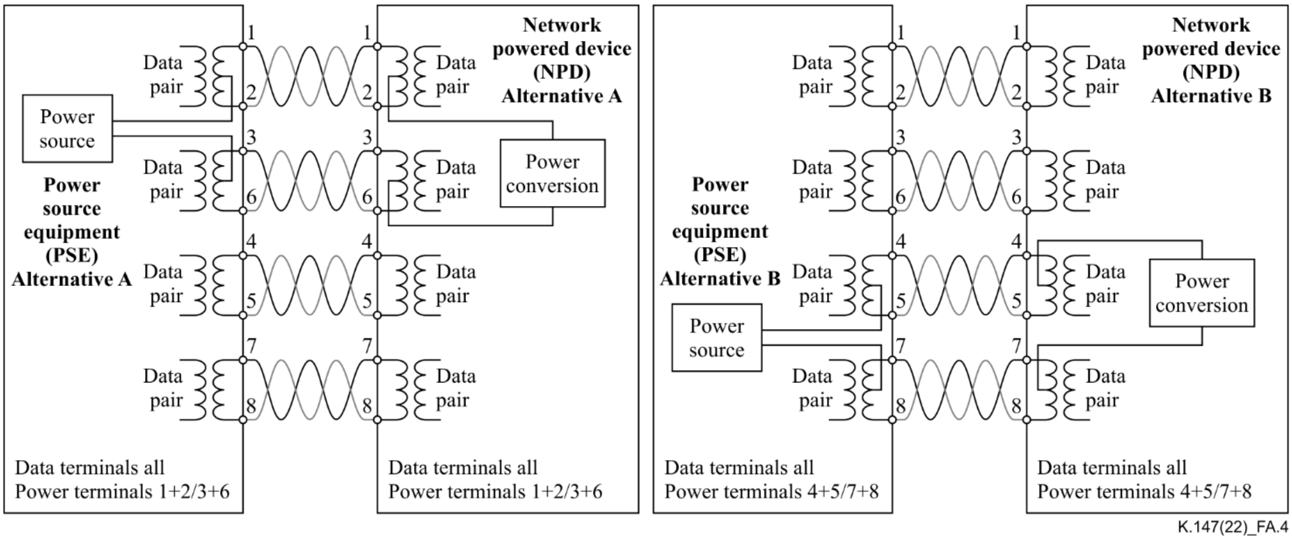


Figure A.4 – ≥1000 Mb/s PoE alternatives A and B (based on Figure 33–5 and Figure 145–5 of [b-IEEE 802.3])

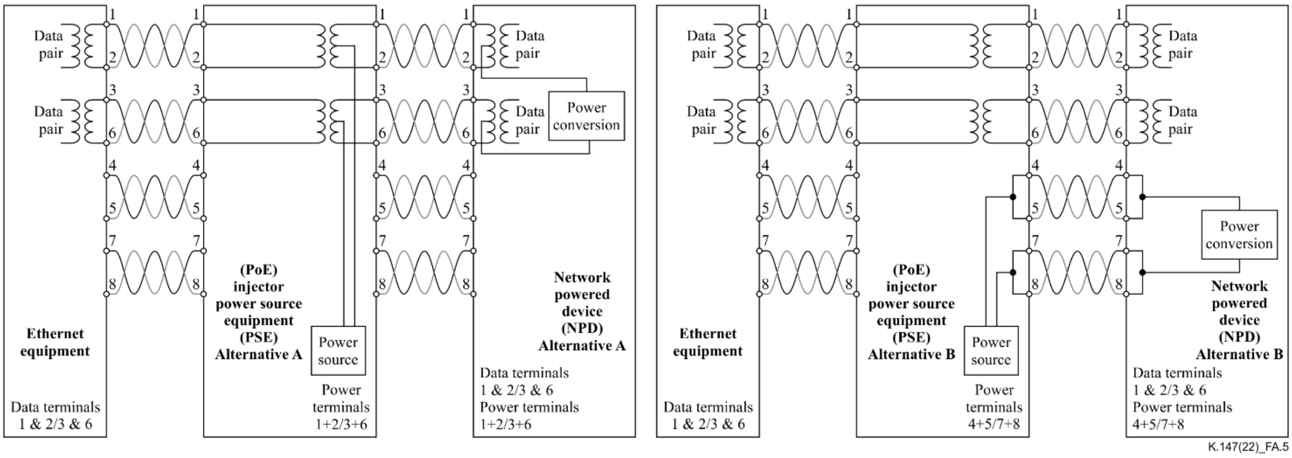


Figure A.5 – 10 Mb/s and 100 Mb/s PoE injector alternatives A and B (based on Figure 33–6 and Figure 145–9 of [b-IEEE 802.3])

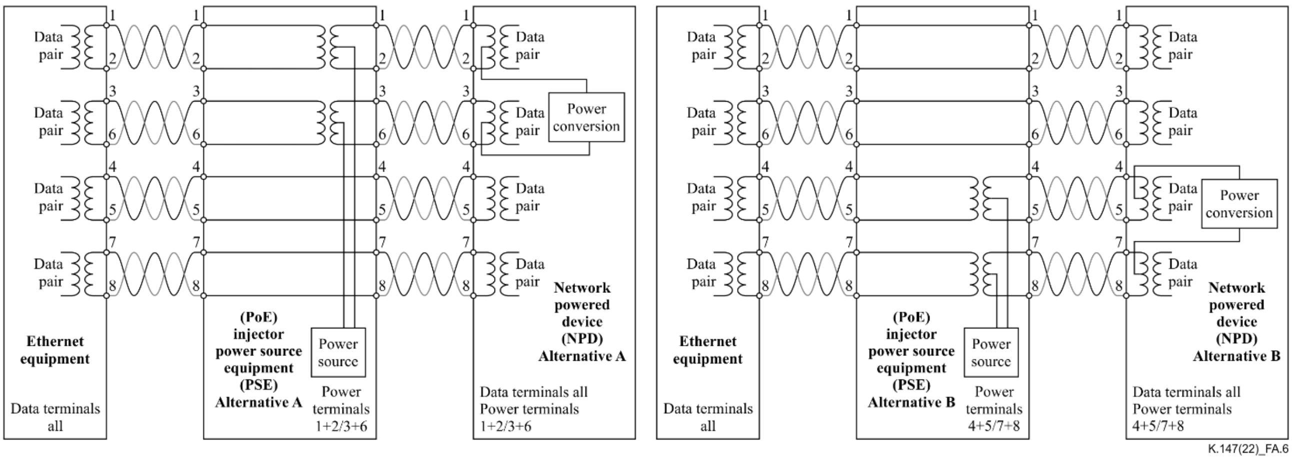


Figure A.6 – 1000 Mb/s PoE injector alternatives A and B (based on 33–7 and Figure 145–8 of [b-IEEE 802.3])

A.4 Powering over four twisted pairs

In this case, powering uses four twisted pairs, two for feed and two for return, see Figures A.7, A.8, A.9 and A.10.

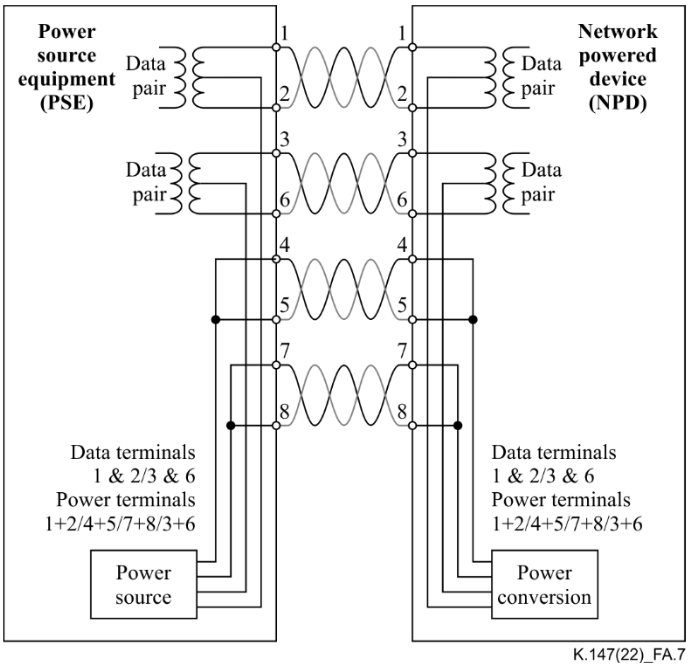


Figure A.7 – 10 Mb/s and 100 Mb/s PoE (based on Figure 145–6 of [b-IEEE 802.3])

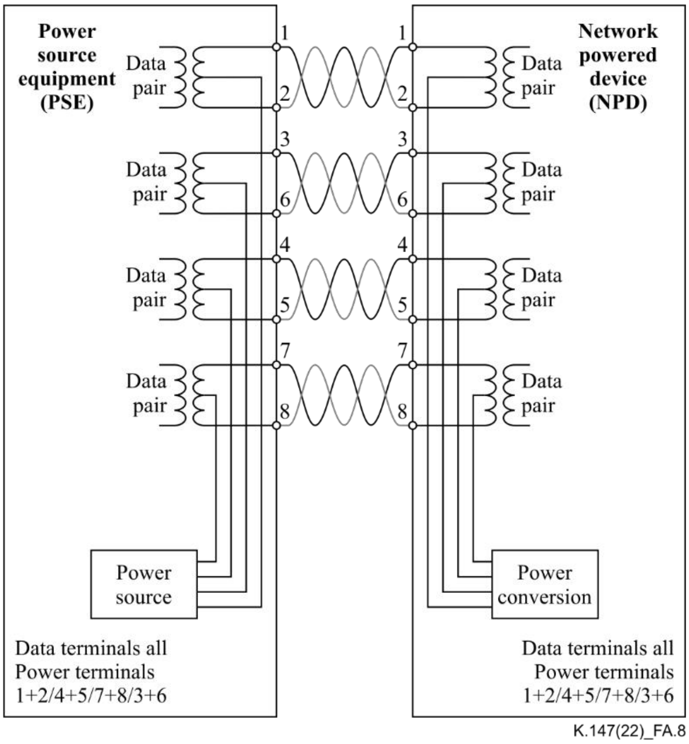


Figure A.8 – 1/2.5/5/10 Gb/s PoE (based on Figure 145–7 of [b-IEEE 802.3])

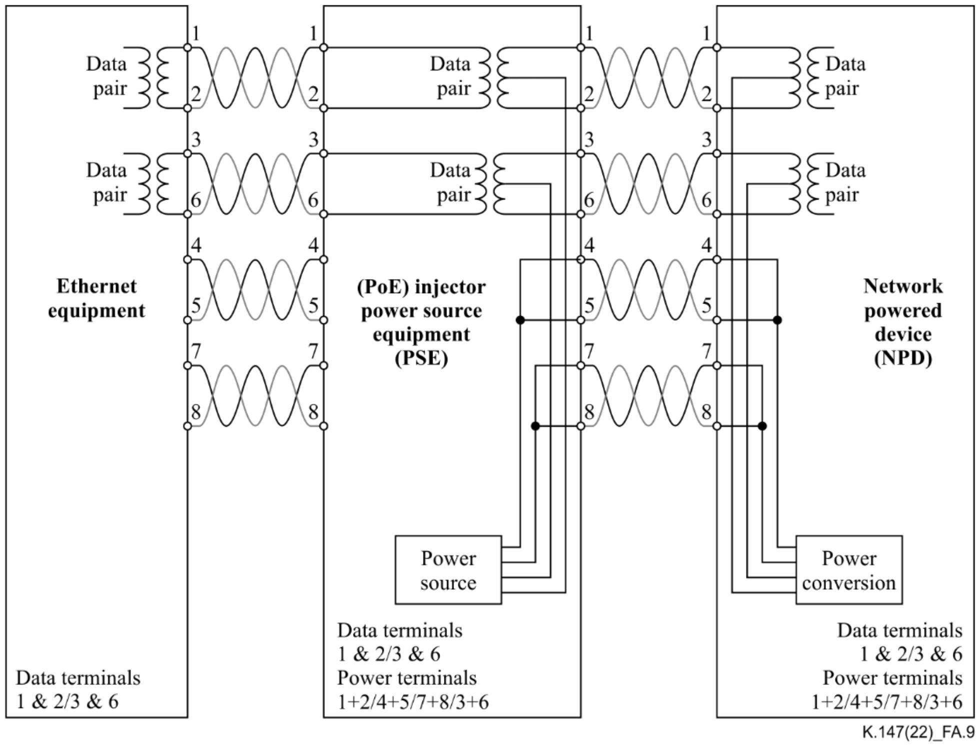


Figure A.9 – 10 Mb/s and 100 Mb/s PoE injector (based on Figure 145–10 of [b-IEEE 802.3])

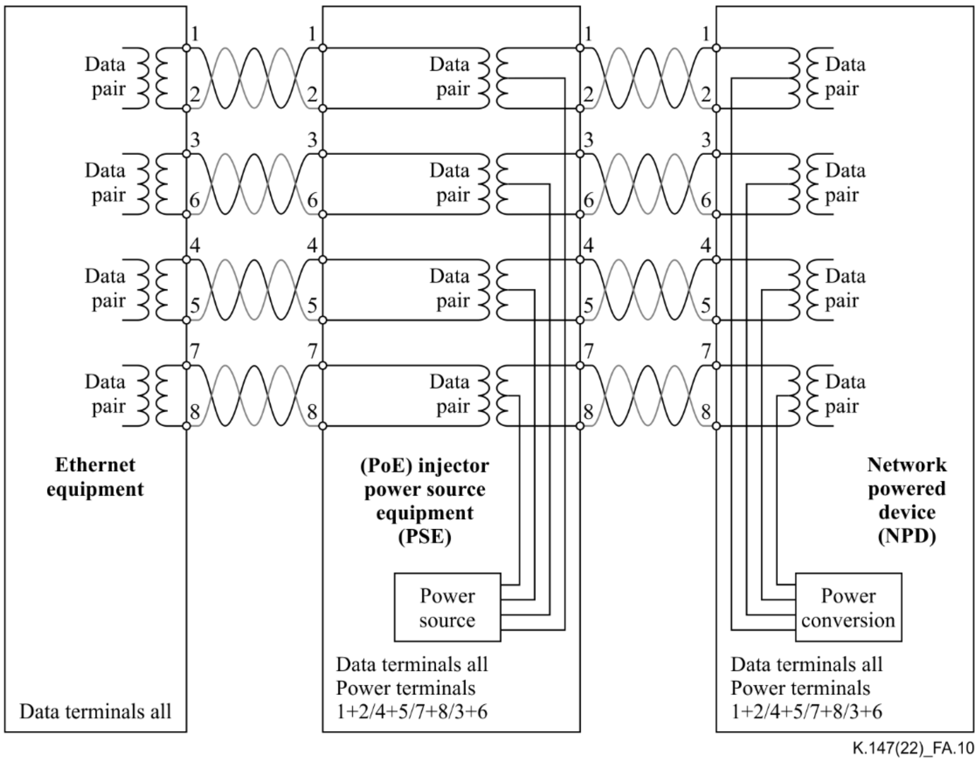


Figure A.10 – 1/2.5/5/10 Gb/s PoE injector (based on Figure 145–11 of [b-IEEE 802.3])

Annex B

Ethernet surge test circuits based on ITU-T K-series Recommendations

(This annex forms an integral part of this Recommendation.)

B.1 Introduction

The circuits in this annex are based on the following ITU-T K Recommendations:

- [ITU-T K.20]
- [ITU-T K.21]
- [ITU-T K.44]
- [ITU-T K.45]
- [ITU-T K.117]

Test levels are location dependent and specific values are given in [ITU-T K.20] (telecommunication centre), [ITU-T K.21] (customer premises) and [ITU-T K.45] (access and trunk networks). Ethernet ports are classified as either internal ports, whose connection cables are entirely within the building, or external ports, whose connection cables leave the building. Testing covers lightning surges, AC mains power cross, DC insulation resistance and screened cable connection bonding.

B.2 Test generators

B.2.1 1.2/50-8/20 generator

Figure B.1 shows a combination wave generator.

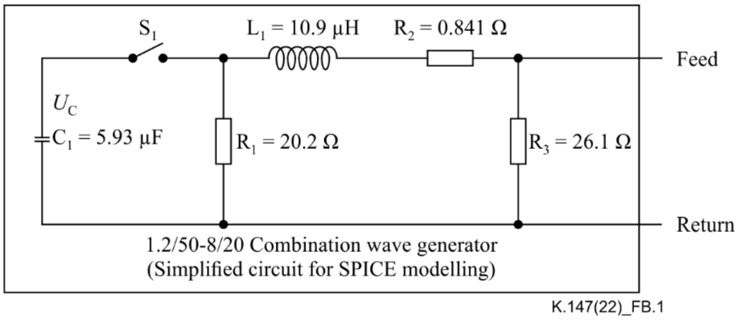


Figure B.1 – Combination wave generator based on Figure A.3-5 of [ITU-T K.44]

B.2.2 AC generator

Figure B.2 shows an AC generator.

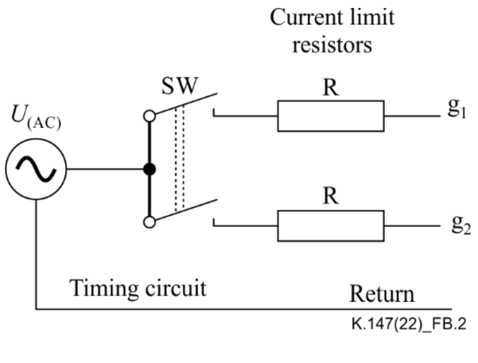


Figure B.2 – Power induction, power contact and rise of neutral potential generator based on Figure A.3-6 of [ITU-T K.44]

For the resistance value, see the test table in the appropriate product Recommendation.

B.3 Untested port termination and coupling network

Figure B.3 shows termination and coupling to earth of untested Ethernet ports.

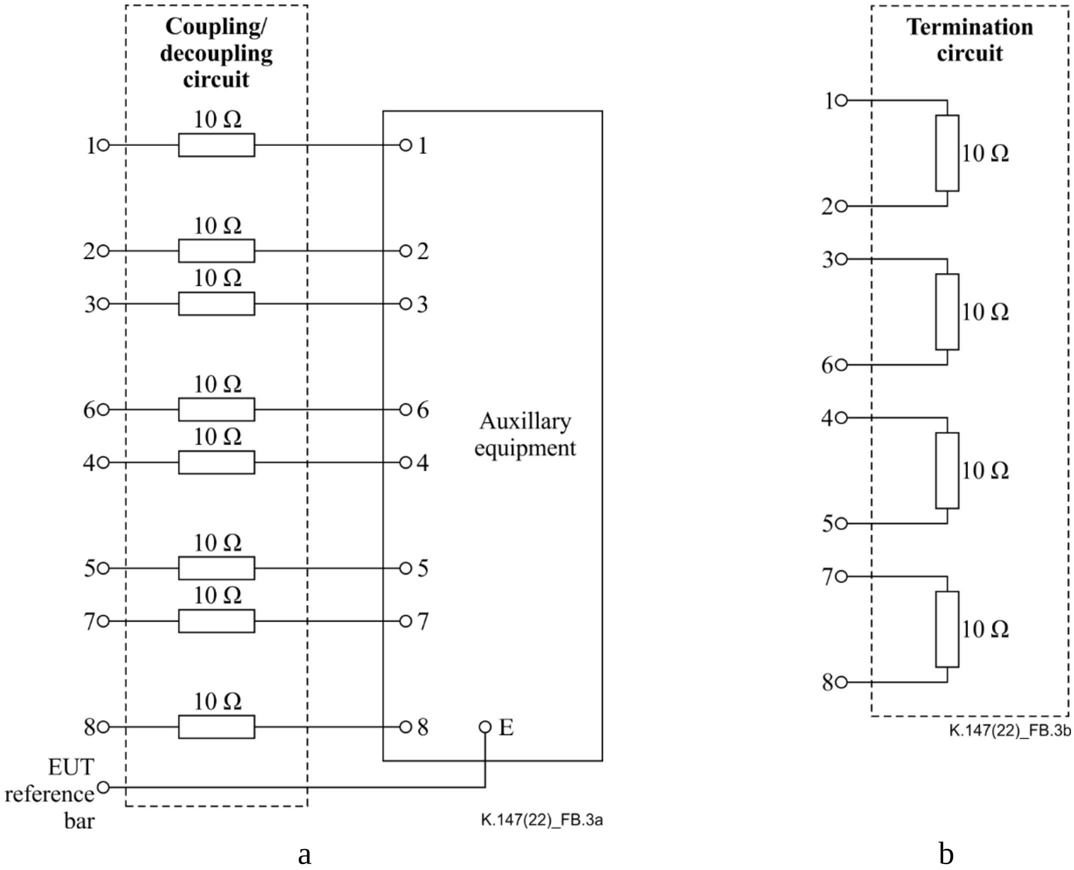
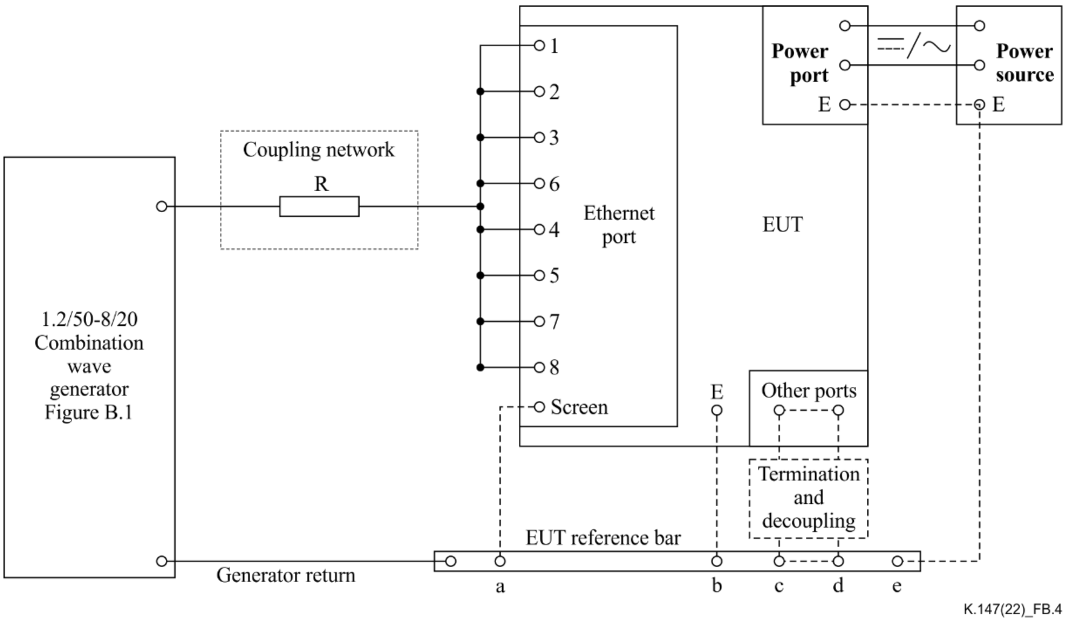


Figure B.3 – Termination and coupling to earth of untested Ethernet ports based on Figure A.6.7-1 of [ITU-T K.44]: a – Ethernet coupling circuit from the equipment under test (EUT); b – termination circuit for an untested Ethernet port

B.4 Common-mode test circuits

In Figure B.4, the single resistor feed maximizes the current into protected terminals that current hog. If there is no protective function, then the insulation withstand voltage is verified.



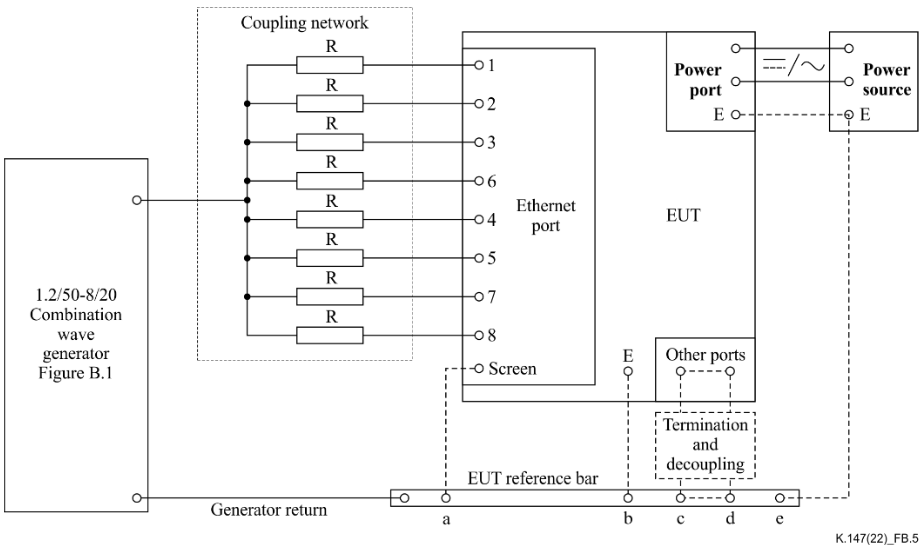
Key

a	RJ45 screen cable connection	A	Ammeter for leakage current, I_L
b	EUT protective or functional earth connection	U_{DC}	DC test voltage (limited to 100 mA)
c, d	terminals of all other signal ports	SW	Switch closed for current measurement
e	Power port terminals		

Insulation resistance = U_{DC}/I_L

Figure B.4 – Ethernet port, including PoE variants, common-mode voltage withstands test circuit based on Figure A.6.7-3a of [ITU-T K.44]

In Figure B.5, feeding each terminal with its own resistor checks if any voltage-limiting function causes a damaging common mode to differential mode conversion.



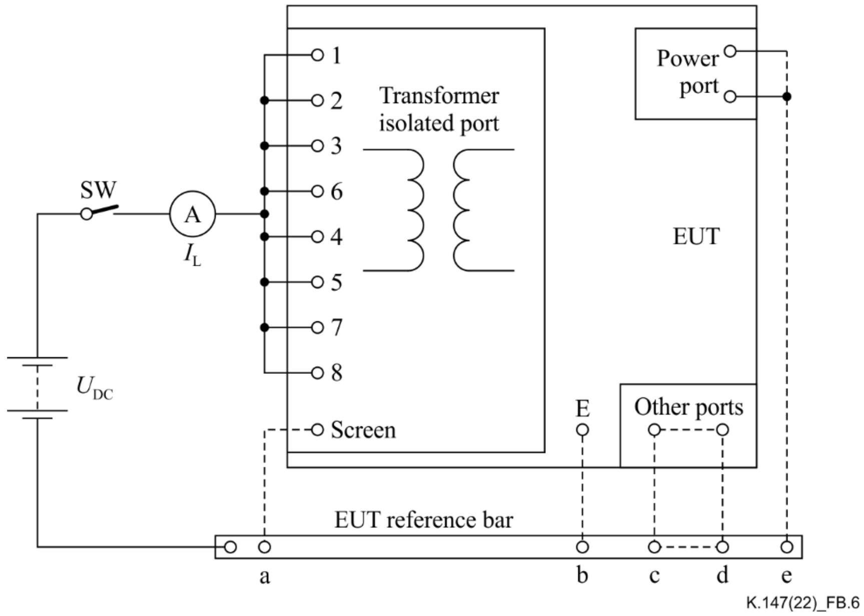
Key

a	RJ45 screen cable connection	A	Ammeter for leakage current, I_L
b	EUT protective or functional earth connection	U_{DC}	DC test voltage (limited to 100 mA)
c, d	terminals of all other signal ports	SW	Switch closed for current measurement
e	Power port terminals		

Insulation resistance = U_{DC}/I_L

Figure B.5 – Ethernet port, including PoE variants, common mode to differential mode conversion surge test circuit based on Figure A.6.7-4 of [ITU-T K.44]

Figure B.6 represents the 500 V DC test used to measure the insulation leakage current, which is required to be below 250 µA.



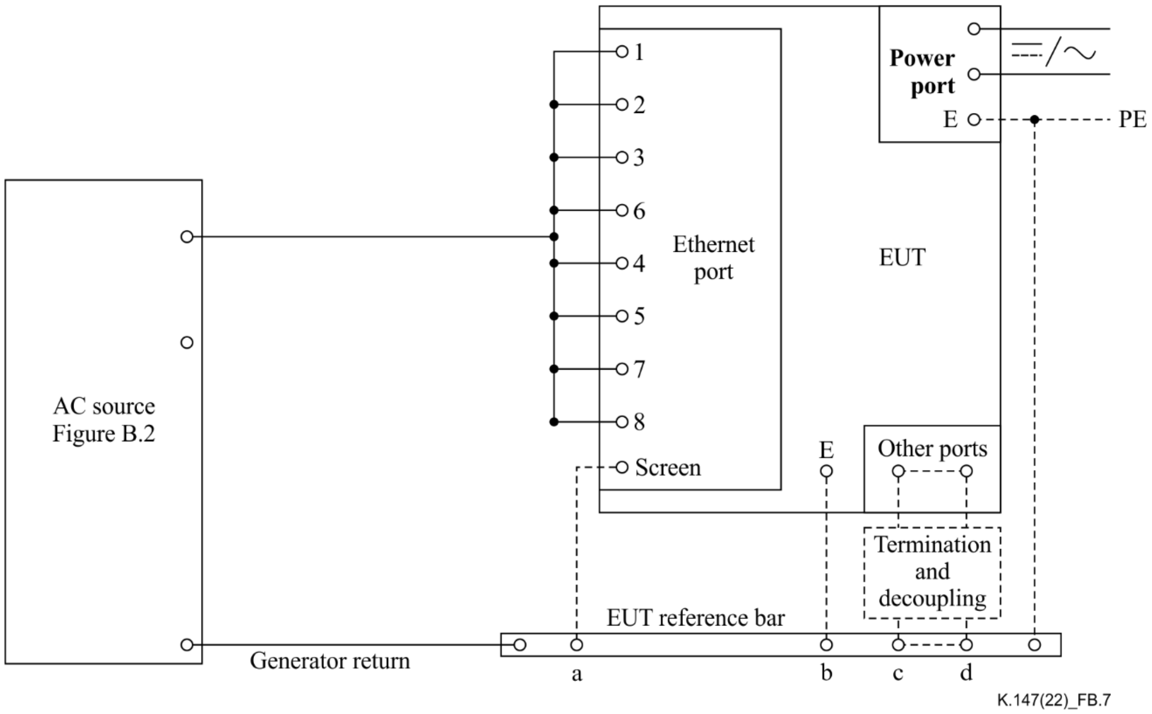
Key

a	RJ45 screen cable connection	A	Ammeter for leakage current, I_L
b	EUT protective or functional earth connection	U_{DC}	DC test voltage (limited to 100 mA)
c, d	terminals of all other signal ports	SW	Switch closed for current measurement
e	Power port terminals		

Insulation resistance = U_{DC}/I_L

Figure B.6 – Ethernet port, including PoE variants, DC insulation resistance test circuit based on Figure A.6.7-3 of [ITU-T K.44]

The test shown in Figure B.7 is only applied to an Ethernet port that fails the 500 V DC insulation resistance test in any polarity. Ports passing the 500 V DC insulation resistance test do not conduct appreciable current when mains voltages of up to 350 V AC are applied.



Key

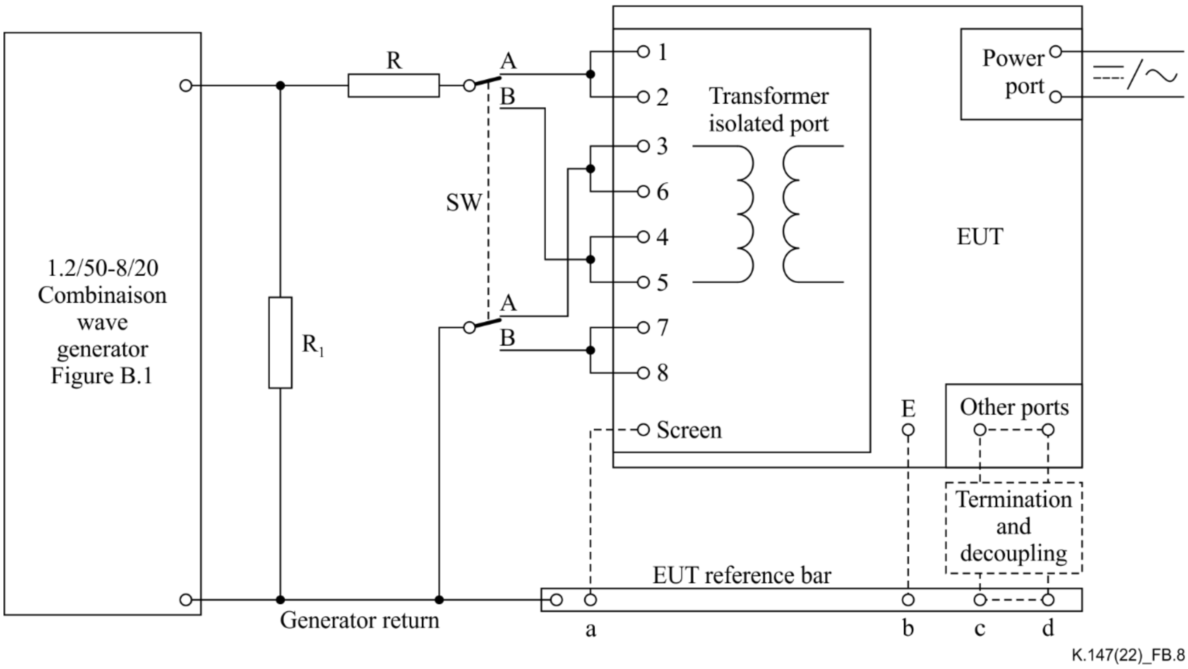
a	RJ45 screen cable connection	A	Ammeter for leakage current, I_L
b	EUT protective or functional earth connection	U_{DC}	DC test voltage (limited to 100 mA)
c, d	terminals of all other signal ports	SW	Switch closed for current measurement
e	Power port terminals		

Insulation resistance = U_{DC}/I_L

Figure B.7 – Ethernet port, including PoE variants, power cross test circuit based on Figure A.6.7-7 of [ITU-T K.44]

B.5 Differential-mode test circuits

In Figure B.8, for PSE, power injection equipment and NPD ports, test in switch (SW) positions A and B. If the PSE specifies the powering pairs, then the testing is only done on those pairs. This configuration verifies PSE or NPD powering resistibility.



Key

a	RJ45 screen cable connection	R	Series current limiting resistor of resistance 10 Ω
b	EUT protective or functional earth connection	R_1	Shunt resistor of resistance 10 Ω
c, d	terminals of all other signal ports	SW	Switch
1,2,3,4,5,6,7,8	Ethernet RJ45 pin numbers		

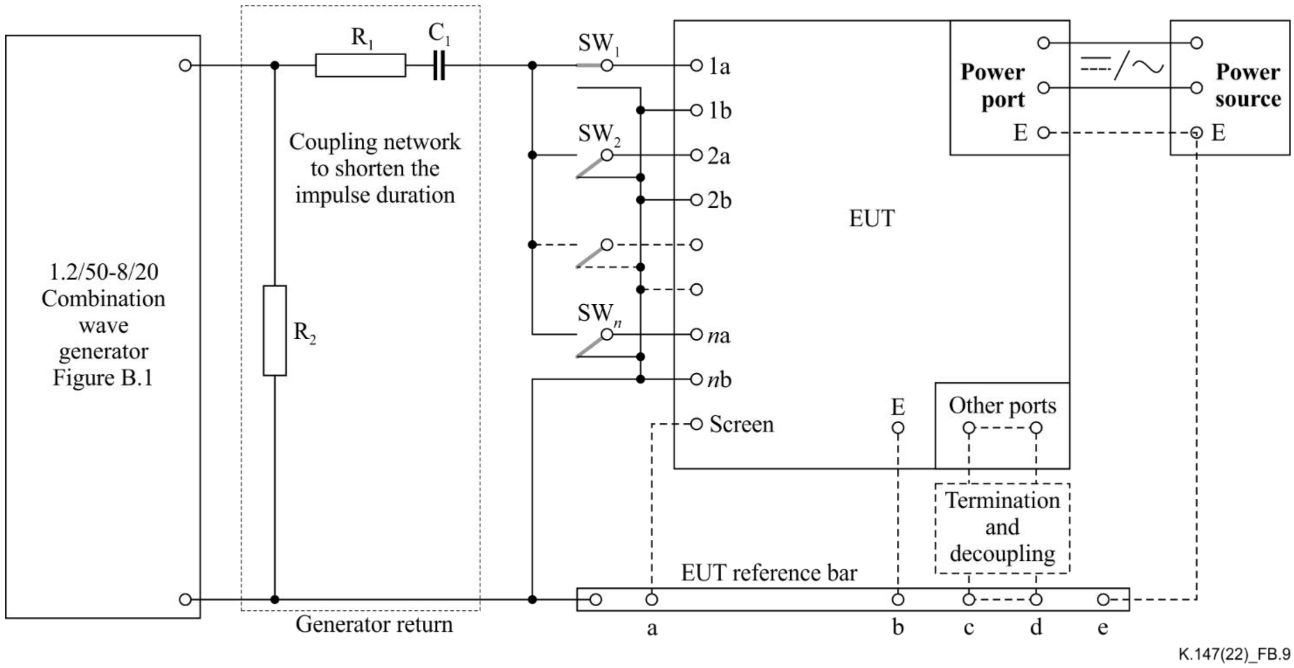
Figure B.8 – PoE port powering pair transverse/differential surge test circuit based on Figure A.6.7-2 of [ITU-T K.44]

In Figure B.8:

SW in position A: Test PoE Mode A powering terminals 1/2-3/6;

SW in position B: Test PoE Mode B powering terminals 4/5-7/8.

Figure B.9 tests the resistibility of Ethernet port data terminals under high d*I*/d*t* conditions. Resistor R_1 and capacitor C_1 shorten the surge time to avoid applying too much port energy. This test is conducted on each terminal pair selected by having that pair switch up and the remaining switches down. Surging is done with alternating polarities.



Key

a	RJ45 screen cable connection for screened twisted pair Ethernet (STPE) connections	R_1	10 Ω
b	EUT protective or functional earth connection	R_2	10 Ω
c, d	terminals of all other signal ports	C_1	0.50 ±0.05 µF at 5 kV
e	Power port terminals	SW	Switch

Figure B.9 – Ethernet port differential-mode surge test circuit including PoE variants based on Figure A.6.7-5 of [ITU-T K.44]

In Figure B.9, twisted-pair terminal pairs are 1a + 1b, 2a + 2b to *n*a + *n*b served by the corresponding switches SW_1, SW_2 to SW_n.

For each terminal pair, when the switch is up, one terminal is connected to the coupling network. When the switch is down, that terminal is connected to functional earth.

Capacitor C_1has: equivalent series resistance (ESR): <0.5 Ω; inductance: <1 µH. Different parasitic values are acceptable provided d*I*/d*t* requirements are met.

The initial rate of rise of the short-circuit current, d*I*/d*t*, at 2.5 kV generator charging voltage shall be 60 ±10 A/µs in the first 0.5 µs.

See Figure B.10.

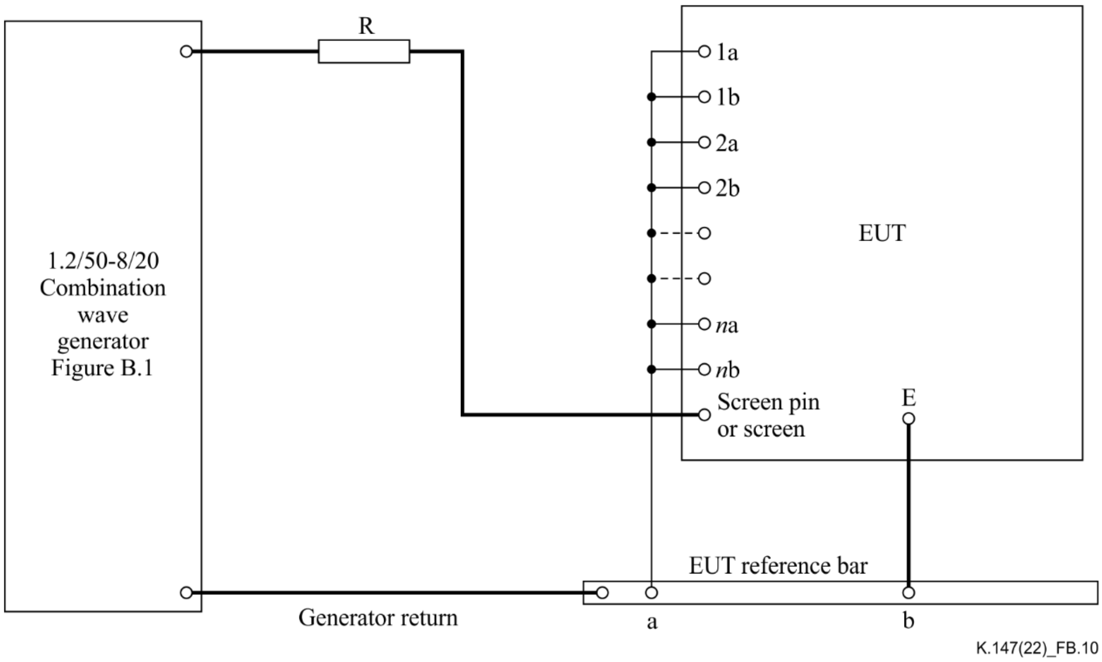


Figure B.10 – Ethernet screened cable port screen connection high current bonding test based on Figure A.6.7-6 of [ITU-T K.44]

This high current surge test verifies that the equipment current capability to earth is adequate.

B.6 Ethernet intermediate link connections

Intermediate link connections are items like connectors, SPDs, injector PSEs and daisy-chained NPDs. Each of these items has two ports. For example, Ethernet SPDs tend to have two ports, one for link cable connection and the other for equipment connection. Special testing is required for these two-port devices as there is a need for additional loads to be attached to the port that are not being directly tested. Such testing is covered by [ITU-T K.117]. Figure B.11 is functionally similar to Figure B4.

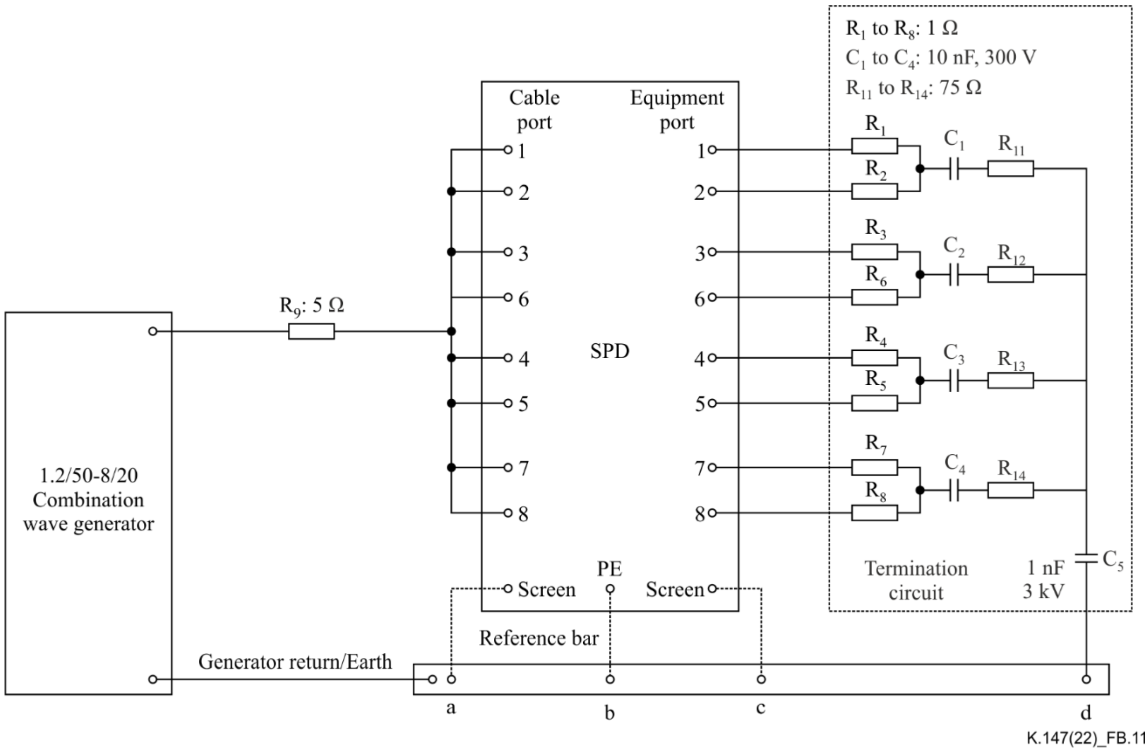


Figure B.11 – Impulse limiting voltage under common-mode surge conditions

Figure B.12 is functionally similar to Figure B.8, but for a single twisted pair.

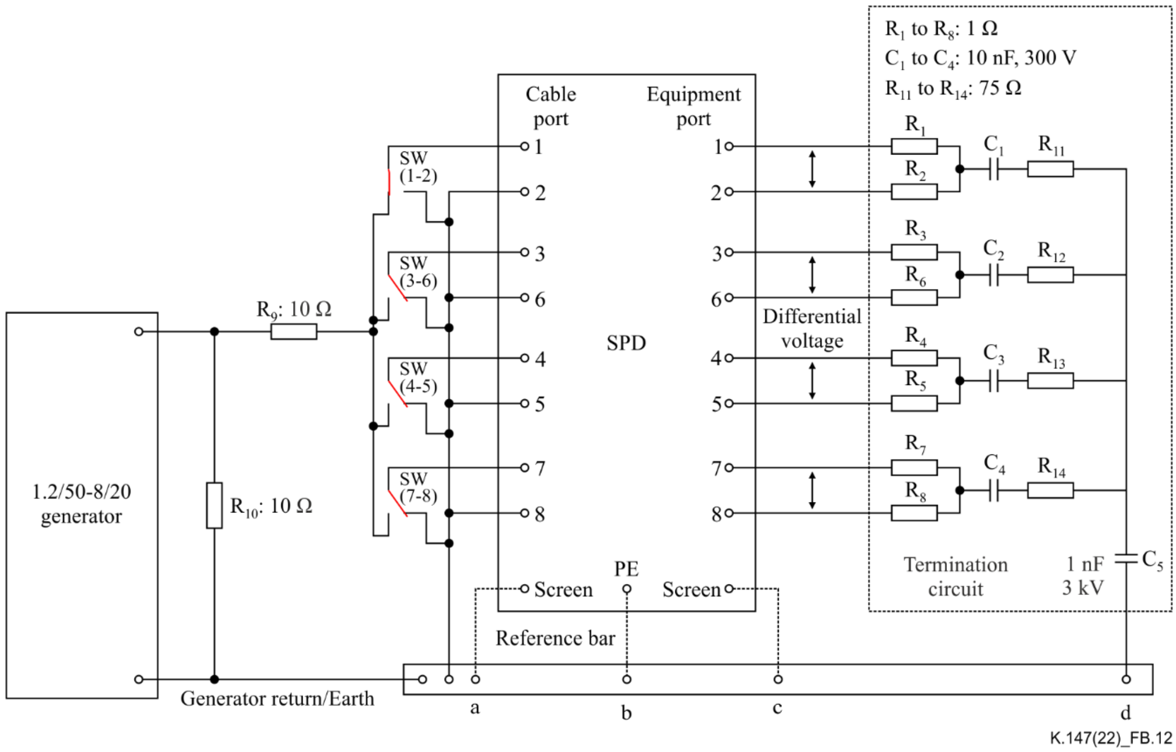
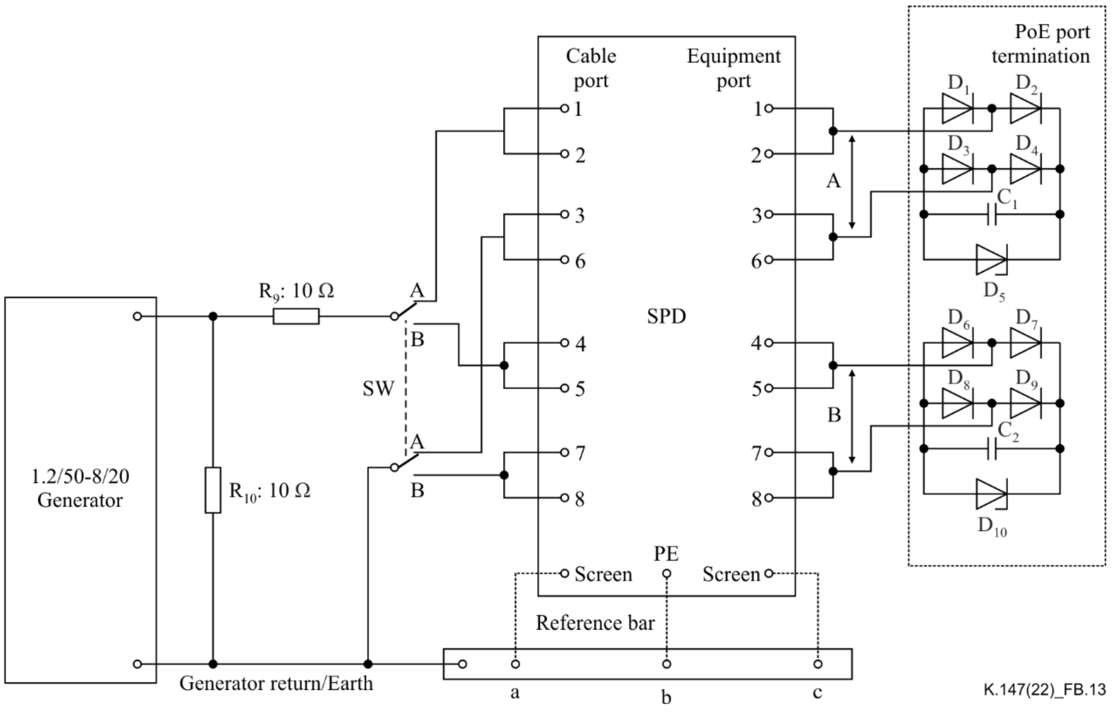


Figure B.12 – Single twisted pair differential-mode surge test circuit

Figure B.13 shows a power feed differential-mode surge test circuit.



Key

D_1 to D_4, D_6 to D_9	B1100/B Schottky rectifier diodes or equivalent 1 A, 100 V diodes	C_1, C_2	100 nF at 100 V
D_5, D_{10}	SMAJ58A or equivalent 400 W avalanche breakdown diodes	R_9, R_{10}	10 Ω
SW	Double pole, two position selector switch		

Figure B.13 – Power feed differential-mode surge test circuit

Figure B.14 shows ae twisted pair common mode to differential-mode voltage surge conversion test circuit.

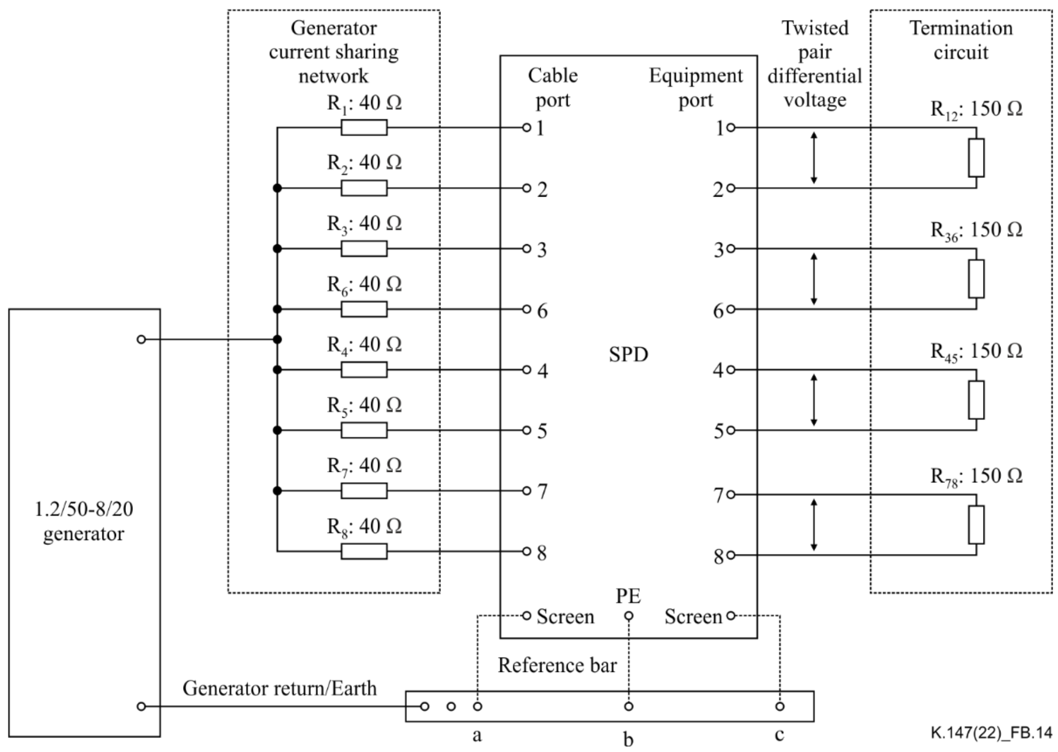


Figure B.14 – Twisted pair common mode to differential-mode voltage surge conversion test circuit

Figure B.15 shows a power feed pair common mode to differential mode surge conversion test circuit.

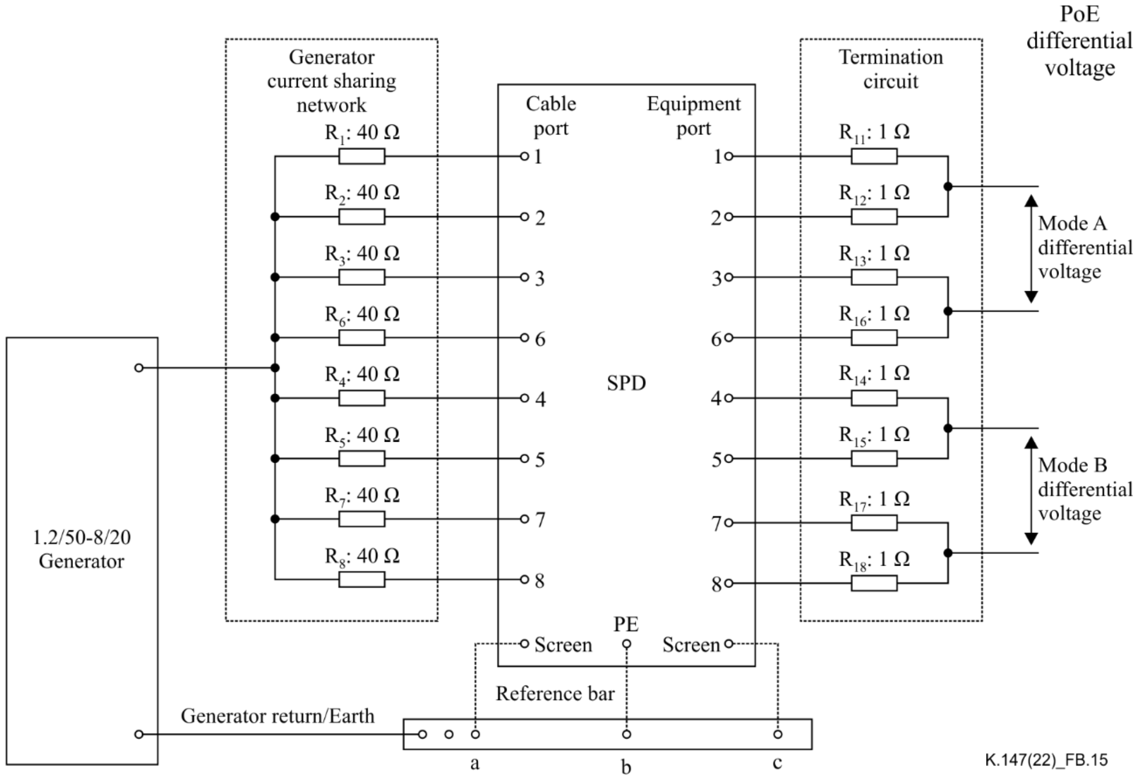
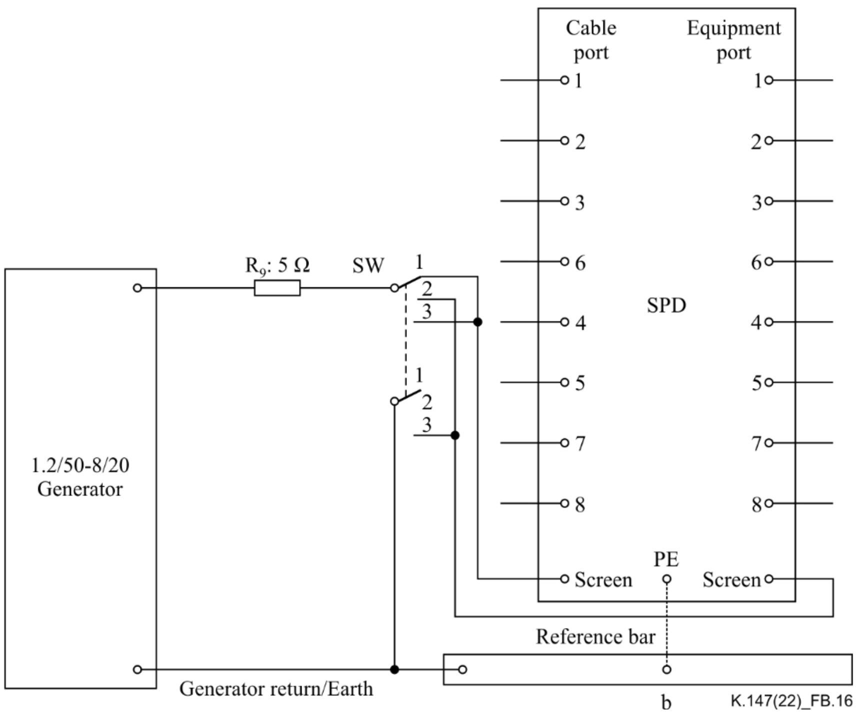


Figure B.15 – Power feed pair common mode to differential mode surge conversion test circuit

Figure B.16 shows a screen bonding test.

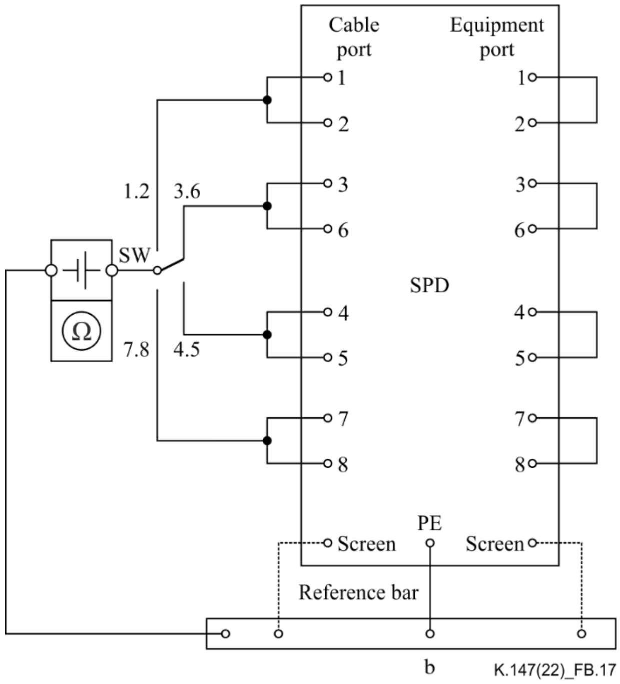


Key

SW Double pole, three position selector switch R_9 5 Ω

Figure B.16 – Screen bonding test

Figure B.17 shows a test circuit to measure the insulation resistance of an SPD with a PE terminal or screen terminals, or both.

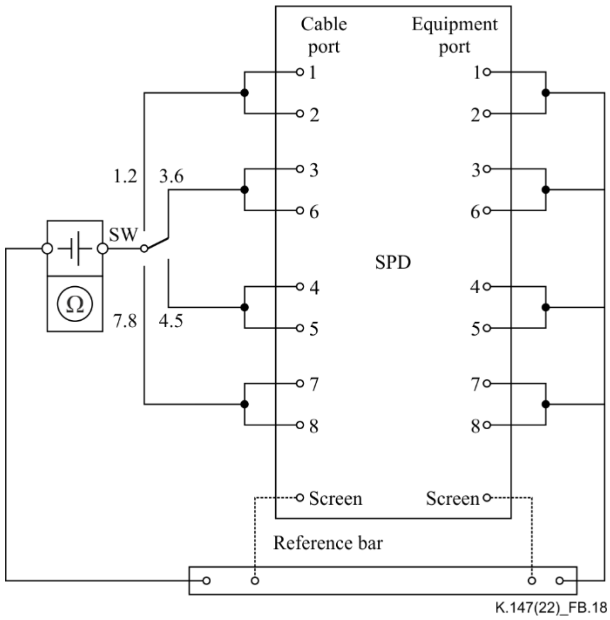


Key

SW Four position selector switch Ω Insulation resistance (IR) meter with defined DC bias

Figure B.17 – Test circuit to measure the insulation resistance of an SPD with a PE terminal or screen terminals, or both

Figure B.18 shows a test circuit to measure the insulation resistance of an isolating transformer SPD without a PE terminal.



Key

SW Four position selector switch Ω IR meter with defined DC bias

Figure B.18 – Test circuit to measure the insulation resistance of an isolating transformer SPD without a PE terminal

Figure B.19 shows a test circuit to measure the PoE SPD DC input/output voltage drop.

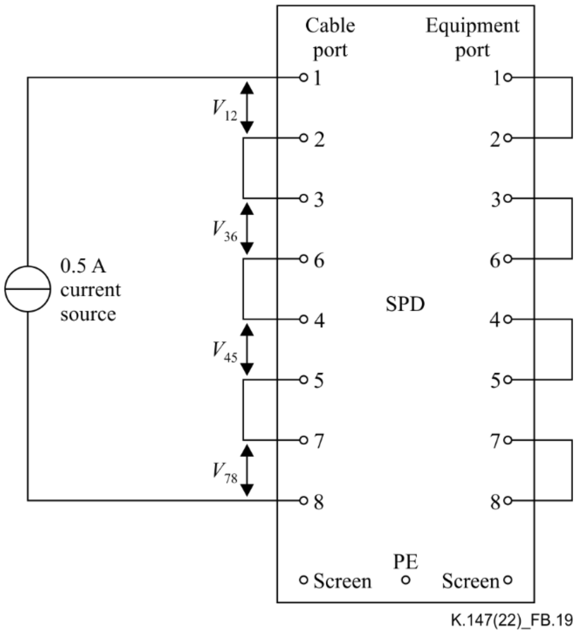


Figure B.19 – Test circuit to measure the PoE SPD DC input/output voltage drop

Appendix I

Networking evolution

(This appendix does not form an integral part of this Recommendation.)

I.1 General

Networking capabilities are evolving continuously. As network evolution depends on many factors, some of the content of this appendix is speculative and it is up to the reader to determine the latest standardization for the applications they are designing for.

The [b-Ivans] presentation suggests that PoE has come to mean power over everything. Evolution changes items such as testing requirements, link distances and hardware, PD levels, data rates, equipment components and network configurations. Techniques introduced for one networking type could also be applied to other networking applications.

I.2 B.2 Universal serial bus

The Universal serial bus (USB) PD specification [b-USB PD] enables PD of up to 240 W (48 V and 5 A) over the USB type-C cable and connector. To accompany this, the USB type-C specification [b-USB C2.1] has been updated to specify higher current 3 A to 5 A electronically marked (E-mark) cable requirements. Figure I.1 shows the series of standardized USB powering voltages and currents. The lowest traditional powering voltage is 5 V, which supports source currents up to 3 A (15 W). At 3 A, increasing the source voltages to 9 V and 15 V provides source powers of 27 W and 45 W. Increasing the rated current to 5 A requires an E-mark cable, which contains an integrated circuit that has a system dialogue to allow sourcing a 5 A current. A power source voltage increase to 20 V allows 100 W to be sourced. For use at even higher voltages, the cable also needs to be an extended power range E-mark type. Source voltages of 28 V, 36 V and 48 V then deliver source powers of 140 W, 180 W and 240 W.

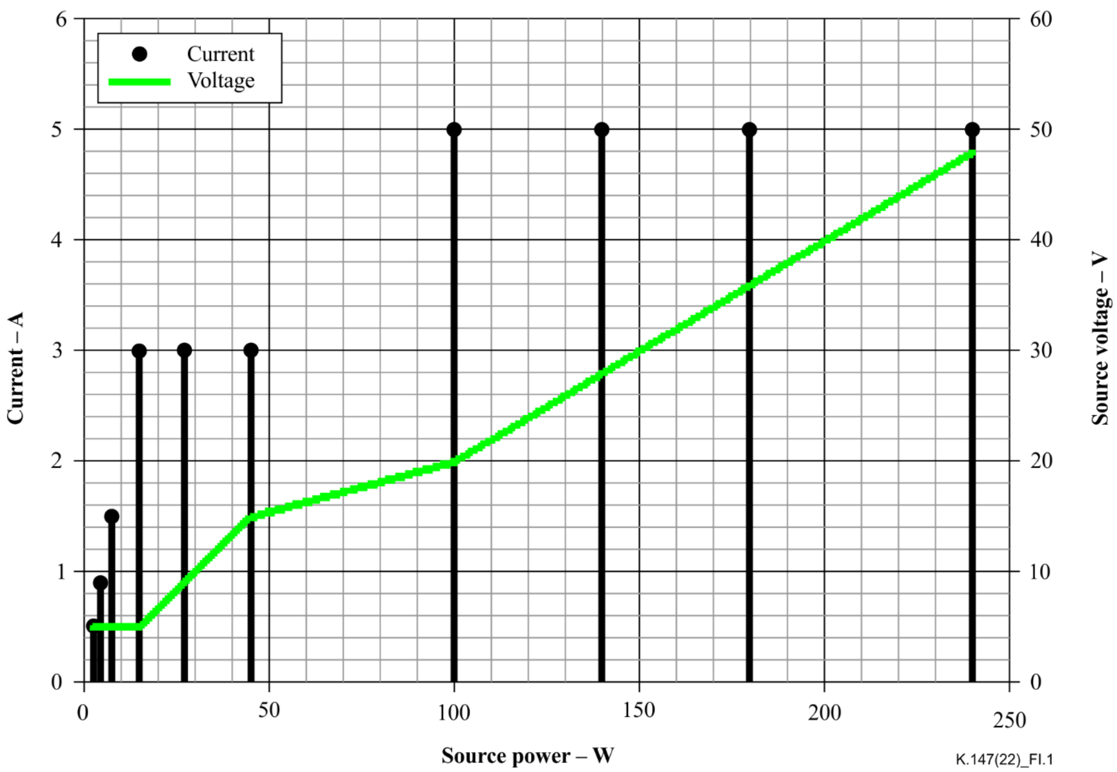


Figure I.1 –Current and voltage versus power for USB PD

Whether the concept of intelligent E-mark cabling can be used in other networking applications remains to be seen.

I.3 Profinet

Profinet is an industrial Ethernet fork with increased performance, diagnostics, safety, energy management and machine building capabilities targeted at industrial automation use, see [b-Profinet]. Typical items are ruggedized cables, static and flexible (for robotics) cables, shrouded connectors (both plug-in and screw-in), data transfer optimization for mission critical applications, hybrid cables (wire and fibre) and powering.

I.4 SPE

SPE is a high activity and evolution area. [b-IEEE 802.3] standardizes on a maximum reach of 1 km at 10 Mb/s, but some transceiver manufacturers claim a 2 km capability using the highest data signal level. Cabling standardization is addressing a 400 m reach option as well as 1 km. An active SPE manufacturer organization is [b-SPE], which holds regular webinars on the latest advances in SPE implementation.

I.5 Testing

Increased link distances mean that the link screen can carry larger impulse currents due the difference of local EPR of the connected equipment. Established cable screen current testing circuits can be used for verification, but the test current level may need to be increased.

If the link uses unscreened or screened cable that is not sufficiently well bonded at both ends, equipment withstand testing may need to be done at higher than normal voltage levels.

Because of interactions between the PSE, NPD and possibly the link, a system level test, rather than an equipment test, is often desirable. Test circuits often employ a network coupler decoupler (NCD) to direct the surge stress into the equipment under test. However, in certain DC powered systems, the use of a standard NCD has caused equipment to become non-operational or in extreme cases to fail. This problem has led to a change in DC powered test configurations, the rationale for this is covered in [b-ITU-T K-Suppl.15].

Bibliography

[b-ITU-T K.12] Recommendation ITU-T K.12 (2010), *Characteristics of gas discharge tubes for the protection of telecommunications installations*.

[b-ITU-T K.39] Recommendation ITU-T K.39 (2019), *Risk assessment of damages to telecommunication sites due to lightning discharges*.

[b-ITU-T K.96] Recommendation ITU-T K.96 (2014), *Surge protective components: Overview of surge mitigation functions and technologies*.

[b-ITU-T K.99] Recommendation ITU-T K.99 (2017), *Surge protective component application guide – Gas discharge tubes*.

[b-ITU-T K.103] Recommendation ITU-T K.103 (2015), *Surge protective component application guide – Silicon PN junction components*.

[b-ITU-T K.126] Recommendation ITU-T K.126 (2017), *Surge protective component application guide – High frequency signal isolation transformers*.

[b-ITU-T K.128] Recommendation ITU-T K.128 (2018), *Surge protective component application guide – Metal oxide varistor (MOV) components*.

[b-ITU-T K.129] Recommendation ITU-T K.129 (2018), *Characteristics and ratings of silicon PN junction voltage clamping components used for the protection of telecommunication installations*.

[b-ITU-T K.140] Recommendation ITU-T K.140 (2019), *Surge protective component application guide – Fuses*.

[b-ITU-T K.144] Recommendation ITU-T K.144 (2019), *Surge protective component application guide – Self-restoring thermally activated overcurrent protectors*.

[b-ITU-T K-Suppl.15] ITU-T Series K Supplement 15 (2018), *ITU-T K.20, K.21 and K.44 – Internal DC powering interface surge testing factors*.

[b-ISO/IEC 11801-1] ISO/IEC 11801-1:2017, *Information technology – Generic cabling for customer premises – Part 1: General requirements*.

[b-ISO/IEC TR 29108] ISO/IEC TR 29108:2013, *Information technology – Terminology for intelligent homes*.

[b-ISO/IEC TS 29125] ISO/IEC TS 29125:2017, *Information technology – Telecommunications cabling requirements for remote powering of terminal equipment*.

[b-IEC 60099-5] IEC 60099-5:2018, *Surge arresters – Part 5: Selection and application recommendations*.

[b-IEEE 802.3] IEEE 802.3-2018, *IEEE Standard for Ethernet*.

[b-Gazivoda-Nikolic] Gazivoda-Nikolic, T. (2018). *Gas discharge tube (GDT) operation in Ethernet protection*. Paper presented at: ATIS Protection Engineers Group Conference 2018. Washington, DC: Alliance for Telecommunications Industry Solutions. Available [viewed 2022-03-18] at: https://peg.atis.org/presentation/gas-discharge-tube-gdt-operation-in-ethernet-protection/

[b-Ivans] Ivans, R. (2019). *The proliferation of powering over LAN cables: The powering of everything (PoE)*. Paper presented at: ATIS Protection Engineers Group 2019 Conference. Washington, DC: Alliance for Telecommunications Industry Solutions. Available [viewed 2022-03-20] at: https://peg.atis.org/wp-content/uploads/sites/16/2019/03/Proliferation_of_Powering_over_LAN_Cables-RIvans.pdf

[b-Maytum] Maytum, M. (2021). *Single twisted pair Ethernet and powering 1 km and more*. Paper presented at: ATIS Protection Engineers Group Conference 2021. Washington, DC: Alliance for Telecommunications Industry Solutions. Available [viewed 2022-03-19] at: https://peg.atis.org/wp-content/uploads/sites/16/2021/02/Single_twisted_pair_Ethernet_and_powering_to_1km_and_more.pdf.

[b-Profinet] Profibus and Profinet International (PI) (2022). *Profibus and Profinet*. Karlsruhe: Profibus. Available [viewed 2022-03-19] at: https://www.profibus.com/

[b-SPE] SPE Industrial Partner Network (Internet). *Single pair Ethernet*. Rahden: SPE Industrial Partner Network. Available [viewed 2022-03-20] at: https://www.single-pair-ethernet.com/en

[b-SPE-R] SPE Industrial Partner Network (Internet). *Resources*. Rahden: SPE Industrial Partner Network. Available [viewed 2022-03-19] at: https://www.single-pair-ethernet.com/en/ressourcen

[b-USB C2.1] Ling, Y., Saunders, B., Dunstan, B., Cox, A. (editors) (2021). *USB Type-C® cable and connector specification*, Revision 2.1. Beaverton, OR: USB 3.0 Promoter Group. 410 pp. Available [viewed 2022-03-19] from: https://www.usb.org/document-library/usb-type-cr-cable-and-connector-specification-release-21

[b-USB PD] Dunstan, B., Petrie, R. (editors) (2022). *Universal serial bus – Power delivery specification*, Revision 3.1, Version 1.3. Beaverton, OR: USB 3.0 Promoter Group. 747 pp. Available [viewed 2022-03-19] from: https://www.usb.org/document-library/usb-power-delivery

SERIES OF ITU-T RECOMMENDATIONS

Series A	Organization of the work of ITU-T
Series D	Tariff and accounting principles and international telecommunication/ICT economic and policy issues
Series E	Overall network operation, telephone service, service operation and human factors
Series F	Non-telephone telecommunication services
Series G	Transmission systems and media, digital systems and networks
Series H	Audiovisual and multimedia systems
Series I	Integrated services digital network
Series J	Cable networks and transmission of television, sound programme and other multimedia signals
Series K	**Protection against interference**
Series L	Environment and ICTs, climate change, e-waste, energy efficiency; construction, installation and protection of cables and other elements of outside plant
Series M	Telecommunication management, including TMN and network maintenance
Series N	Maintenance: international sound programme and television transmission circuits
Series O	Specifications of measuring equipment
Series P	Telephone transmission quality, telephone installations, local line networks
Series Q	Switching and signalling, and associated measurements and tests
Series R	Telegraph transmission
Series S	Telegraph services terminal equipment
Series T	Terminals for telematic services
Series U	Telegraph switching
Series V	Data communication over the telephone network
Series X	Data networks, open system communications and security
Series Y	Global information infrastructure, Internet protocol aspects, next-generation networks, Internet of Things and smart cities
Series Z	Languages and general software aspects for telecommunication systems

Printed in Switzerland
Geneva, 2022