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Fault Managed Power Distribution Technologies – Human Contact Fault Analysis

TECHNICAL REPORT

ATIS-0600040, *Fault Managed Power Distribution Technologies – Human Contact Fault Analysis*

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ATIS Technical Report on

Fault Managed Power Distribution Technologies – Human Contact Fault Analysis

Alliance for Telecommunications Industry Solutions

Approved April 26, 2024

Abstract

This technical report includes requirements for a centralized powering approach that can be used to support distributed powered nodes such as those utilized in 5G cellular network deployment. This centralized powering solution leverages a single connection to an energy source such as renewables or the commercial power grid to deliver power to multiple remotely located elements that can be installed thousands of feet away from the centralized power source with a previously unattainable combination of safety and transmission efficiency. These Fault Managed Power Systems (FMPSs) employ sophisticated monitoring and controls, including an electronic handshake to verify that the powered device (PD) is present and operating correctly before greater than Class 2 power is applied to the circuit. This TR establishes a human contact fault analysis methodology to determine whether a risk of ventricular fibrillation exists in powering systems evaluated to the criteria herein.

Reason for reissue

This technical report is being reissued to provide additional testing requirements and to provide corrections and clarifications to a number of clauses as summarized below:

- Addition of a short circuit testing requirement.
  - Intended to demonstrate that the system under test does not present an arc flash hazard in the event of line to line and line to ground short circuit situations.

- Added minimum voltage & current waveform measurement instrumentation specifications applicable to short circuit testing.
- A short circuit current magnitude-duration limit based on an arc flash incident energy level of 1.2 calories / cm^2 (5.021 Joules / cm^2) is established as the short circuit pass/fail threshold. This incident energy level is considered to be the lowest threshold of incident energy constituting an arc flash hazard. Development of the short circuit current magnitude-duration limit is explained in the newly added Annex G.

* Added text to make it clear that ATIS does not promote bare handed contact with live system parts.
  - Simulated human contact testing prescribed by the TR is intended to ensure that the system under test will not cause ventricular fibrillation in the event of “inadvertent” bare-handed contact with live parts. Use of appropriate personal protective equipment and proper safety precautions to minimize the possibility of bare-handed contact with live parts is highly recommended whenever working on live power systems.
* Clarified the statement made in the scope of this Technical Report pertaining to simulated human contact testing of systems that employ interlock equipped barrier / contact preclusion mechanisms.
* Eliminated previously specified charge transfer pass/fail limits. It has been determined that the charge transfer limits are irrelevant because simulated human contact fault testing prescribed by this TR is performed at maximum cable length as is required to be specified by the system manufacturer. However, the charge transfer measurement requirement is retained for port performance variance testing analysis and for validation of Equivalent Load Circuit (ELC) modelling calculations described in Annex C. The original charge transfer measurement setup has been modified to specify the use of the worst-case 500Ω fault resistance value.
* When pair bonding is allowed by the system manufacturer, simulated human contact fault testing requirements and manufacturer pair bonding configuration information requirements are specified in greater detail.
* When system testing is performed with a shielded cable, additional information is provided regarding shield treatment requirements with respect to grounding or isolation of the cable shield.
* A listing of power cable parameters is provided to aid in the determination of whether additional power cables approved for use with a fault managed power system can be considered to be identical in design to a previously tested and certified cable type. Cable types that are identical in design to previously tested and certified cables can be approved for use without the need for formal certification testing prescribed in the technical report.
* Addition of a new simulated human contact fault testing requirement to demonstrate that proper operation of the circuit under test is not adversely affected by other circuits operating simultaneously in the cable under test. The worst-case line to line and line to ground fault test cases performed with a single active circuit are to be retested utilizing the maximum number of active circuits possible as specified by the manufacturer. The maximum number of active circuits is based on the number of conductor pairs and manufacturer specified allowable pair bonding configurations per cable under test.
* Modified and clarified the first level lightning surge and power fault transient tolerance testing requirement specified in section 6 of this Technical Report.
* Made required corrections to Annex D to reflect a previously adopted change from 1 to 5 microsecond rise time requirement associated with the TRIA circuit.

Foreword

The Alliance for Telecommunications Industry Solutions (ATIS) serves the public through improved understanding between carriers, customers, and manufacturers. The Sustainability in Telecom: Energy and Protection (STEP) Committee – formerly the Network Interface, Power, and Protection (NIPP) Committee – engages industry expertise to develop standards and technical reports for telecommunications equipment and environments in the areas of energy efficiency, environmental impacts, power, and protection. The work products of STEP enable vendors, operators, and their customers to deploy and operate reliable, environmentally sustainable, energy efficient communications technologies. STEP is committed to proactive engagement with national, regional, and international standards development organizations and forums that share its scope of work.

ANSI guidelines specify two categories of requirements: mandatory and recommendation. The mandatory requirements are designated by the word *shall* and recommendations by the word *should*. Where both a mandatory requirement and a recommendation are specified for the same criterion, the recommendation represents a goal currently identifiable as having distinct compatibility or performance advantages. The word *may* denotes an optional capability that could augment the standard. The standard is fully functional without the incorporation of this optional capability.

Suggestions for improvement of this document are welcome. They should be sent to the Alliance for Telecommunications Industry Solutions, STEP, 1200 G Street NW, Suite 500, Washington, DC 20005.

At the time of consensus on this document, STEP, which was responsible for its development, had the following leadership:

J. Jackson, STEP Chair and NPS Vice Chair (Southwire)

E. Gallo, STEP Vice Chair and NPS Chair (NEBScore)

E. Badon, STEP NPS Technical Editor (EnerSys)

The **Network Power Systems (NPS)** Subcommittee was responsible for the development of this document.

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Fault Managed Power Distribution Technologies – Human Contact Fault Analysis

1 Scope, Purpose, & Application

1.1 Scope

This document establishes a methodology to determine fault managed power system response to various simulated human contact scenarios. A human body resistance model is defined and presented in Annex A to include total body resistance values representing the vast majority of the population under a wide range of surface area of contact and skin conditions. Detailed fault test plans are presented for use in conjunction with the human body resistance model to measure system response to simulated human hand to hand and hand to foot contact situations.

The intent of this Technical Report (TR) is to review only the fault managed portion(s) of fault managed power systems. The fault managed portion(s) of a fault managed power system (FMPS) are comprised of the output power terminals of the Power Sourcing Equipment (PSE), the input and output power terminals of Active Extension Nodes (AEN) (when employed), the input power terminals of the Powered Device (PD) and the conductors connecting them. See figures 4.2 and 4.4 for graphical representations of the fault managed portion(s) of fault managed power systems.

This TR does not review power input to the PSE or power output of the PD or power within the PSE, AEN or PD equipment. This TR is not intended to cover or review the PSE, PD and AEN equipment. The PSE, PD and AEN equipment would be covered under their applicable hazard-based safety reviews.

This Technical Report addresses the risk of ventricular fibrillation under various human contact fault scenarios and is not intended to review reaction or startle response. While this Technical Report is primarily focused on human contact fault analysis pertaining to Fault Managed Power Systems, a short circuit test requirement is included to demonstrate that the system under test does not present an arc flash hazard in the event of a line to line or line to ground short circuit condition.

The FMPS criteria and test protocols established by this Technical Report:

- Apply to the fault managed portion of FMPSs used exclusively to provide power to communications equipment located in the communications space as defined by the NESC.
- Have been developed on the premise that only qualified communication workers who are trained to work with powered communication circuits shall have access to live parts.

The human contact fault test cases and analysis procedures presented in this TR are intended to verify that *inadvertent* bare-handed human contact with live parts of the fault managed portions of a fault managed power system will not result in ventricular fibrillation. Use of appropriate personal protective equipment and proper safety precautions to minimize the possibility of bare-handed contact with live parts is highly recommended whenever working on live power systems. Human contact fault analysis presented in this TR is expected to serve as a subset of functional safety testing for fault managed power systems. This TR is not intended to evaluate facility access systems in the form of physical barriers or safety interlocks that may be incorporated into the design of some fault managed power systems. The effectiveness of a facility access system, if present, may be evaluated as part of the NRTL Listing of the overall fault managed power system. See Annex F for additional information on systems that provide preclusion from hazardous voltage contact.

At the time of the publication of this technical report, it is anticipated that in the fourth quarter of 2024, Technical Report 0600040.01 *Fault Managed Power Systems – Interlock Equipped Barriers for Limiting Access to Energized Conductors and Terminals* shall be published.

There may be fault managed power systems or sections of systems that provide additional inherent safety through the use of contact preclusion devices such as interlocks and physical barriers. Such systems or sections of systems can offer an additional safeguard to the monitoring, human contact fault detection and source shutdown safeguard inherent to fault managed power systems. For systems or sections of systems that provide contact preclusion, the interlock and/or physical barrier protection mechanisms must be disabled or defeated to perform the simulated human contact fault testing prescribed in this TR. If it is not possible to disable or defeat a contact preclusion device without invoking shutdown of the PSE output power, the test lab evaluating a system that incorporates preclusions to prevent contact with live parts, would indicate in the test report that the testing prescribed in this TR is not applicable to the preclusion portion of the system.

This TR is limited to human contact fault analysis and does not address any fire safety requirements or testing procedures.

Additional topics discussed in this TR as they relate to FMPSs include transient tolerance testing, thermal exposure / thermal management, and software analysis & functional safety standard compliance.

1.2 Background & Purpose

The convergence of two independent developments in the communications and power industries has led to the generation of this ATIS Technical Report. The proliferation of distributed communications network access elements along with increasing power consumption requirements has created a need for a cost effective, higher power alternative to traditional RFT-V technology. At the same time, technological advancements in power distribution system fault management techniques have made it possible to transport greater magnitudes of power while significantly reducing the risk of human shock and fire hazard. Systems that employ fault managed power distribution technology provide for rapid fault detection and power source shut down in the event of human contact under a wide range of line to ground and line to line fault scenarios. This technology precisely controls and minimizes the amount of fault energy that can be transferred to a person during a human contact fault event.

Fault test cases defined in this TR are intended to measure the magnitude and duration of body current flow under a wide range of human contact scenarios. Line to line and line to ground faults are applied at specified points in the power distribution circuit under a full range of load conditions to ensure that all likely contact scenarios are tested.

The results of each fault test case are plotted on a merged version of IEC 60479-1 [Ref 1] Figure 22 and IEC 60479-2 [Ref 2] Figure 23 to determine which DC zone the system response falls under. For a FMPS to qualify as acceptable per this TR for inadvertent bare handed human contact, the plotted fault test results must fall within either DC zone 1 or 2 for fault events greater than 10 milliseconds in duration or to the left of the hypothetical extended "b line" for fault events less than 10 milliseconds in duration for the entire range of total body resistance values specified in table A.1 of Annex A. The hypothetical extended "b line" depicted in Figure 5.1 has been mathematically developed by Dr. Francisco Paz based on information provided in the IEC 60479 series of standards. Details regarding the methodology used to develop the extended "b line" are discussed in the white paper, "On Extending the $Td{-}Ib$ Curve b Limit For Td Shorter Than 10ms." Rev. A0.4. 11/23/2020 By *Dr. Francisco Paz (*franciscopaz@ieee.org [Ref 22]. The fault test plans presented in this TR are designed to evaluate system response across a wide spectrum of operating conditions. Methods described in IEC 60479-2, "Effects of current on human beings and livestock – Part 2: Special aspects" [Ref 2] for quantifying arbitrary unidirectional DC current waveforms, produced by some fault managed powering products, are summarized and presented in this document. To assist in plotting of test results as required by Clauses 5.3 and 5.4 of this Technical Report, a software-based Random Complex Irregular Waveform Analysis (RCIWA) tool is included with this TR to ensure accurate plotting of fault test data. The theory of operation for the software-based tool is explained in Annex E.

The total charge transfer measurement procedure presented in Section 4.3 of this TR is intended to serve as a means to verify that Equivalent Load Circuit (ELC) modelling calculations described in Annex C accurately depict actual circuit parameters for bus architecture fault managed systems. The charge transfer measurement procedure also provides a convenient way to implement port performance variance testing analysis as described in Section 4.5.3.1.

2 References

The following standards contain provisions which, through reference in this text, constitute provisions of this Standard. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this Standard are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below.

[Ref 1] IEC 60479-1, *Effects of Current on Human Beings and Livestock, Part 1- General Aspects.*[1]
[Ref 2] IEC 60479-2, *Effects of Current on Human Beings and Livestock, Part 2- Special Aspects.*[1]
[Ref 3] IEC 60990, *Methods of measurement of touch current and protective conductor current.*[1]
[Ref 4] Telcordia GR-1089-CORE, *Electromagnetic Compatibility and Electrical Safety - Generic Criteria for Network Telecommunications Equipment.*[2]
[Ref 5] ASTM B258, *Standard Specification for Standard Nominal Diameters and Cross-Sectional Areas of AWG.*[3]
[Ref 6] ANSI/NFPA® 70, *National Electrical Code (NEC®) 2020 Edition.*[4]
[Ref 7] IEC 62602, *Conductors of Insulated Cables – Data for AWG and kcmil Sizes.*[1]
[Ref 8] ITU-T K.50, 4th ed. *Safe Limits of Operating Voltages and Currents for Telecommunications Systems.*[5]
[Ref 9] UL/CSA 60950-21, *Information Technology Equipment – Safety – Remote Power Feeding.*[6]
[Ref 10] ANSI/IEEE C2, *National Electrical Safety Code (NESC).*[7]
[Ref 11] ANSI/ATIS-0600337, *Requirements for Maximum Voltage, Current, and Power Levels in Network-Powered.*[8]
[Ref 12] UL/CSA 60950-1, *Information Technology Equipment – Safety – General Requirements.*[6]
[Ref 13] IEC/UL/CSA 62368-1, Ed. 3*, Audio/Video, Information and Communication Technology Equipment- Part 1: Safety Requirements.*[6]
[Ref 15] Telcordia GR-3164-CORE, *Generic Requirements for Metallic Telecommunications Premises Wires.*[2]
[Ref 16] ASTM E1004, *Standard Test Method for Determining Electrical Conductivity Using the Electromagnetic (Eddy-Current) Method.*[3]
[Ref 17] ASTM B193, *Standard Test Method for Resistivity of Electrical Conductor Materials.* [3]
Sizes of Solid Round Wires Used as Electrical Conductors.[4]
[Ref 18] Telcordia GR-421-CORE, *Generic Requirements for Metallic Telecommunications Cables.*[2]
[Ref 19] RUS RDUP 7 CFR 1775.390, *PE-39-Omnicable.*[9]
[Ref 20] RUS RDUP 7 CFR 1755.890, *PE 89 Direct Burial.*[9]
[Ref 21] NIOSH 98-131, *Worker Deaths by Electrocution.*[10]

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[1] This document is available from the International Electrotechnical Commission (IEC) at: < https://webstore.iec.ch/ >.

[2] This document is available from Ericsson at: < https://telecom-info.njdepot.ericsson.net/ >.

[3] This document is available from ASTM International at: < https://www.astm.org/ >.

[4] This document is available from the National Fire Protection Association (NFPA®) at: < http://www.nfpa.org/ >.

[5] This document is available from the International Telecommunications Union. < https://www.itu.int/ >.

[6] This document is available from Underwriters Laboratories at < http://ulstandards.ul.com/>.

[7] This document is available from the Institute of Electrical and Electronics Engineers (IEEE) at: < http://standards.ieee.org/ >.

[8] This document is available from the Alliance for Telecommunications Industry Solutions, 1200 G Street N.W., Suite 500, Washington, DC 20005 at: < http://www.atis.org >.

[9] This document is available from the Code of Federal Regulations at: < https://www.ecfr.gov/ >.

[Ref 22] On Extending the $Td{-}Ib$ Curve b Limit For Td Shorter Than 10ms. Rev. A0.4. 11/23/2020 By *Dr. Francisco Paz.*[11]
[Ref 23] Comparison Between the GR-1089 Class A2 and A3, and the Proposed FEMS Requirements for Line-to-Ground Faults Rev A0.2 12/14/20 By *Dr. Francisco Paz.*[11]
[Ref 24] NIST/NBS - *Handbook 100 - Copper Wire Tables.*[12]
[Ref 25] NFPA® 70E, Standard For Electrical Safety in the Workplace.[4]

3 Definitions, Acronyms, & Abbreviations

For a list of common communications terms and definitions, please visit the *ATIS Telecom Glossary*, which is located at < http://www.atis.org/glossary >.

3.1 Definitions

Active Extension Node (AEN): A transmission line mounted device that is used in a bus configuration to terminate PD(s) and create shorter cable segments of fault managed power. The AEN is a PSE like device in that it provides fault energy management but differs because it does not act as a power source.

American Wire Gauge (AWG): American wire gauge [5], also known as the Brown & Sharpe wire gauge, is a standardized wire size description system for non-ferrous electrical conductors (AWG is also used for body piercing and needles, but not for steel) in diameters from 0.00314 to 0.46 inches (40 AWG to 0000 or 4/0 AWG, respectively), invented in 1857, and predominantly used in North America. Most other areas of the world use square millimeters, for which there are comparison charts to AWG. The AWG directly relates to the cross-sectional area of the wire (sometimes also measured in circular mils, or as noted in the preceding sentence, in mm^2), which directly relates to its current-carrying capacity and resistance. The larger the gauge number, the smaller the wire diameter – for example, 26 AWG is much smaller than 2 AWG. This gauge system originated in the number of drawing operations (through dies of decreasing diameter) used to produce a given gauge of wire. A given AWG is determined by the total cross-sectional area of the conductor(s); therefore, a stranded wire will always have a slightly larger overall diameter than a solid wire of the same AWG due to the small air gaps between the strands. *Additional information can be found in [IEC 62602] [Ref 7].

Ampacity: Ampacity refers to the current that a wire of a given size can carry without producing excessive heat (thus unacceptably increasing resistance, softening the insulation, or presenting an ignition risk to nearby materials) at a given nominal ambient temperature, and specific to the type of run (e.g., in a conduit, in free air, bundled with 3 other conductors, direct-buried, etc.) and insulation type. Ampacity is usually determined by a combination of calculation and testing and is available from many sources (including the NEC® [Ref 6], which even gives a somewhat complex formula for calculating ampacity). The melting point of copper is almost 1100°C (almost 2000°F), and the current required (fusing current) to produce that much heat is typically at least 5-10 times the rated ampacity. The insulation will typically melt long before the metal, and ampacity is calculated so as not to closely approach the melting point of the insulation. In fact, ampacity is typically calculated to avoid even the slightest potential of approaching ignition temperatures of materials that may be near the conductor(s).

Bus Configuration: A powering architecture that connects any number of PSE power output circuits to the input terminals of any number of PDs via a common power transmission path (pair of conductors) typically referred to as a bus.

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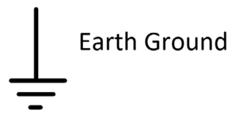
[10] This document is available from The National Institute for Occupational Safety and Health (NIOSH) at: < https://www.cdc.gov/niosh/pubs/ >.

[11] This document is available from Dr. Francisco Paz at: < franciscopaz@ieee.org >.

[12] This document is available from the National Institute of Standards and Technology (NIST) at: < https://www.nist.gov/ >.

Circular mil: A circular mil refers to the cross-sectional area of a circle, 1 thousandth of an inch in diameter. The largest wire sizes are often referred to in thousands of circular mils (kcmil); but even small wire gauges have an equivalent circular mil cross-sectional area.

Earth Ground: Also known as "Ground" depending on context. A reference point with a direct physical connection to earth, in an electrical circuit from which voltages are measured. See symbol below.



Equivalent Load Circuit (ELC): An ELC is a lumped element device that simulates the resistance and capacitance of a worst-case system to be qualified under this TR for the purpose of testing in accordance to Sections 4 and 5 for bus configurations. The ELC includes the capacitances, L-L and L-G for interconnecting cables, I/O of AENS, and the input to PDs. See Annex C for further explanation and use in a bus configured system.

Fault Managed Power System (FMPS): Powering system that monitors for ~~emulated~~ human contact faults and controls power delivered to ensure fault energy is limited. Fault managed power systems must operate within DC zone 1 or DC zone 2 for fault events greater than 10 milliseconds in duration as defined in IEC 60479-1, Figure 22 [Ref 1] or to the left of a hypothetical extended "b line" plotted onto IEC 60479-2 [Ref 2], Figure 23 for each of the applicable fault test cases specified in this standard. The hypothetical extended "b line" has been mathematically developed by Dr. Francisco Paz based on information provided in the IEC 60479 series of standards. Details pertaining to the creation of the extended "b line" can be found in the whitepaper, "On Extending the $Td{-}Ib$ Curve b Limit For Td Shorter Than 10ms" Rev. A0.4. 11/23/2020 By *Dr. Francisco Paz (*francispaz@ieee.org *)* [Ref 22]

Informational notes:

I. When used in this TR in association with FMPS, a fault is human contact that results in excessive or unintended voltage and/or electrical current flow, that could lead to ventricular fibrillation.

2. This TR reviews the ability of a system to react to human contact. Where sections of fault managed power distribution systems employ interlocks and/or physical barriers to preclude human contact to provide shock hazard safety, those sections are outside of the scope of this definition and TR.

Fault Managed Portion of a FMPS: PSE output terminals, AEN output terminals to PD input terminals including the power conductors connecting them.

Ground: See Earth Ground.

Potentially hazardous power output: System source power output at source voltages of greater than 60Vdc or 50Vac.**Heart-current factor:** F

Factor which relates the electric field strength (current density) in the heart for a given current path to the electric field strength (current density) in the heart for a touch current of equal magnitude flowing from left hand to feet [1]**High Resistance Midpoint Ground (HRMG):** A set of two high value resistors that connects the positive and negative terminals of a floating DC power system to ground to aid in the detection of ground faults.

Load: Communications equipment connected to the output terminals of a PD.

Loop: Round trip current path via conductors connecting nodes of a FMPS.

Loop length: Twice the one-way length of the conductors connecting nodes of a FMPS.

Megohmmeter: A specialized test set (ohmmeter) that can apply a dc voltage (typically 250, 500, or 1000 volts) to a wire or cable to determine if there is insulation failure. The insulation is deemed functional if the measurement yields resistances in the megohm range. A typical VOM or DMM can only apply a dc voltage of approximately 9 V to a circuit, which is not enough to break down weak insulation.

Node: In the context of this TR, a FMPS node is any active circuit element comprising the FMPS. e.g., PSE, AEN and PD.

Non-Fault Managed Portion of a FMPS: PSE input power section and PD output power section, including the PSE, PD and AEN equipment.

Ohm's Law: The relationship between voltage (in volts), current (in amperes), and resistance (in ohms) given by the formula V = I x R.

Pair Bonding: Parallel connection of multiple cable pairs at the PSE and PD locations to effectively reduce loop resistance. (two parallel pairs of the same wire gauge are half the resistance of a single pair, three parallel pairs are a third of the resistance, etc.)

Point to Point Configuration: A powering architecture that connects a single PSE power output circuit to the input terminals of a single dedicated PD via a dedicated power transmission path (pair of conductors). Typical PSE provide multiple isolated power output circuits.

Powered Device (PD): Telecommunications equipment designed to be paired with a specific PSE design to facilitate the fault management functionality of a fault managed power system. PD power output is intended to provide non-fault managed power for remotely located telecommunications equipment. A PD can be a stand-alone device or integrated directly into the telecommunications network element.

Power Sourcing Equipment (PSE): Telecommunications equipment supplying fault managed dc power to remotely located active extension nodes (AENs) and/or powered devices (PDs). The PSE provides power and fault management functionality when connected to a properly functioning AEN and/or PD specifically designed to be used with the PSE. The PSE power output is limited to Class 2 power source limits* until the PSE is connected to a properly functioning AEN or PD specifically designed for use with the PSE.

*Class 2 Direct-Current power source limits are defined in Table 11(B) of NFPA® 70, *National Electrical Code (NEC®)*. [Ref 6]

Power Transport Portion of a FMPS: Fault managed portion of a FMPS comprised of the PSE output power terminals, the PD input terminals and the power conductors connecting the PSE to the PD(s). Input and output terminals of AENs are also included when AENs are employed. e.g., for certain bus configurations

Qualified Communication Worker: One who has demonstrated skills and knowledge and is trained to work with powered communication circuits, shall have access to live parts and has received safety training to identify the hazards and reduce the associated risk.

Skin Conditions:

dry condition: condition of the skin of a surface area of contact with regard to humidity of a living person being at rest under normal indoor environmental conditions [1]

saltwater-wet condition: condition of the skin of a surface area of contact being exposed for 1 min to a 3 % solution of NaCl in water (average resistivity ρ = 30 Ωcm, pH = 7 to 9) [1]

Surface Areas of Contact: [1]

Large Surface Area of Contact: 10,000 mm^2

Medium Surface Area of Contact: 1,000 mm^2

Small Surface Area of Contact: 100 mm^2

Telecommunication Technician Electrically Energized Safe Work Condition: Exists when a system with fault current magnitude and time characteristics allow for qualified communication worker bare hand operation without risk of ventricular fibrillation. Determined by conducting line to line and line to ground fault test cases using the human body resistance model defined in this standard and falling within zone 1 or 2 of IEC 60479-1 [Ref 1], Figure 22 or to the left of a hypothetical extended "b line" plotted onto IEC 60479-2 [Ref 2], Figure 23 for each of the applicable fault test cases specified in this standard. The hypothetical extended "b line" has been mathematically developed by Dr. Francisco Paz based on information provided in the IEC 60479 series of standards.

Additionally, a state in which an electrical conductor or circuit part has been disconnected from energized parts, locked/tagged in accordance with NFPA® 70E, Standard for Electrical Safety in the Workplace [Ref 25], tested to verify the absence of voltage, and, if necessary, temporarily grounded for personnel protection.

Test Resistance Insertion Apparatus (TRIA): A solid state switching device designed to apply test resistances required to perform test cases defined in this TR. The use of a MOSFET or IGBT as a switching device eliminates any possibility of creating unwanted transients due to mechanical contact bounce. Reference Annex D of this TR.

Total body resistance (R_T):

Sum of the internal resistance of the human body and the resistances of the skin for a specific current path through the body [1]

Touch Voltage: Voltage between conductive parts when touched simultaneously by a person.

Note: The touch voltage may be different from the open-circuit voltage between those conductive parts.

Trunk: for this TR, trunk is synonymous with Loop. See definition for Loop above.

3.2 Acronyms & Abbreviations

A or Amps	Amperes
AEN	Active Extension Node
AENx	AEN at location 1, 2, … n
ANSI	American National Standards Institute
ASTM International	(Formerly) American Society for Testing and Materials
ATIS	Alliance for Telecommunications Industry Solutions
AWG	American Wire Gauge
C	(degrees) Celsius
CO	Central Office
CSA	Canadian Standards Association
Cx/m	Cable capacitance per unit length (Line to Line)
Cy/m	Cable capacitance per unit length (Line to Earth)
DC	Direct Current
DDS	Digital Data Service
DMM	Digital Multimeter (measures at least voltage, current, and resistance)
DPU	Distribution Point Unit
DS1	Digital Signal Level 1
DSLAM	Digital Subscriber Line Access Multiplexer
F	(degrees) Fahrenheit
FL0	Fault location at output of PSE
FLxy	Fault locations at each JBx AENx where input is y=1, load connection is y=2, and bus output y=3
FTTC	Fiber-To-The-Curb
FTTH	Fiber-To-The-Home
FMPS	Fault Managed Power System
GPR	Ground Potential Rise
GR	Generic Requirements
HDSL	High-bit-rate Digital Subscriber Line
HRMG	High resistance midpoint ground
I	current (in Amperes)
IACS	International Annealed Copper Standard
IEC	International Electro-Technical Commission

IEEE	Institute of Electrical and Electronics Engineers
ITU	International Telecommunications Union
kft	kilofeet (thousands of feet)
L/m	Cable inductance per unit length
Load	Local load consisting of powered device (PD) with X and Y capacitance
m	meter(s)
mA	milliAmpere
MDU	Multi-Dwelling Unit
mega-	million
mil	thickness or diameter of 1 thousandth of an inch
mm	millimeter
msec	millisecond
MOV	Metal-Oxide Varistor
N/A	not applicable
NB	Number of Branches
NEBS	Network Equipment – Building Systems (a series of Telcordia testing standards)
NEC®	National Electrical Code®
NESC	National Electrical Safety Code
NFPA®	National Fire Protection Association
NID	Network Interface Device
NIOSH	National Institute for Occupational Safety and Health
NRTL	Nationally Recognized Testing Laboratory
Ω	Ohms (omega)
ONT	Optical Network Terminal
ONU	Optical Network Unit
OSHA	Occupational Safety and Health Administration
OSP	Outside Plant
P	Power
PD	Powered Device
PoE	Power over Ethernet
POTS	Plain Old Telephone Service
PSE	Power Sourcing Equipment

PTC	Positive Temperature Coefficient
R	Resistance (in ohms)
RCIWA	Random Complex Irregular Waveform Analysis
R/m	Cable resistance per unit length
RFT	Remote Feeding Telecommunication Circuit
RFT-V	Remote Feeding Telecommunication Circuit – Voltage Limited
RT	Remote Terminal
SELV	Safety Extra Low Voltage
SFU	Single Family Unit
SI	Système International (d'unités) – the metric system
T-1	Telecommunications carrier for DS1
TLE	Telecommunications Load Equipment
TLPU	Telecommunications Line Protector Unit
TRIA	Test Resistance Insertion Apparatus
TNV	Telecommunications Network Voltage
UL	Underwriters Laboratories
V	Volt
VA	Volt-Amperes
VOM	Volt-Ohmmeter (measures at least voltage and resistance)
W	watts

4 Basics of Fault Managed Power Distribution Systems

Technological advancements in power distribution system fault management techniques have made it possible to transport electrical power while reducing the risk of human shock and fire hazard. Systems that employ fault managed power distribution technology provide for rapid fault detection and power source shut down in the event of human contact under a wide range of line to ground and line to line fault scenarios. This technology precisely controls and minimizes the amount of fault energy that can be transferred to a person during a human contact fault event. While adhering to the same source voltage limits defined for RFT-V [8] technology, fault managed power distribution systems make it possible to safely deliver higher levels of power to remotely located telecommunications network elements than existing RFT-V powering methods. No power limitation is placed on fault managed power system (FMPS) sources, however, unlike RFT-V systems, this TR imposes a limit on the amount of fault energy that can be transferred to a human during a human contact fault event. For a FMPS to qualify as acceptable per this TR for inadvertent bare handed human contact, the plotted fault test results must fall within DC zone 1 or 2 defined in Figure 22 of IEC 60479-1 [Ref 1] for fault events greater than 10 milliseconds in duration or to the left of the extended "b line" for fault events less than 10 milliseconds in duration for the entire range of total body resistance values specified in table A.1 of Annex A. The extended "b line" has been mathematically developed by Dr. Francisco Paz based on information provided in the IEC 60479 series of standards. Details of the methodology used to develop the extended "b line" are discussed in the whitepaper, "On Extending the $Td{-}Ib$ Curve b Limit For Td Shorter Than 10ms." Rev. A0.4. 11/23/2020 By *Dr. Francisco Paz (*franciscopaz@ieee.org *)* [Ref 22] The extended "b line" represents a very conservative approach which ensures that fault managed power system response lies well outside of the region where ventricular fibrillation would become possible.

When performing the test cases prescribed in this TR pertaining to the fault managed portions of FMPSs, access to live terminals and conductors is required at all specified test locations where fault resistances are required to be applied. For tests that specify application of total body resistances after the PSE has been energized and stabilized for 5 seconds, stable operating line to line and line to ground voltages must be verified at the test points prior to application of the fault resistances.

For any portion of a system that has been defined by the manufacturer as fault managed that also employs preclusion mechanisms (e.g., physical barriers or safety interlocks), the preclusion devices for that portion must be removed or bypassed to perform testing prescribed in this TR.

Fault managed power systems employ several types of active elements to provide fault management functionality. At the time that this TR was published, current versions of FMPSs are comprised of PSE, PD and AEN devices. This is subject to change as the technology evolves. In the context of this TR, the following definitions shall apply:

1. Power Sourcing Equipment (PSE): Telecommunications equipment supplying fault managed dc power to remotely located powered devices (PDs). The PSE provides power and fault management functionality when connected to a properly functioning PD specifically designed to be used with the PSE. The PSE does not generally produce output current unless it is connected to a properly functioning PD specifically designed for use with the PSE.
2. Powered Device (PD): Telecommunications equipment designed to be paired with a specific PSE design to facilitate the fault management functionality of a fault managed power system. PD power output is intended to provide non-fault managed power for remotely located telecommunications equipment. A PD can be a stand-alone device or integrated directly into the enclosure of a telecommunications network element.
3. Active Extension Node (AEN): A transmission line mounted device that is used in a bus configuration to terminate PD(s) and create shorter cable segments of fault managed power. The AEN is a PSE like device in that it provides fault energy management but differs because it does not act as a power source.

Fault managed power system configurations covered by this Technical Report are divided into two broad categories:

1. Point to point configuration: Single PSE connected to a single PD by one or more power cable pairs.

2. Bus configuration: Single PSE connected to multiple PDs by one or more power cable pairs. A bus can consist of a PSE and multiple AENs and PDs connected along a single conductive path between the PSE and PDs and it can also include branch conductive paths between the PSE, AENs and PDs.

Figure 4.1 shown below provides a graphical representation of a point to point FMPS configuration.

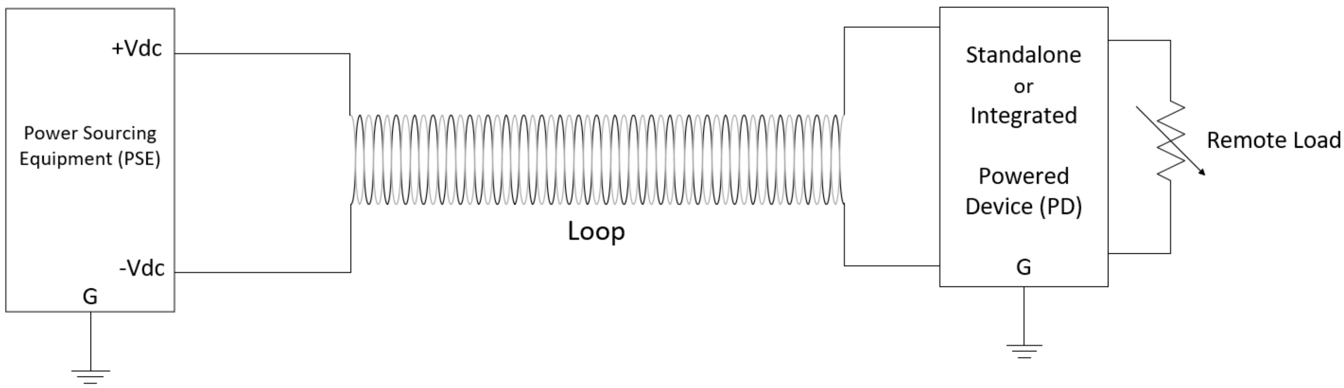


Figure 4.1 – Point-to-Point Fault Managed Power System Configuration

Point to point fault managed power systems are comprised of three sections consisting of a power input section, a power transport section and a power output section. Fault management functionality is limited to the power transport section as illustrated in Figure 4.2 below. The power transport section is comprised of the PSE output terminals, the PD input terminals, and the power cable connecting the PSE to the PD. Fault management criteria and testing protocols presented in this TR are limited to the power transport section of fault managed power systems.

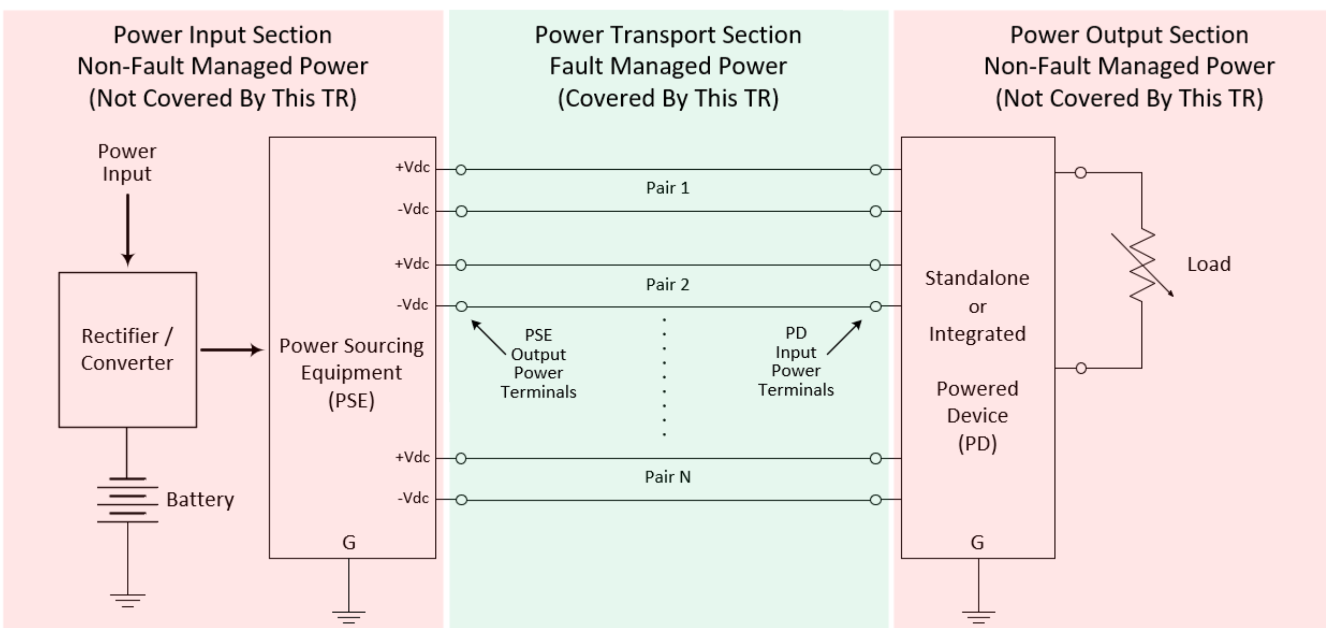


Figure 4.2 – Fault Managed and Non-Fault Managed Sections of a Point-to-Point FMPS

Figure 4.3 shown below provides a graphical representation of a point to multipoint bus FMPS configuration from one output terminal of the power sourcing equipment.

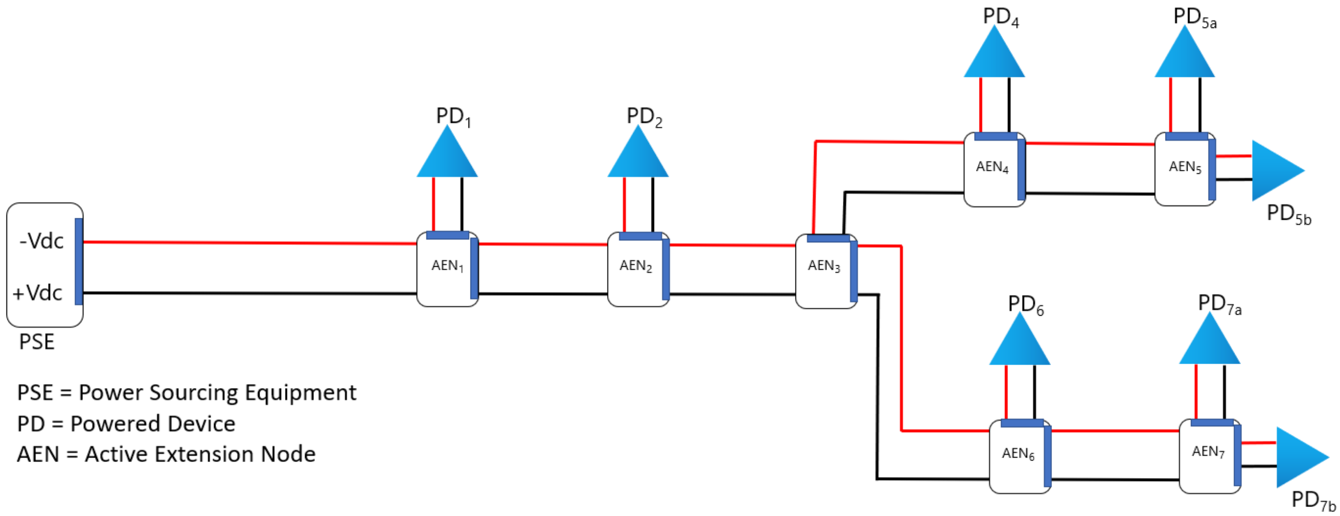


Figure 4.3 – Point-to-Multipoint Fault Managed Power System Bus Configuration

These point to multipoint or bus configured fault managed power systems are comprised of four basic sections consisting of a power sourcing equipment, power transport, AEN(s) for bus to bus and/or PD termination point(s) and powered device(s). Fault management functionality is limited to the power transport section as illustrated in Figure 4.4 below. The power transport section is comprised of the PSE output/test terminals, the power cable connecting the PSE to subsequent AENs and powered devices. Fault management requirements and testing presented in this TR are limited to the power transport section between test terminals when fault managed power is used as a safeguard.

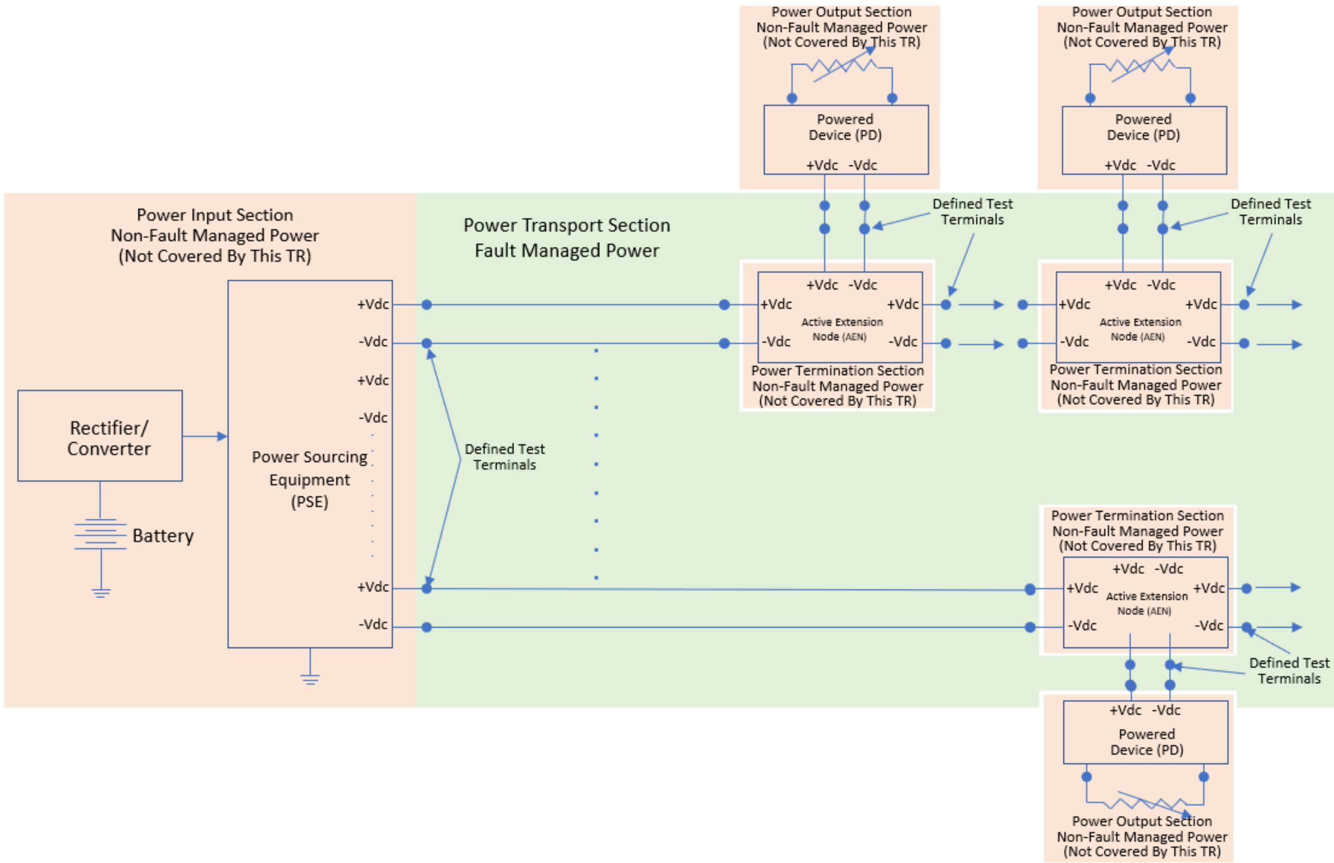


Figure 4.4 – Fault Managed and Non-Fault Managed Sections of a Bus Configured FMPS

4.1 Nominal Voltages

4.1.1 PSE Output Voltage Limits

Maximum PSE output voltage levels for fault managed power distribution systems in scope for this ATIS Technical Report are limited to 200 Vdc line to ground and 400 Vdc line to line. Fault managed power systems typically employ a dual polarity approach in order to maximize line to line voltage while meeting the 200 Vdc line to ground limit.

4.1.2 PD Output Voltages

Users of this document should refer to ATIS/ANSI-0600337 [Ref 11], UL/CSA 60950-1 [Ref 12], UL/CSA 62368-1 [Ref 13], ANSI/NFPA® 70, *National Electrical Code (NEC®)* [Ref 6], ANSI/IEEE C2, *National Electrical Safety Code (NESC)* [Ref 10] and ITU-T K.50 [Ref 8] for further information regarding voltage limitations on the output side of the PD. PD output voltage is subject to the same rules and requirements that apply to any other source voltage applicable to the environment and conditions where the end use equipment is installed.

4.2 Conductor Properties

Since fault managed power distribution systems in scope for this Technical Report are not power limited, it is expected that a wide range of power cables and wire gauges will be utilized depending on the specific application. Factors influencing wire gauge selection include source voltage, loop length, PD power consumption, minimum PD input voltage threshold, ambient loop conductor temperature and maximum allowable loop loss. System manufacturers must specify wire gauge based on maximum loop length and maximum power available at the output terminals of the PD when submitting a system for fault testing prescribed in this technical report.

The properties detailed in clause 4.2.1 are for uncoated copper conductors. If aluminum, copper-clad aluminum, copper-clad steel, or other conductor materials are used, then separate calculations will need to be completed.

4.2.1 Wire Gauges, Ampacities and Resistance

Loop conductor wire gauges 18 AWG and larger, as specified by the fault managed power system manufacturer is based on conductor ampacity data specified in Article 310 and Chapter 9 of ANSI/NFPA® 70, *National Electrical Code (NEC®)* [Ref 6]. Conductor resistance data is provided in Table 8 located in Chapter 9 of ANSI/NFPA® 70, *National Electrical Code (NEC®)* [Ref 6]. Table 4.2 below specifies typical loop resistance values for copper conductors at various operating temperatures for wire gauges 18 through 12 AWG.

- Conductor sizes, areas and resistances are provided in Table 8 of Chapter 9 of the NEC® for 18AWG and larger conductor sizes.
- Ampacity limits for copper conductors with 90°C rated insulations are found in Article 310 of the NEC®.
  - ➢ Table 310.16 lists ampacity data for 18 AWG and larger size conductors with adjustment factors for cables with more than 3 current-carrying conductors in a cable found in Table 310.15C.
  - ➢ Table 310.17 lists ampacity data for 18 AWG and larger size conductors for single-insulated conductors in free air.
- Adjustments to ampacities for different operating and ambient temperature are found in NEC®:
  - ➢ Table 310.15B1 and B2 - Ambient temperature corrections.
  - ➢ Table 310.15C - Ambient temperature corrections for multi-conductor (i.e., more than 3) cables.
- These ampacity calculations and adjustments assume defined resistances with NEC® rules 310.16 through 310.20 applying to voltages up to 2000 volts.

Systems that employ 26 AWG through 19 AWG twisted-pair OSP telecommunications (telco) cable are based on conductor sizing and resistance data specified in Telcordia GR-421-CORE, *Generic Requirements for Metallic Telecommunications Cables* [Ref 18]. Fault managed power systems using twisted-pair OSP telco cable may require more than 1 pair (bonded at both ends), depending on the loop wire gauge used, the end power requirements, and the PD operating voltage window. Installation guidelines supplied by the equipment manufacturer typically provide a calculation method or table to determine the number of pairs needed so that the PD minimum voltage window is met. However, to calculate it manually, the following information must be known:

- The maximum expected operating temperature (since higher temperatures increase the cable resistance Note that aerial cable will typically operate at a higher temperature than buried cable.
- The wire gauge(s) and their resistance (typically given per kft) at the expected maximum operating temperature.
- The number of available bonded parallel pairs
- The maximum power usage (in watts or constant current amps) expected at the output of the PD; and
- The minimum operating voltage of the PD

The resistivity of copper (International Annealed Copper Standard [IACS]) is an SI-derived unit and is 1.7241×10^{-8} Ω m at 20°C (68°F) [16] which is equivalent to 10.371 ohms-cmil/ft [16, 24]. Over normal operating temperature ranges, the coefficient of resistivity for copper is approximately 0.393%/°C (≈ 0.218%/°F) [17]. The following table gives some baseline values [7] of twisted pair resistivity at various temperatures, which can be adjusted for the expected maximum temperature based on the coefficient values given in the preceding sentence.

Table 4.1 - Loop Resistance of Common Sizes of OSP Copper Pairs

AWG Wire Size	Cross-Sectional Area		Diameter		Resistance (ohms/kft per Pair) at Various Operating Temperatures				
	mm^2	circular mils	inches	mm	20°C (68°F)	25°C (77°F)	50°C (122°F)	65°C (149°F)	75°C (167°F)
26	0.129	254	0.0159	0.405	87.8	89.53	98.32	104.12	108.21
24	0.205	404	0.0201	0.511	54.6	55.67	61.14	64.75	67.29
22	0.326	640	0.0253	0.644	34.4	35.08	38.52	40.79	42.4
20	0.518	1024	0.032	0.812	21.5	21.92	24.08	25.5	26.5
19	0.653	1290	0.0359	0.912	17	17.33	19.04	20.16	20.95

Table Notes:

(1) - These resistance values are derived on the maximum DC resistance for conductors from Section 7.1 of GR-421 [18] at 20°C with the values at various temperatures calculated using the thermal coefficient for copper of 0.393% per °C. The values for 20 AWG and 19 AWG were extrapolated from the GR-421 values for other gauge sizes.

(2) The resistances are approximate and are those of the complete circuit created by a pair of solid un-tinned soft annealed copper wires (e.g., the resistance of 1 kft of a 26 AWG copper pair is actually the resistance of 2000 ft of 26 AWG copper conductor).

Table 4.2 - Loop Resistance of 18 - 12 AWG Copper Pairs

AWG Wire Size	Cross-Sectional Area		Diameter		Resistance (ohms/kft per Pair) at Various Operating Temperatures				
	mm2	circular mils	inches	mm	20°C (68°F)	25°C (77°F)	50°C (122°F)	65°C (149°F)	75°C (167°F)
18	0.823	1625	0.015	0.39	13.2	13.6	15.2	16.2	16.9
16	1.31	2580	0.019	0.49	8.3	8.5	9.5	10.2	10.6
14	2.08	4110	0.024	0.62	5.2	5.4	6.0	6.4	6.7
12	3.31	6530	0.030	0.78	3.3	3.4	3.8	4.0	4.2

Table Notes:

(1) - 18 AWG through 12 AWG conductors are based on resistance values from NEC Table 8, Chapter 9 from 2020 NEC for 7 strand conductors. The resistance values apply to Class B,C,D stranded bare copper
(2) - Resistance values are adjusted to account for multiple conductor cables & twisted assemblies of single conductor cables per in accordance with Note 5 from Table 8, Chapter 9 of the 2020 NEC per NEMA WC/ 70-2009 (Table 2-2)

4.2.2 Pair Bonding

Minimum Number of Cable Pairs Required Based on Loop Voltage Drop

If the PD is constant current, use the cable resistances at maximum expected operating temperature and Ohm's Law to calculate the voltage drop.

If the PD is constant power (much more common than constant current for modern line-powered equipment) use the minimum operating voltage of the PD, divided into its maximum watt draw, to determine the maximum operating current. Using Ohm's law, the current and resistance can be used to determine the voltage drop. If the voltage drop from the PSE normal operating voltage reduces the PD input voltage below its operating window, then more pairs must be used. Add pairs until the resistance decreases enough (two parallel pairs of the same wire gauge are half the resistance of a single pair, three parallel pairs are a third of the resistance, etc.) so that the voltage window for the PD is met. Note that the equipment (both PSE and PD) may be limited in the number of pairs they can accept.

The following formula condenses the text of the paragraph above into equation format in order to determine the number of pairs needed for end-use equipment that is relatively constant power:

$$N_p > \frac{R_{p/k} \times d_k \times P_{max}}{{V_{min}}^2}$$

Where:

N_p is the minimum number of pairs needed.

$R_{p/k}$ is the loop resistance per kft for the wire size to be used at the expected maximum temperature.

d_k is the one-way distance (in kft) from the source to the load end of the line-powering circuit.

P_{max} is the maximum power usage of the PD.

V_{min} is the minimum PD input voltage.

4.3 System Charge Transfer

Fault managed power distribution systems inherently present a total system capacitance value which can be characterized as the summation of the managed capacitances associated with PSE, AEN and PD devices and the un-managed capacitance contributed by the power cable connecting them. PSE, AEN and PD devices used in FMPSs employ various methods to control the energy stored in their associated capacitances to minimize energy transferred during fault events. Active and/or passive management techniques employed to limit fault energy transfer make it necessary to differentiate between actual capacitance and effective capacitance of PSE, AEN and PD devices in order to accurately determine how much stored energy is allowed to transfer during fault events. The active and/or passive controls employed in FMPSs make it difficult or impossible to directly measure the effective capacitance presented by PSE, AEN and PD devices so this Technical Report specifies a method to accurately quantify the amount of energy transferred under fault conditions due to the magnitude of charge associated with system capacitance.

A charge transfer measurement methodology is presented in ITU-T K.50 [Ref 8]. Figure 7 from ITU-T K.50 [Ref 8] shown in Figure 4.6 below illustrates the basic charge measurement circuit. A test fault resistance of 500Ω is applied to a FMPS while operating under normal conditions and the time required for the system voltage to decay to 120 volts is measured. The amount of charge transferred is calculated based on the discharge current waveform.

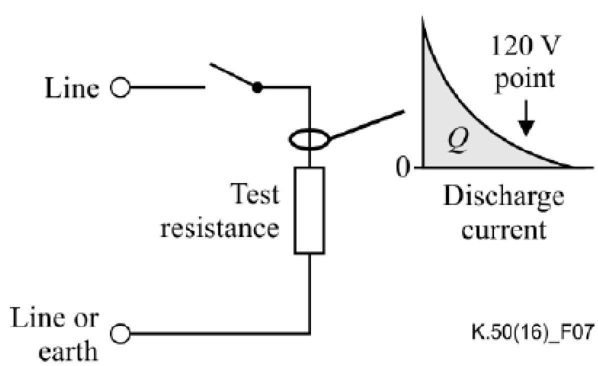


Figure 7 – Basic charge measuring circuit

Figure 4.5 – Basic charge measuring circuit per ITU-T K.50 Figure 7

4.4 System Charge Transfer Test & Measurement Plan

Maximum available charge for transfer during fault events occurs adjacent to the active elements of a FMPS. Therefore, application of the test resistance shall be located at the output of the PSE and the input of the PD via less than 10 feet of test cable. Test cases shall include line to line and line to ground fault configurations under no load and full load conditions. All charge transfer test cases are to be performed using a test apparatus that complies with the criteria outlined Annex D. All test cases are to be performed with maximum allowable length of power cable connecting the PSE, AEN(s) and the PD. The system manufacturer shall specify a range of maximum allowable cable lengths based on the percent of maximum load ranging from minimum rated load to 100% of maximum rated load for each cable type certified for use with the system by the manufacturer. If pair bonding is allowed by the system manufacturer, then the number of bonded cable pairs required for various maximum cable lengths / percent of maximum load combinations shall be specified and tested. Multiple maximum allowable cable lengths corresponding to specific pair bonding configurations versus percent of maximum load shall be specified by the system manufacturer in tabular format or by means of a software-based calculator tool.

Table 4.4 provides a summary of system charge measurement test cases.

Table 4.3 - System Charge Measurement Test Case Summary

Test Location	PD Output Power	Fault Type	Fault Resistance
Output of PSE	0%	Line - Line	500Ω
Output of PSE	0%	Line - Ground	500Ω
Output of PSE	100%	Line - Line	500Ω
Output of PSE	100%	Line - Ground	500Ω
Input of PD*	0%	Line - Line	500Ω
Input of PD*	0%	Line - Ground	500Ω
Input of PD*	100%	Line - Line	500Ω
Input of PD*	100%	Line - Ground	500Ω

*Note – For cases of multiple AEN outputs feeding PDs, these tests shall be repeated. For instance, in the case of two AEN outputs serving two PDs, a total of 12 tests shall be performed.

The system charge transfer test plan defined in this section is limited to the fault managed portion(s) of the FMPS.

Manufacturer provided system installation and operation (I & O) manuals shall clearly delineate the PSE power input section and PD power output section of the fault managed power system as potentially hazardous non-fault managed power. Additionally, the system I & O manuals and labeling shall clearly identify and differentiate the fault managed portion of the FMPS from the non-fault managed portions. See Figures 4.2 and 4.4 for graphical representations of the non-fault managed and fault managed portions of FMPSs.

A worst-case resistance value of 500 ohms shall be used for all charge transfer measurements. Maximum allowable cable lengths and associated pair bonding configurations specified for connected loads of both minimum rated PD power output and 100% of maximum rated PD output shall be used to conduct no load charge transfer measurements.

The charge transfer test and measurement plan defined in this clause can either be conducted at a third-party Independent Testing Laboratory (ITL) or alternatively, it may be conducted in-house at the system manufacturer facility and audited by ITL personnel.

Proper safety precautions should be followed when conducting all system testing prescribed in this Technical Report. Tests should be conducted only by properly trained personnel. Live parts of the fault managed portions of fault managed power systems meeting the criteria set forth in this Technical Report can be safely contacted with bare hands, however, in the event that a system under test is non-compliant, the voltages and currents can be potentially hazardous. Use of appropriate personal protective equipment and proper safety precautions are highly recommended.

4.4.1 Charge Measurement at the Power Sourcing Equipment (PSE) output terminals - Point to Point Configurations

4.4.1.1 Simulated human contact applied at the output of the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with maximum cable length*, PD connected, no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance value of 500Ω.

Application of total body resistance after PSE is energized and stabilized for 5 seconds.

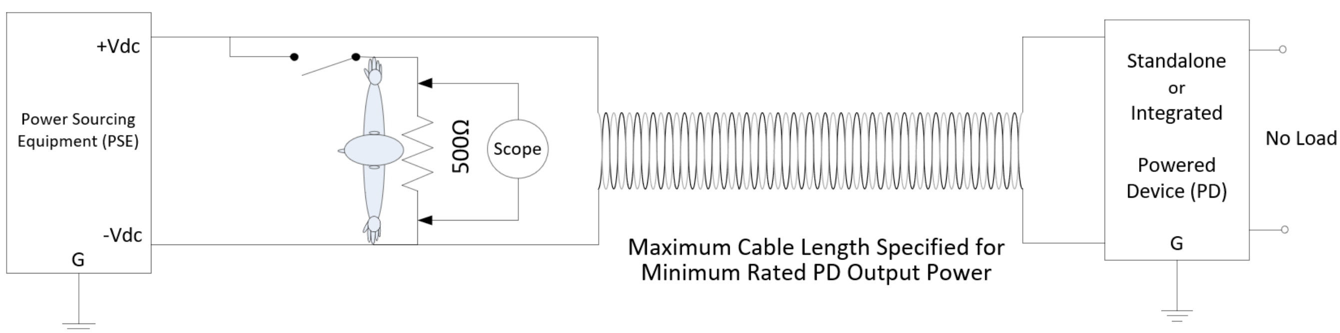


Figure 4.6 – Charge Transfer, Point to Point Configuration, Hand-to-Hand at PSE Output, No Load

b) Hand-to-foot human contact (line to ground) current path. Total body resistance value of 500Ω.

Application of total body resistance after PSE is energized and stabilized for 5 seconds.

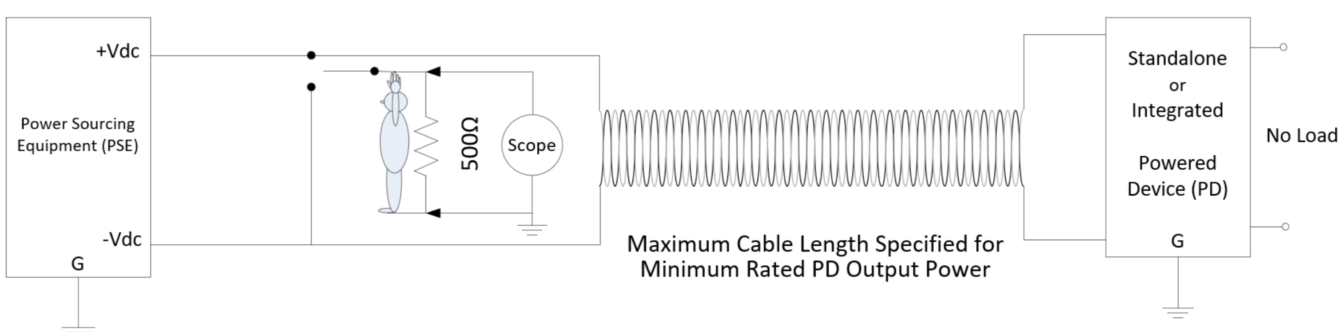


Figure 4.7 – Charge Transfer, Point to Point Configuration, Hand-to-Foot at PSE Output, No Load

* No load charge measurement conducted at maximum cable length specified for connected load of minimum rated PD output power.

4.4.1.2 Simulated human contact applied at the output of the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with maximum cable length*, PD connected, 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance value of 500Ω. Application of total body resistance after PSE is energized and stabilized for 5 seconds.

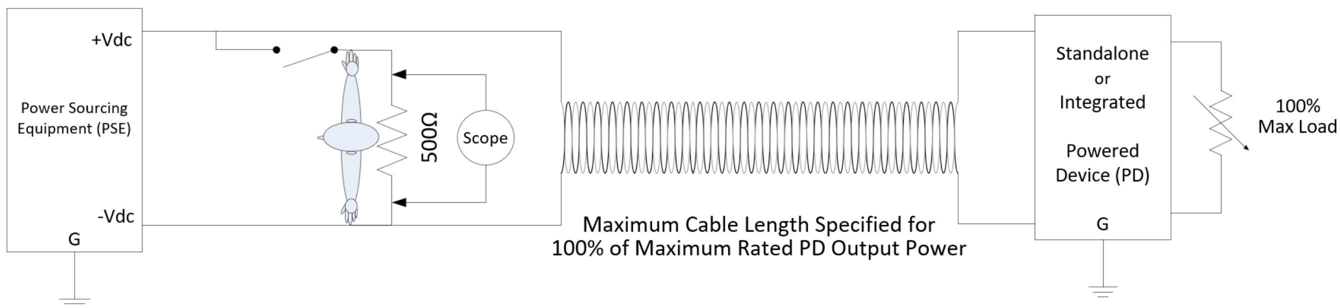


Figure 4.8 – Charge Transfer, Point to Point Configuration, Hand-to-Hand at PSE Output, Maximum Load

b) Hand-to-foot human contact (line to ground) current path. Total body resistance value of 500Ω. Application of total body resistance after PSE is energized and stabilized for 5 seconds.

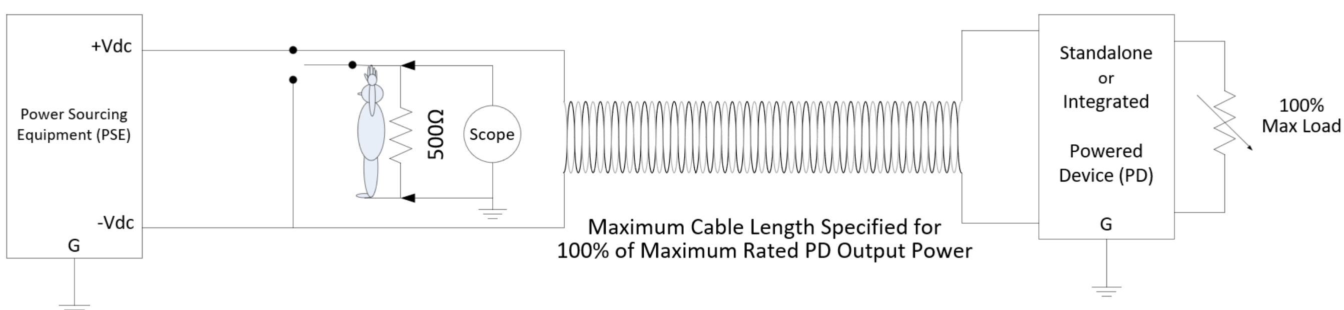


Figure 4.9 – Charge Transfer, Point to Point Configuration, Hand-to-Foot at PSE Output, Maximum Load

* 100% load charge measurement conducted at maximum cable length specified for connected load of 100% of maximum rated PD output power.

4.4.2 Charge Measurement at the Powered Device (PD) input terminals - Point to Point Configurations

4.4.2.1 Simulated human contact applied at the input to the Powered Device (PD) via less than 10 ft of test cable with maximum cable length*, PD connected, no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance value of 500Ω. Application of total body resistance after PSE is energized and stabilized for 5 seconds.

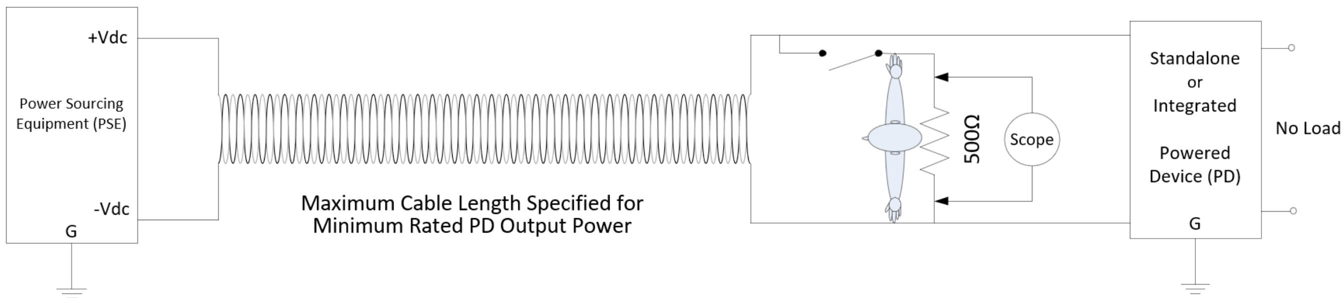


Figure 4.10 – Charge Transfer, Point to Point Configuration, Hand-to-Hand at PD Input, No Load

b) Hand-to-foot human contact (line to ground) current path. Total body resistance value of 500Ω. Application of total body resistance after PSE is energized and stabilized for 5 seconds.

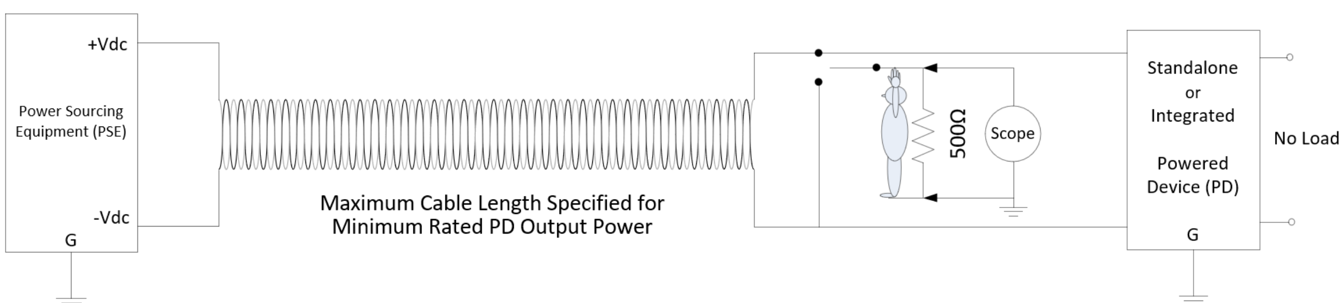


Figure 4.11 – Charge Transfer, Point to Point Configuration, Hand-to-Foot at PD Input, No Load

* No load charge measurement conducted at maximum cable length specified for connected load of minimum rated PD output power.

4.4.2.2 Simulated human contact applied at the input to the Powered Device (PD) via less than 10 ft of test cable with maximum cable length*, PD connected, 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance value of 500Ω. Application of total body resistance after PSE is energized and stabilized for 5 seconds.

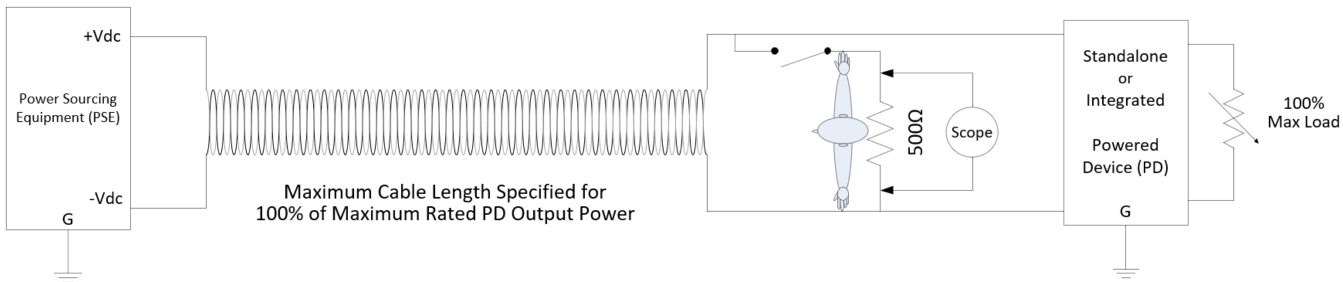


Figure 4.12 – Charge Transfer, Point to Point Configuration, Hand-to-Hand at PD Input, Maximum Load

b) Hand-to-foot human contact (line to ground) current path. Total body resistance value of 500Ω. Application of total body resistance after PSE is energized and stabilized for 5 seconds.

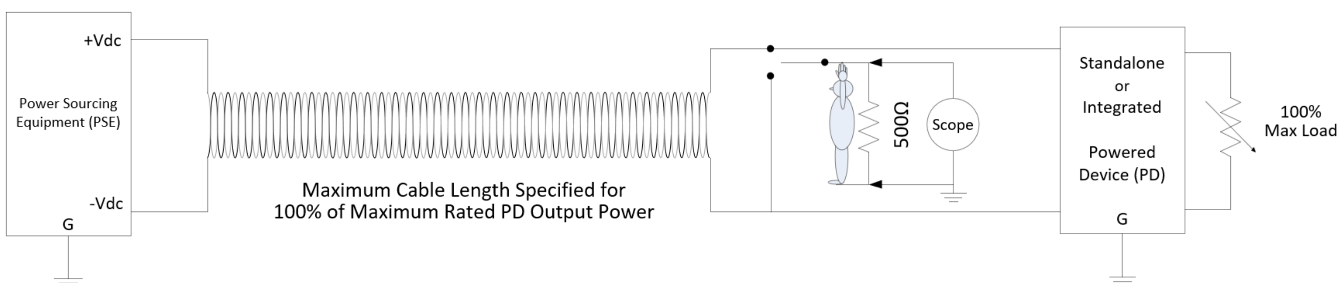


Figure 4.13 – Charge Transfer, Point to Point Configuration, Hand-to-Foot at PD Input, Maximum Load

* 100% load charge measurement conducted at maximum cable length specified for connected load of 100% of maximum rated PD output power.

4.4.3 Charge Measurement at the PSE output terminals - Bus Configurations

4.4.3.1 Simulated human contact applied at the output of the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with maximum cable length*, PD connected, no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance value of 500Ω. Application of total body resistance after PSE is energized and stabilized for 5 seconds.

b) Hand-to-foot human contact (line to ground) current path. Total body resistance value of 500Ω. Application of total body resistance after PSE is energized and stabilized for 5 seconds.

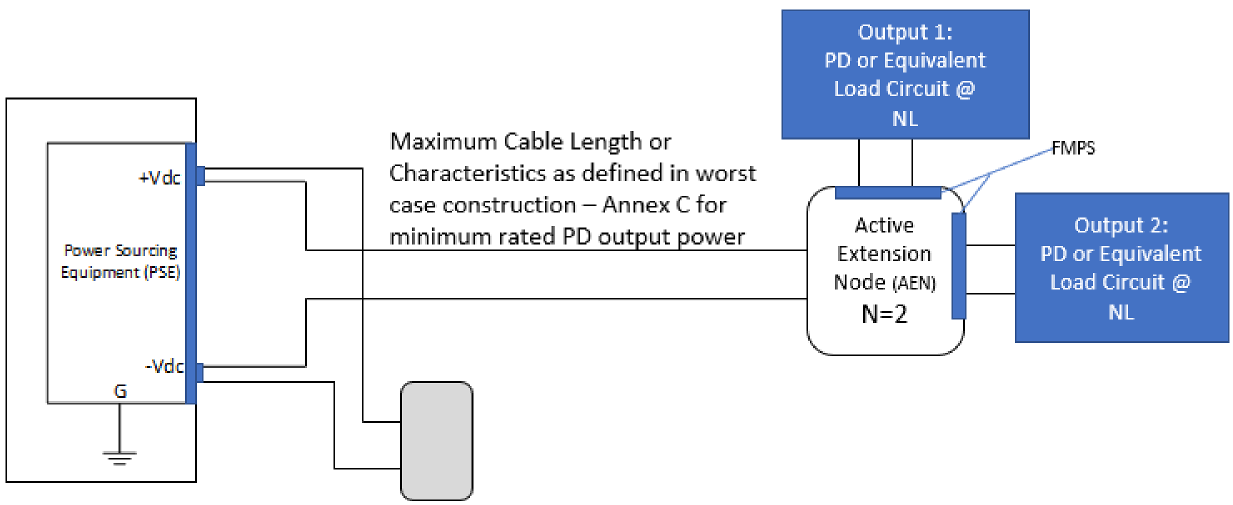


Figure 4.14 – Charge Transfer, Bus Configuration, Hand-to-Hand / Hand-to-Foot, at PSE Output, No Load

* No load charge measurement conducted at maximum cable length specified for connected load of
of minimum rated PD output power.

4.4.3.2 Simulated human contact applied at the output of the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with maximum cable length*, PD connected, 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance value of 500Ω. Application of total body resistance after PSE is energized and stabilized for 5 seconds.

b) Hand-to-foot human contact (line to ground) current path. Total body resistance value of 500Ω. Application of total body resistance after PSE is energized and stabilized for 5 seconds.

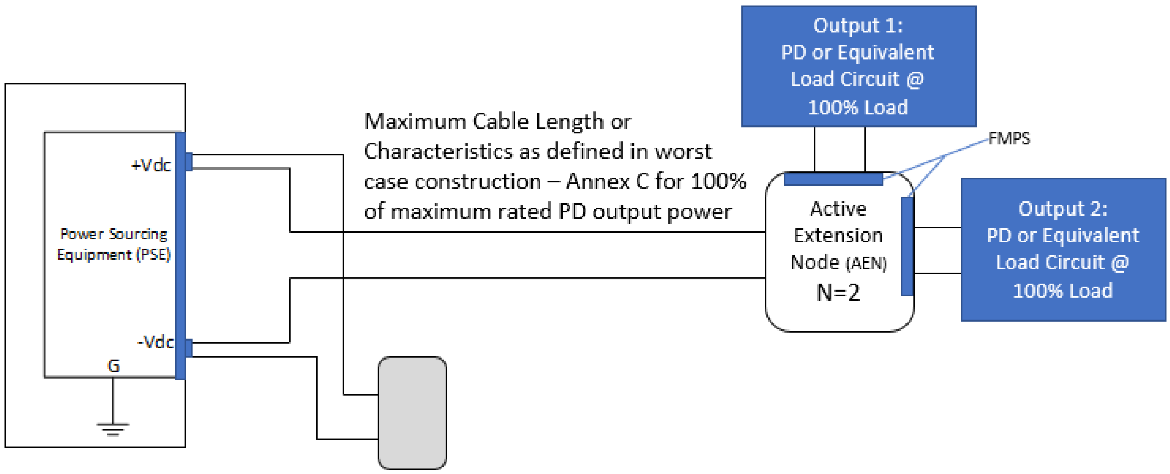


Figure 4.15 – Charge Transfer, Bus Configuration, Hand-to-Hand / Hand-to-Foot, at PSE Output, Maximum Load

* 100% load charge measurement conducted at maximum cable length specified for connected load of 100% of maximum rated PD output power.

4.4.4 Charge Measurement at the PD or ELC input terminals - Bus Configurations

4.4.4.1 Simulated human contact applied at the input to the Powered Device (PD) via less than 10 ft of test cable with maximum cable length*, Output 1, no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance value of 500Ω. Application of total body resistance after PSE is energized and stabilized for 5 seconds.

b) Hand-to-foot human contact (line to ground) current path. Total body resistance value of 500Ω. Application of total body resistance after PSE is energized and stabilized for 5 seconds.

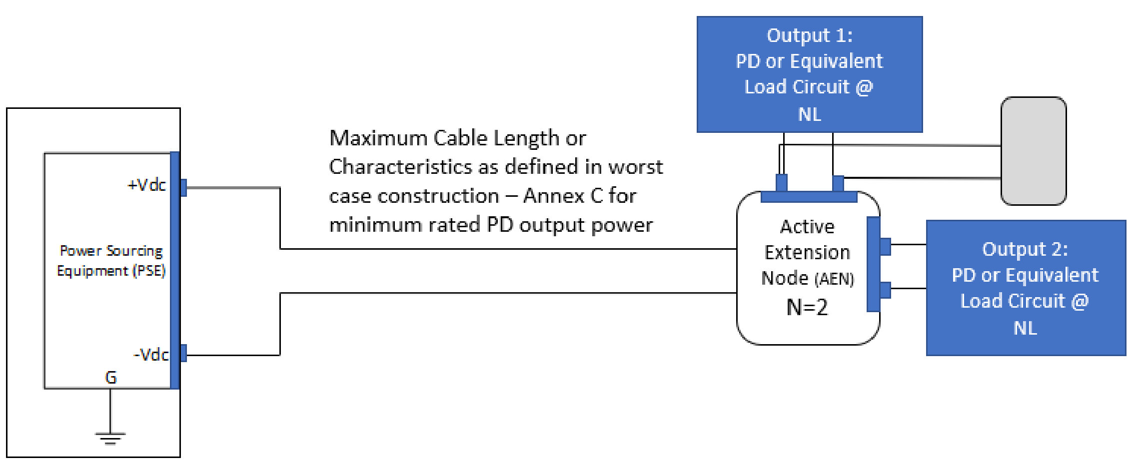


Figure 4.16 – Charge Transfer, Bus Configuration, Hand-to-Hand / Hand-to-Foot, at AEN Output 1, No Load

* No load charge measurement conducted at maximum cable length specified for connected load of minimum rated PD output power.

4.4.4.2 Simulated human contact applied at the input to the Powered Device (PD) via less than 10 ft of test cable with maximum cable length*, Output 1, 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance value of 500Ω. Application of total body resistance after PSE is energized and stabilized for 5 seconds.

b) Hand-to-foot human contact (line to ground) current path. Total body resistance value of 500Ω. Application of total body resistance after PSE is energized and stabilized for 5 seconds.

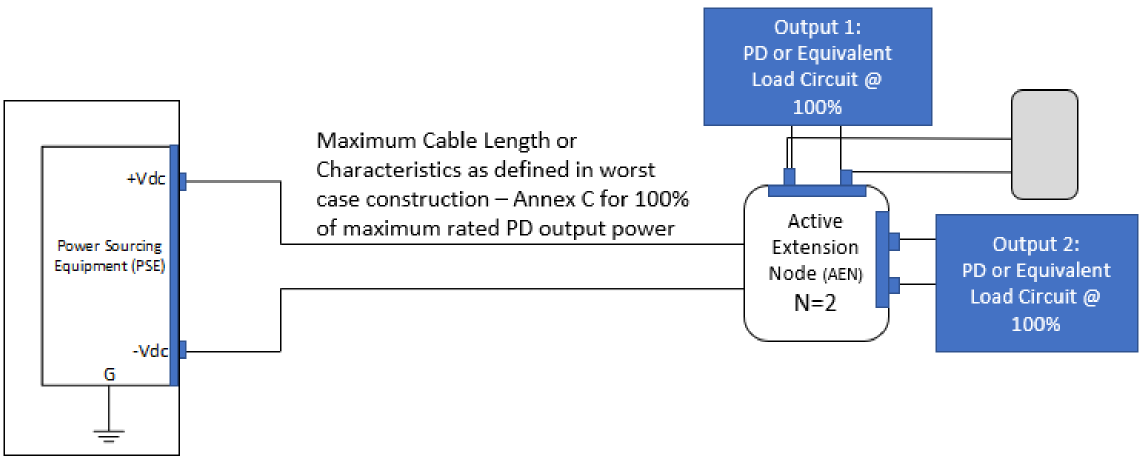


Figure 4.17 – Charge Transfer, Bus Configuration, Hand-to-Hand / Hand-to-Foot, at AEN Output 1, Maximum Load

* 100% load charge measurement conducted at maximum cable length specified for connected load of 100% of maximum rated PD output power.

4.4.5 Charge Measurement at the PD or ELC input terminals - Bus Configurations

4.4.5.1 Simulated human contact applied at the input to the Powered Device (PD) via less than 10 ft of test cable with maximum cable length*, Output 2, no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance value of 500Ω. Application of total body resistance after PSE is energized and stabilized for 5 seconds.

b) Hand-to-foot human contact (line to ground) current path. Total body resistance value of 500Ω. Application of total body resistance after PSE is energized and stabilized for 5 seconds.

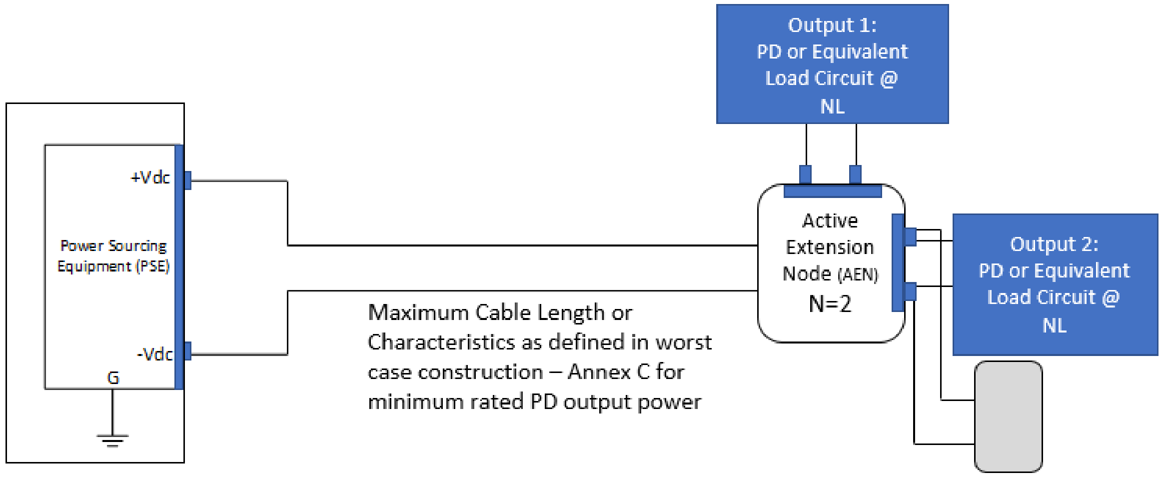


Figure 4.18 – Charge Transfer, Bus Configuration, Hand-to-Hand / Hand-to-Foot, at AEN Output 2, No Load

* No load charge measurement conducted at maximum cable length specified for connected load of minimum rated PD output power.

4.4.5.2 Simulated human contact applied at the input to the Powered Device (PD) via less than 10 ft of test cable with maximum cable length*, Output 2, 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance value of 500Ω. Application of total body resistance after PSE is energized and stabilized for 5 seconds.

b) Hand-to-foot human contact (line to ground) current path. Total body resistance value of 500Ω. Application of total body resistance after PSE is energized and stabilized for 5 seconds.

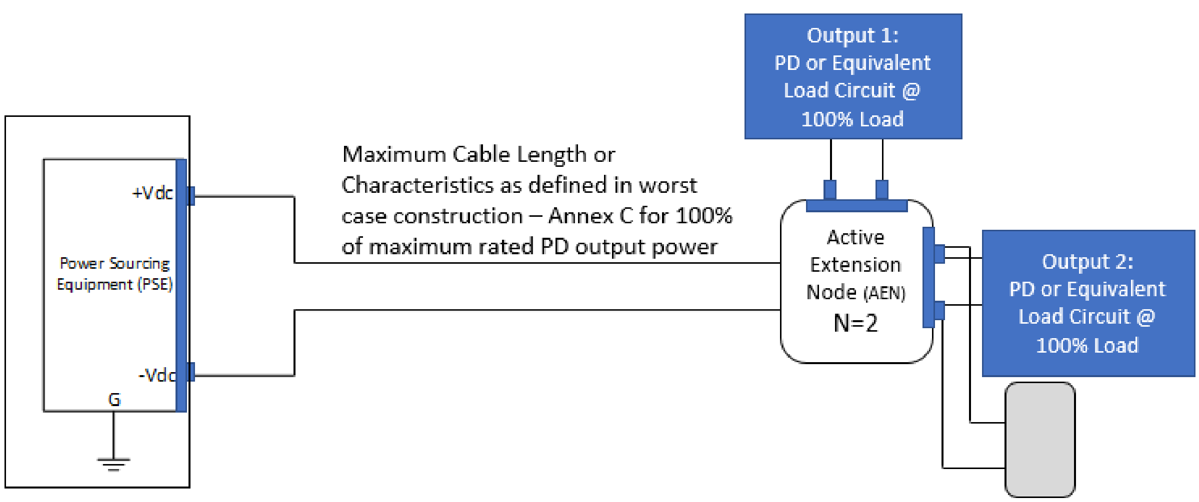


Figure 4.19 – Charge Transfer, Bus Configuration, Hand-to-Hand / Hand-to-Foot, at AEN Output 2, Maximum Load

* 100% load charge measurement conducted at maximum cable length specified for connected load of 100% of maximum rated PD output power.

4.5 Fault Managed Power System Compliance Criteria

4.5.1 Performance Criteria

4.5.1.1 Fault Test Pass / Fail Criteria

For a FMPS to qualify as acceptable per this TR for inadvertent bare handed human contact, the plotted fault test results for all fault test cases specified in Sections 5.4 and 5.5 must fall within DC zone 1 or 2 defined in Figure 22 of IEC 60479-1 [Ref 1] for fault events greater than 10 milliseconds in duration or to the left of the extended “b line” depicted in Figure 5.1 for fault events less than 10 milliseconds in duration for the entire range of total body resistance values specified in table A.1 of Annex A. The extended “b line” depicted in Figure 5.1 has been mathematically developed by Dr. Francisco Paz based on information provided in the IEC 60479 series of standards. Details of the methodology used to develop the extended “b line” are discussed in the white paper, “On Extending the $Td{-}Ib$ Curve b Limit For Td Shorter Than 10ms.” Rev. A0.4. 11/23/2020 By *Dr. Francisco Paz (*franciscopaz@ieee.org *)* [Ref 22]. The extended “b line” represents a very conservative approach which ensures that fault managed power system response lies well outside of the region where ventricular fibrillation would become possible.

4.5.1.2 Transient Tolerance Test Criteria

Fault managed power systems must meet the requirements for all transient tolerance testing specified in Section 6 of this TR.

Fault managed power systems must remain fully functional following First Level lightning surge and power fault testing.

There shall be no potentially hazardous PSE power output following Second Level lightning surge and power fault testing or there shall be no failure of fault management functionality if system is still providing potentially hazardous PSE power output.

4.5.2 Fault Managed Power System Specifications

The FMPS manufacturer shall include the following specifications for each system model produced:

- Maximum rated PD power output
- Minimum rated PD power output
- Maximum PSE power output
- Maximum allowable cable length of specified wire gauge at maximum rated PD power output*
- Maximum allowable cable length of specified wire gauge at minimum rated PD power output*
- Minimum PD input voltage
- Cable type(s) and wire gauges certified for use with FMPS

* The system manufacturer shall specify a range of maximum allowable cable lengths based on the percent of maximum load ranging from minimum rated load to 100% of maximum rated load for each cable type certified for use with the system by the manufacturer. If pair bonding is allowed by the system manufacturer, then the number of bonded cable pairs required for various maximum cable lengths / percent of maximum load combinations shall be specified and tested. Multiple maximum allowable cable lengths corresponding to specific pair bonding configurations versus percent of maximum load shall be specified by the system manufacturer in tabular format or by means of a software-based calculator tool.

4.5.3 Fault Managed Power System Testing Criteria

To conduct the measurement and test cases defined in this Technical Report, the system manufacturer must provide a complete system. A complete system is comprised of PSE, PD(s), AEN(s) (when employed) and connecting power cable. If a system is to be certified with multiple power cable types as acceptable (per this TR) for inadvertent bare handed human contact, all fault tests and charge transfer measurements specified in this TR must be performed for each power cable type. However, once a system has been tested and certified with a particular cable type consisting of some number of conductor pairs, recertification is not necessary for identical cable designs of equal or lesser pair count.

Cable designs are considered to be identical if all of the following apply:

- Same conductor wire gauge.
- Same conductor material. (stranding and metal alloy)
- Capacitance per unit length within the system manufacturer tolerance requirement.
- Same cable pair lay length per the system manufacturer tolerance requirement as applicable. (Degree of conductor twist per unit length of cable with common axis cabling. Degree of conductor twist rate can include parallel conductors with no twist rate.)
- Consistent Shielding vs. Non-Shielding.

Note: Power transmission cables to be used with Fault Managed Power Systems must be approved for use by the system manufacturer. Determination of the suitability of power cables for use with a particular Fault Managed Power System is the sole responsibility of the system manufacturer. System end users are not permitted to use unapproved power cables.

Note: System testing of shielded cables must be performed with cable shield grounded or isolated as intended and instructed for installation by the system manufacturer. If both cable shield treatment options are allowed by the system manufacturer, then all testing prescribed in this TR must be performed for both shield treatment options. If a previously tested and certified shielded cable has only been tested with the shield either grounded or isolated and a manufacturer subsequently seeks to approve the cable or a cable of identical design with equal or lesser conductor pair counts for use with the system with an additional cable shield treatment option, then full system certification testing is required to qualify the additional cable shield treatment method.

The charge transfer measurements and simulated human contact fault test cases defined in this TR can either be conducted at a certified third-party Independent Testing Laboratory (ITL) or alternatively, they may be conducted in-house at the system manufacturer facility and audited by ITL personnel.

For systems with multiple power output ports per PSE: In order to limit/reduce the number of tests required, similar fault management performance across the ports must be verified. Additionally, when/since power transmission conductors from multiple ports can be routed in the same physical path, cross-port faults must be assessed for hazards presented, again by conducting a minimum number of tests. To achieve these goals, the following additional testing is required for multiple output port devices.

4.5.3.1 Verification of Port Performance Variance

Verify similar fault management performance from a randomly-selected second port as follows:

a. Perform ten (10) total iterations of the test listed in Table 4.5 below on the original port, and average the charge delivered in each fault. Test the port in accordance with Clause 4.4.1.1 (for Point-to-Point systems) or 4.4.3.1 (for Bus Configurations), utilizing the parameters from Table 4.5.
b. Repeat (step a) for the randomly selected second port, and average the charge delivered in each fault.
c. Verify that the average value of charged transfer from each of the two tested ports does not vary by greater than 10%.

4.5.3.2 Cross-Port Testing

Test cross-port combinations between the original and the randomly selected second port from Clause 4.5.3.1 above, as specified in the four test cases listed below. In addition to testing opposite polarity PSE output terminals of two randomly selected ports, consideration is also given to performing cross-port testing of like polarity PSE output terminals when there is a possibility that a potential difference of greater than 60 volts can exist between two positive or two negative terminals at any point during the 10 second fault test period. This condition would likely occur when the PSE outputs are periodic and out of phase with each other. The last two test cases are included to address this condition.

- Positive terminal of first port to negative terminal of second port
- Negative terminal of first port to positive terminal of second port
- Positive terminal of first port to positive terminal of second port
- Negative terminal of first port to negative terminal of second port

Test the port in accordance with Clause 4.4.1.1 (for Point-to-Point systems) or 4.4.3.1 (for Bus Configurations), utilizing the parameters from Table 4.5. Verify system response to specified fault test is to the left of the b line using the RCIWA tool as described in Annex B.

Table 4.4 - Charge delivery testing parameters for multiple output port PSE

Test Location	PD Output Power	Fault Type	Fault Resistance
Output of PSE	0%	Line - Line	500Ω

4.6 Fault Current and Voltage Measurement Instrumentation Minimum Specifications

A digital oscilloscope or other suitable waveform data acquisition instrument shall be used to measure voltage and current waveforms associated with all simulated human contact fault test cases defined in Sections 5.3 and 5.4 and all charge transfer measurements specified in Section 4.4 of this TR. The current waveform may be measured directly using a suitable current clamp-on probe or alternatively, the current waveform can be derived based on a voltage measurement across the applied fault resistance divided by the value of the fault resistance. A true RMS voltmeter capable of measuring AC, DC and peak voltage shall be used to verify proper PSE output voltage prior to insertion of simulated human contact fault resistances for all test cases where PSE energization and stabilization are required for at least five seconds prior to application of fault resistances.

4.6.1 Minimum Voltage & Current Waveform Measurement Instrumentation Specifications for simulated human contact fault test cases and charge transfer measurements

The digital oscilloscope or other waveform data acquisition instrument used to capture fault current and charge transfer waveforms produced by the simulated human contact fault test and measurement cases defined in this TR must be able to perform the following functions:

- *Capture the voltage across the fault resistance at the point of insertion.*
- *Capture the current through the emulated fault resistance.*
- *Provide a record of both the voltage and current traces for at least 10s;* with no less than 100ms before the insertion of the fault and no less than 9.5s after the insertion of the fault.
- *The sampling period not to exceed 10us such that a significant number of samples are recorded for the minimum duration considered (100us being the shortest duration depicted in IEC 60479-2 [Ref 2], Figure 23).*

- *The scale is such that the peak and minimum values of the signals are measured (400V Line to Line / 200V Line to Ground or 800mA for a test case of 400V/500Ohm).*
- *The resolution of the probes is such that the minimum value of interest of the voltage and current can be resolved accurately (60V and 25mA or 62.5mA depending on the body current path).*
- *Produce a CSV file that includes the measured time in seconds, current in amperes, and voltage in volts channel data.*

The following are the minimum oscilloscope or other waveform data acquisition instrument performance specifications:

Time measurement

- *Bandwidth of all measurement instruments involved should be 50KHz or more.*
- *Sampling time of the oscilloscope should be set to 10us.*
- *The captured fault or charge transfer transient should clearly record at least 10 seconds of data* with no less than 100ms before the insertion of the fault and no less than 9.5s after the insertion of the fault.
-

Note: The sampling time is selected as 10us to ensure that the capture includes at least 10 samples in the smallest duration window covered in IEC60479-2 [Ref 2] Fig. 23 (100us). By taking several samples in the 100us windows the capture will reflect the detailed high frequency components in the body current, which are then incorporated in the RMS calculation.

The total record length should be 10s to match the maximum duration window in IEC60479-1 [Ref 1] Fig. 22 (upper limit). By recording the 10s transient, complex behavior such as pulsating output and restart procedures will be captured and analyzed.

The transient capture shall start at least 100ms before the insertion of the fault resistance to show, through the voltage measured at the fault insertion point, that the system is operating as expected before the insertion of the fault.

Voltage measurement

- *The offset of the voltage probe should be removed before the measurement is taken.*
- *The voltage probe shall have an appropriate range to measure the selected configuration based on maximum PSE output voltage.*
- *The resulting accuracy of the probe & scope, at the selected range, should be less than +/- 8V (+/-2% of 400V) and represents 4 counts of the digitized measure in an 8bit oscilloscope set to 50V/div.*
- *The voltage probe shall have a bandwidth of at least 1MHz.*
- *The voltage probe input impedance shall be at least 1Mohm.*

Current measurement

- *The offset of the current probe should be removed before the measurement is taken.*
- *The current probe shall have an appropriate range to measure the applicable test configuration. (maximum 800mA for a 400V/500Ohm fault test case)*
- *The resulting accuracy of the probe & scope, at the selected range, shall be enough to clearly measure the lower limit of the curve b, affected by the heart current factor (25mA or 62mA)*. For example, +/- 5mA. This represents 1 count of an 8bits oscilloscope configure at 100mA/div.*
- *The bandwidth of the current probe shall be at least 1Mhz*.

Data file saving capability:

- *Measured fault waveform data shall be saved in a CSV file that includes the time, current, and voltage channels. The file can be modified (header) to ensure it matches the requirements of the automated tool.*

*Note: Minimum range of oscilloscope current probes typically top out at about 5A, so 25mA represents about 0.5% of the range. To make an accurate analysis of low-level fault currents associated with FMPSs, current magnitudes on the order of 25mA must be captured with relatively high resolution. Ideally, the accuracy of the current probe should be on the order of 0.1% of 5A yielding reasonable accuracy down to around 5mA, however, probes of this resolution can be difficult to come by. Current measuring resolution can be improved with a 5A probe by looping the fault current carrying conductor 5 turns in the current clamp portion of the probe to reduce the range of the probe to 1A.

4.6.2 Minimum Voltage & Current Waveform Measurement Instrumentation Specifications for short circuit test cases

The digital oscilloscope or other waveform data acquisition instrument used to capture fault current waveforms produced by the short circuit test cases defined in Section 5.3 this TR must be able to perform the following functions:

- *Capture the voltage across the fault insertion points.*
- *Capture the current through the short circuit.*
- *Provide a record of both the voltage and current traces for at least 2s;* with no less than 100ms before the insertion of the fault and no less than 1.8s after the insertion of the fault.
- *The sampling period not to exceed 100us such that a significant number of samples are recorded for the minimum duration considered (1ms being the shortest duration depicted in Figure 5.44).*
- *The scale is such that the peak and minimum values of the voltage signal are measured (400V Line to Line / 200V Line to Ground).*
- *The scale is such that the peak value of the fault current is visible (the measurement does not clip)*
- *The resolution of the probes is such that the minimum value of interest of the current can be resolved accurately (164.8 A at 2 seconds)[13].*
- *Produce a CSV file that includes the measured time in seconds, current in amperes, and voltage in volts channel data.*

The following are the minimum oscilloscope or other waveform data acquisition instrument performance specifications:

Time measurement

- *Bandwidth of all measurement instruments involved should be 50KHz or more.*
- *Sampling time of the oscilloscope should be set to 100us or less.*
- *The captured fault or charge transfer transient should clearly record at least 2 seconds of data with no less than 100ms before the insertion of the fault and no less than 1.8s after the insertion of the fault.*

Note: The sampling time is selected as 100us to ensure that the capture includes at least 10 samples in the smallest duration window covered in fault current - duration limit curve shown in Figure 5.44. By taking several samples in the 1ms windows the capture will reflect the detailed high frequency components in the fault current, which are then incorporated in the RMS calculation.

[13] It is expected that this value will be much larger than any current produced in one of these systems. Test laboratories and manufacturers should come up with an acceptable range that captures the behavior of the system under test.

The total record length should be 2s to match the maximum duration window in the fault current duration limit. By recording the 2s transient, complex behavior such as pulsating output and restart procedures will be captured and analyzed.

The transient capture shall start at least 100ms before the insertion of the fault resistance to show, through the voltage measured at the fault insertion point, that the system is operating as expected before the insertion of the fault.

Voltage measurement

- *The offset of the voltage probe should be removed before the measurement is taken.*
- *The voltage probe shall have an appropriate range to measure the selected configuration based on maximum PSE output voltage.*
- *The resulting accuracy of the probe & scope, at the selected range, should be less than +/- 8V (+/-2% of 400V) and represents 4 counts of the digitized measure in an 8bit oscilloscope set to 50V/div.*
- *The voltage probe shall have a bandwidth of at least 1MHz.*
- *The voltage probe input impedance shall be at least 1Mohm.*

Current measurement

- *The offset of the current probe should be removed before the measurement is taken.*
- *The current probe shall have an appropriate range to measure the applicable test configuration.*
- *The resulting accuracy of the probe & scope, at the selected range, shall be enough to clearly measure the lower limit of the current-duration limit curve*
- *The bandwidth of the current probe shall be at least 1Mhz*.

Data file saving capability:

- *Measured fault waveform data shall be saved in a CSV file that includes the time, current, and voltage channels. The file can be modified (header) to ensure it matches the requirements of the automated RCIWA tool as described in Annex B.*

4.6.3 Minimum Voltmeter Specifications

The voltmeter used for making voltage measurements prescribed in this TR must be capable of making DC, RMS and peak voltage measurements. The following are minimum required voltmeter specifications:

- Input resistance: ≥1MΩ
- Input capacitance: ≤200pF
- Frequency range: 15Hz to 1MHz
- Floating or differential input with common mode rejection of ≥ 40 dB up to 1MHz
- Measurement accuracy as described below:

Voltage Range	Frequency Range	Instrument Accuracy*
≤ 1000 Volts	≤ 1 kHz	± 1.5%
≤ 1000 Volts	> 1 kHz ≤ 5 kHz	± 2.0%
≤ 1000 Volts	> 5 kHz ≤ 20 kHz	± 3.0%
≤ 1000 Volts	> 20 kHz	± 5.0%

* Effective accuracy of measured value. Typically specified as ± ([% of Reading] + [number of counts])

5 Electrical Protection Considerations

Nationally Recognized Testing Laboratory (NRTL) Listing is required in accordance with US/Canadian Electrical Codes (NEC®/CEC) and OSHA requirements, with exemptions to the Listing requirements if certain provisions are met, such as the system and all equipment being installed in an area under the exclusive control of the communications utility. It is recommended that the fault managed power system equipment vendor consult with the service provider regarding specific Listing requirements if there is any question.

The intent of this Technical Report is to review the fault managed portion of the FMPS as a safeguard. This TR does not review power input to the PSE or power output of the PD or power within the PSE, AEN or PD equipment.

Manufacturer provided system installation and operation (I & O) manuals shall clearly delineate the PSE power input section and PD power output section of the fault managed power system as potentially hazardous non-fault managed power. Additionally, the system I & O manuals and labeling shall clearly identify and differentiate the fault managed sections of the FMPS from the non-fault managed sections. See Figures 4.2 and 4.4 for graphical representations of the non-fault managed and fault managed sections of FMPSs.

The short circuit and simulated human contact fault test plans defined in Sections 5.3, 5.4 and 5.5 of this TR are limited to the fault managed portion of the FMPS.

The fault current test plans consider the possibilities of inadvertent contact with live parts and conductors by qualified/skilled personnel. Access to live parts and conductors is possible when e.g., a cable is cut or when safeguards in terminal equipment are removed.

Fault managed power distribution system manufacturers shall provide information depicting the characteristic fault current flow of their equipment when configured as described in the test criteria presented in this clause. The test configurations described in this clause are chosen to reflect representative line-powering deployment conditions. Each test configuration is performed for three values of total body resistance, however, the intent of this test plan is to verify that system fault response remains within the confines of DC zone 1 or 2 defined in IEC 60479-1 [Ref 1] for fault events greater than 10 milliseconds in duration or to the left of the extended “b line” for fault events less than 10 milliseconds in duration for the entire range of total body resistance values specified in table A.1 of Annex A. Resistors carrying a 5% tolerance specification or tighter shall be used for applied fault resistances. For test configurations that include a powered device (PD), the prescribed tests are dependent on whether the system’s PDs are stand-alone devices or are integrated with their load circuits. Systems employing standalone PDs shall be tested under no load, 50% load and 100% load conditions, plus or minus 5%. Systems with integrated PDs generally have a fixed range of power consumption, limiting the range of practical input power variation, however, both minimum and full load test cases shall be performed. It is the intent of this test plan to determine system fault response over the entire PD load range under no load (or minimal load for integrated PDs) to full load conditions.

Fault magnitude and duration data shall be measured and recorded for each fault test case described in clause 5.4 or 5.5 depending on whether the system under test is a point to point or bus configured system. The fault tests are designed to emulate bare-handed human contact with live parts under a wide range of line to line and line to ground fault scenarios and system configurations. A line diagram and specific fault configuration information is provided for each of the required fault test cases. The fault resistance shall be applied for a duration of ten seconds for each of the required fault test cases. Two fault tests shall be performed for each specified test configuration and fault resistance value. One of the two tests shall be conducted with the fault resistance applied prior to energization of the power sourcing equipment (PSE) and the other test shall be preceded by at least five seconds of steady-state no-fault PSE operation. All fault test cases shall be performed using a Test Resistance Insertion Apparatus (TRIA) that complies with the criteria outlined in Annex D. All fault waveform voltage measurements shall be conducted using a high voltage differential probe. A current probe shall be used to measure and record the simulated human body fault current over a 10 second time-period commencing with application of the fault. See Section 4.6.1 for minimum oscilloscope and voltmeter specifications. Fault managed power systems with rated PSE output voltage less than 60 Vdc potential conductor to conductor and conductor to ground do not need to be tested. Any fault current flow at less than 60 Vdc potential conductor to conductor or conductor to ground need not be included in the plotting of test results.

When testing a system with shielded cable, the cable shield shall be grounded or isolated as intended and instructed for installation by the system manufacturer. If both cable shield treatment options are allowed by the system manufacturer, then all testing prescribed in this TR must be performed for both shield treatment options.

After completion of all required simulated human contact fault tests, analysis of the recorded data shall be performed using the software-based Random Complex Irregular Waveform Analysis (RCIWA) tool provided with this Technical Report. Passing test results must plot to the left of the "b line" depicted on the graph shown in Figure 5.1. The RCIWA tool will provide a pass/fail test result along with a trace plot of the fault current magnitude and duration on the simulated human contact fault current test result graph. Worst-case passing test results are those that plot to the left of the "b line" but are closest to the line. To demonstrate that proper operation of the circuit under test is not adversely affected by other circuits operating in the cable under test, the worst-case line to line and line to ground fault test cases shall be retested with the maximum number of active circuits possible as specified by the manufacturer based on the number of conductor pairs per cable under test. The active circuits not under test shall be operated at 0, 50 and 100% of rated load during the retest of the two worst-case fault test cases. Retest results must plot to the left of the "b line" to achieve a final passing test outcome.

Exempt from testing: Systems with less than 60V peak or those with short transients (less than 100us in duration) in excess of 60V peak due to ringing or other causes are ignored so long as they do not exceed the 400V line to line / 200V line to ground limits and are separated by at least 10ms.

See Figures 5.3 through 5.28 below for specific test configurations pertaining to point to point FMPSs. See Figures 5.30 through 5.38 below for specific test configurations pertaining to bus architecture FMPSs.

These tests are designed to simulate two types of human contact fault conditions as described in Annex A:

a) Hand-to-hand human contact (line-to-line) current path.

b) Hand-to-foot human contact (line-to-ground) current path.

NOTE: If the PSE output is bi-polar and the voltage is greater than ± 60Vdc with respect to ground (120Vdc conductor to conductor) then both Positive Conductor to Ground and Negative Conductor to Ground must be tested.

Power cable wire gauge, maximum loop length and maximum power available at the output terminals of the PD are to be specified by the power system manufacturer. Power cable of the wire gauge(s) specified by the fault managed power system manufacturer shall be provided by the system manufacturer for system fault testing. The test lab shall record the power cable type and gauge used to conduct fault testing. Test cable used for application of fault resistances must be equal to or greater than the wire gauge of the loop or bus power cable.

The system manufacturer shall specify a range of maximum allowable cable lengths based on the percent of maximum load ranging from minimum rated load to 100% of maximum rated load for each cable type certified for use with the system by the manufacturer. If pair bonding is allowed by the system manufacturer, then the number of bonded cable pairs required for various maximum cable lengths / percent of maximum load combinations shall be specified and tested. Multiple maximum allowable cable lengths corresponding to specific pair bonding configurations versus percent of maximum load shall be specified by the system manufacturer in tabular format or by means of a software-based calculator tool.

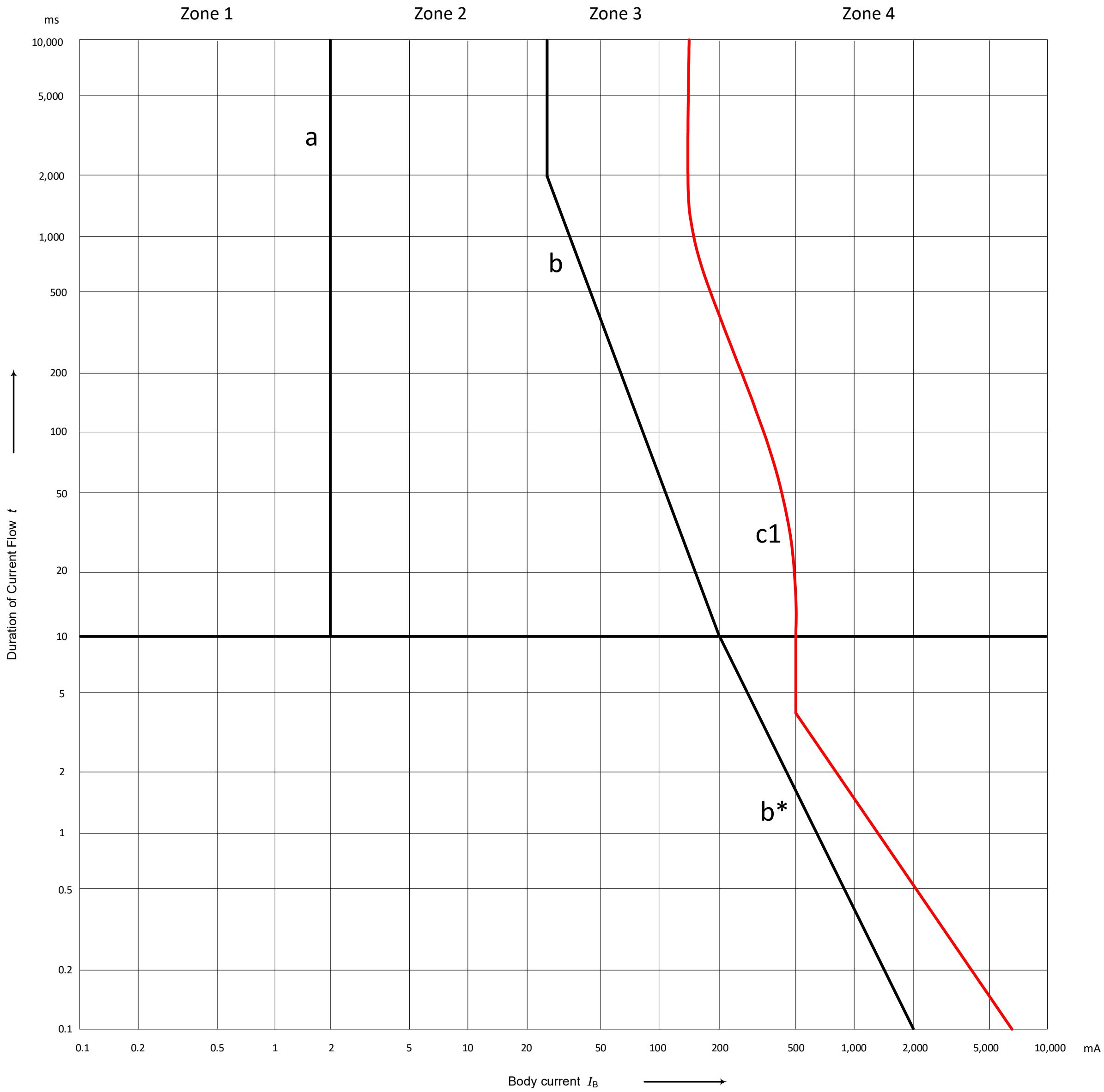
Fault data gathered from the test configurations described in this clause shall be presented in graphical format showing log10 (effective fault current magnitude through the fault resistance, in milliamperes) on the x axis and log10 (time, one tenth millisecond to ten seconds) on the y axis, as shown in Figure 5.1 below. This figure is derived from the merger of Figure 22 of IEC 60479-1, *Effects of Current on Human Beings and Livestock, Part 1-General* Aspects [Ref 1] and Figure 23 of IEC 60479-2, *Effects of Current on Human Beings and Livestock, Part 2- Special Aspects*. [Ref 2] The "b line" defining the boundary between DC zones 2 and 3 for current flow periods greater than 10msec in duration is extended to the region depicting durations from 0.1msec to 10msec. The hypothetical extended "b line" depicted in Figure 5.1 has been mathematically developed by Dr. Francisco Paz based on information provided in the IEC 60479 series of standards. Details regarding the methodology used to develop the extended "b line" are discussed in the white paper, "On Extending the $Td{-}Ib$ Curve b Limit For Td Shorter Than 10ms." Rev. A0.4. 11/23/2020 By *Dr. Francisco Paz (*franciscopaz@ieee.org [Ref 22].

IEC 60479-1 [Ref 1] and IEC 60479-2 [Ref 2] together provide methods for determining effective fault current for a variety of waveforms and for plotting that effective current on a graph with zones of expected physiological effects due to current flow through the body. To assist in plotting of test results as required by Clauses 5.3 and 5.4 of this Technical Report, a software-based Random Complex Irregular Waveform Analysis (RCIWA) tool is included with this TR to ensure accurate plotting of fault test data. The theory of operation for the software-based tool is explained in Annex E.

System fault testing prescribed in Sections 5.4 or 5.5 must be completed prior to performance of transient tolerance testing prescribed in Section 6 of this TR. Fault test results derived from Section 5.4 or 5.5 (depending on system type, e.g., point to point vs. bus) shall form the baseline for a properly functioning system.

All short circuit and simulated human contact fault test cases defined in clauses 5.4 and 5.5 can either be conducted at a third-party Independent Testing Laboratory (ITL) or alternatively, they may be conducted in-house at the system manufacturer facility and audited by ITL personnel.

Proper safety precautions should be followed when conducting all system testing prescribed in this Technical Report. Tests should be conducted only by properly trained personnel. Live parts of the fault managed portions of fault managed power systems meeting the criteria set forth in this Technical Report can be safely contacted with bare hands, however, in the event that a system under test is non-compliant, the voltages and currents can be potentially hazardous. Use of appropriate personal protective equipment and proper safety precautions are highly recommended.



* Extension of "b" line below 10ms. Reference:
On Extending the $Td{-}Ib$ Curve b Limit For Td Shorter Than 10ms. Rev. A0.4. 11/23/2020
By *Dr. Francisco Paz* (franciscopaz@ieee.org)

Figure 5.1 – Simulated Human Contact Fault Current Magnitude – Duration Test Result Graph

5.1 Human Susceptibility

5.1.1 Thresholds for Voltages & Current

Through testing, various voltage and current thresholds (in conjunction with contact time) have been established as "cross-over" points for risk of human shock and safety. This Clause is based on IEC 60479, *Effects of Current on Human Beings and Livestock* [Ref 1] [Ref 2], as the most authoritative reference for current and voltage levels as well as human body resistance.

Current levels are typically determined by the voltage, the current path through the body, and the resistance of the body. Depending on the path through the body and the individual person, the typical resistance of the human body ranges from 2,000Ω to 1,000,000Ω. However, the resistance of a wet or sweaty human body (or the resistance through an open wound since the skin is the most resistive element of the body) can be as low as 500Ω to 2,000Ω [21]. The following dc voltage levels represent thresholds relevant to this document for differing physiological effects with wet-skin human body resistance as depending greatly on the current levels and body path resistances (they do not cover the increased danger to humans as voltage increases from arc flash and arc blast events associated with inadvertent metal contact):

- Below 60 V is generally classified as "extra low voltage" [8] or "ES1" [13], and will have little effect on a body (unless it is wet or has open wounds).
- 60-150 V may produce currents that result in a mild shock and muscle paralysis.
- 150-300 V may produce currents that result in severe burns and ventricular fibrillation.
- Voltages above 300 V may produce currents that result in respiratory or cardiac arrest.[7]

Voltage hazards can be line to ground when one energized conductor is contacted and the current path is from the contact point through the feet or other grounded body point, or it can be across the body when two energized conductors are contacted at separate points (such as inadvertently contacting a positive polarity conductor with one hand and inadvertently contacting a negative polarity conductor with the other hand).

5.2 Fault Current Limits

5.2.1 Human Contact Ground Faults (Hand to Foot)

System fault response criteria of DC zone 1 or 2 for fault events greater than 10 milliseconds in duration or to the left of a hypothetical extended "b line" plotted onto IEC 60479-2 [Ref 2], Figure 23 for faults less than 10 milliseconds in duration for the applicable values of human body resistance listed in Table A.1 – Total Body Resistance of Annex A have been shown to be more conservative than GR1089 Class A2 voltage limits. For additional information, see white paper entitled "Comparison Between the GR-1089 [Ref 23] Class A2 and A3, and the Proposed FEMS Requirements for Line-to-Ground Faults" [Ref 23] Rev A0.2 12/14/20 By *Dr. Francisco Paz (*franciscopaz@ieee.org).

5.2.2 Human Contact Line to Line Faults (Hand to Hand)

Line to line faults have the potential to produce greater currents than line to ground faults but are rapidly detected and limited in duration by fault managed power sources to minimize the amount of fault energy transferred during the fault event. See Clauses 5.4 and 5.5 for testing criteria designed to produce information regarding the system's fault current response to a variety of simulated human contact fault scenarios for point to point and bus system configurations. Just as in the case of line to ground faults, line to line fault response must remain in DC zone 1 or 2 defined in IEC 60479-1 [Ref 1] Figure 22, for fault events greater than 10 milliseconds in duration or to the left of a hypothetical extended "b line" plotted onto IEC 60479-2 [Ref 2], Figure 23, for faults less than 10 milliseconds in duration for the applicable values of human body resistance listed in Table A.1 – Total Body Resistance of Annex A.

5.2.3 Short Circuit Faults – Line to Ground and Line to Line

Short circuit current magnitude and duration shall be limited by fault managed power sources to ensure that the system under test does not present an arc flash hazard in the event of a line to line or line to ground short circuit condition. The magnitude and duration of short circuit current shall be limited such that it plots to the left of the

Current Magnitude – Duration Limit line for Arc Flash illustrated in Figure 5.44. Short circuit current magnitude and duration plotting to the left of the Arc Flash limit line corresponds to an incident energy level of less than 1.2 calories per square centimeter (5.021 Joules / cm^2) at a distance of eighteen inches from the point of origin of arc flash due to a short circuit.

[7] Very short duration (in the microsecond, nanosecond, or shorter range) pulses (such as those used by police in non-lethal weapons) or transient events of extremely high voltage or currents above the top levels given here may not be lethal (even though they are quite painful) because they are not long enough to cause fibrillation or excessive internal body heating.

5.3 Short Circuit Testing

Short circuit testing shall be conducted on point to point and bus configured fault managed power systems as described in clauses 5.3.1 through 5.3.3. The short circuit test requirement defined in this section is intended to demonstrate that the system under test does not present an arc flash hazard under line to line and line to ground short circuit conditions. The pass / fail criteria specified in clause 5.3.3 is based on the industry accepted incident energy level of 1.2 calories per square centimeter (5.021 Joules / cm^2) at a distance of eighteen inches from the point of origin of arc flash due to a short circuit. The incident energy level of 1.2 calories per square centimeter (5.021 Joules / cm^2) represents the lowest threshold of incident energy constituting an arc flash hazard. A passing short circuit test result is defined as a system current - time response plotting to the left of the current - duration curve for arc flash illustrated in Figure 5.44 which corresponds to an incident energy level of less than 1.2 calories per square centimeter (5.021 Joules / cm^2).

The PSE does not need to be operational after conducting short circuit testing. However, if the PSE remains operational after removal of the short circuit condition, it must be able to detect and react normally to all line to line and line to ground fault conditions. For this reason, it is recommended that short circuit testing be performed prior to conducting the simulated human contact fault testing prescribed in this Technical Report.

5.3.1 Test setup

The short circuit shall be applied at the PSE output terminals using no more than one foot of the same cable used to connect the PSE to the PD or AEN/PD combination under test. The shorting mechanism shall consist of a 1.0 milliohm shunt, appropriately rated for the maximum short circuit current that the system under test can produce. The short shall be introduced using either the TRIA circuit described in Annex D or an electro-mechanical switch with a maximum contact resistance of 0.5 milliohms and a maximum closing time, including contact bounce, of 20 milliseconds. If the TRIA circuit option is employed, the solid-state components must be sized appropriately to accommodate the magnitude and duration of short circuit current produced by the system under test.

A battery of six tests shall be conducted with the PD connected to the PSE via minimum cable length and the system operating under no load, 50% load and 100% load conditions for both line to line and line to ground short circuit situations.

Line diagrams for short circuit testing of point to point systems are shown below.

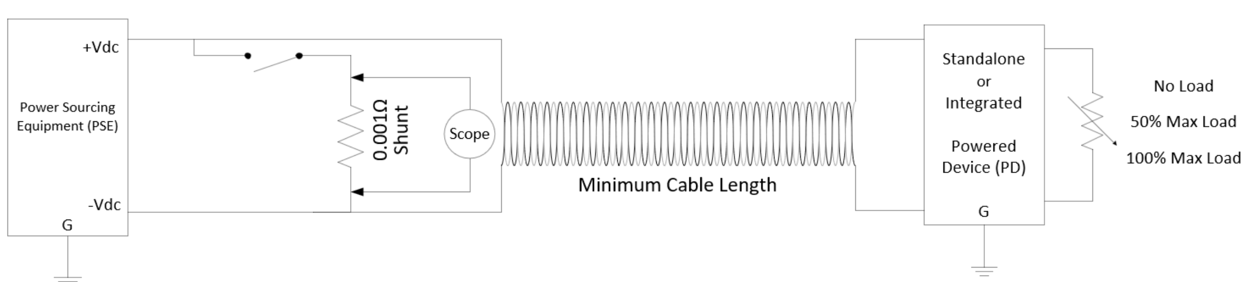


Figure 5.40 – Point to Point system configuration, Line to Line Short Circuit Test Setup

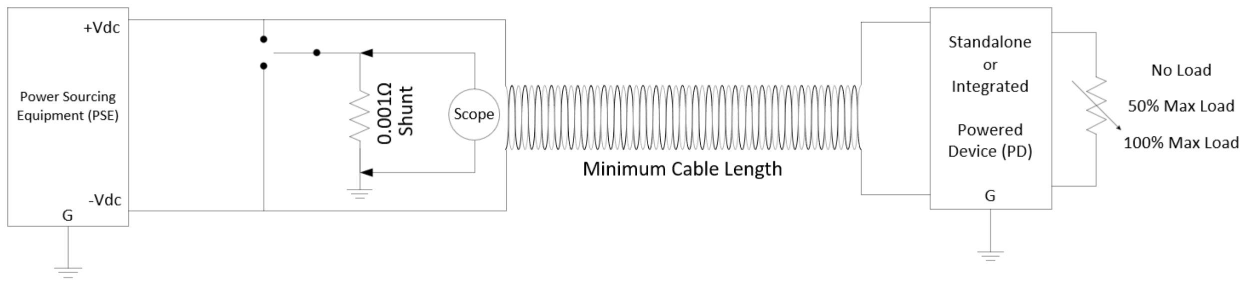


Figure 5.41 – Point to Point system configuration, Line to Ground Short Circuit Test Setup

Line diagrams for short circuit testing of bus configured systems are shown below.

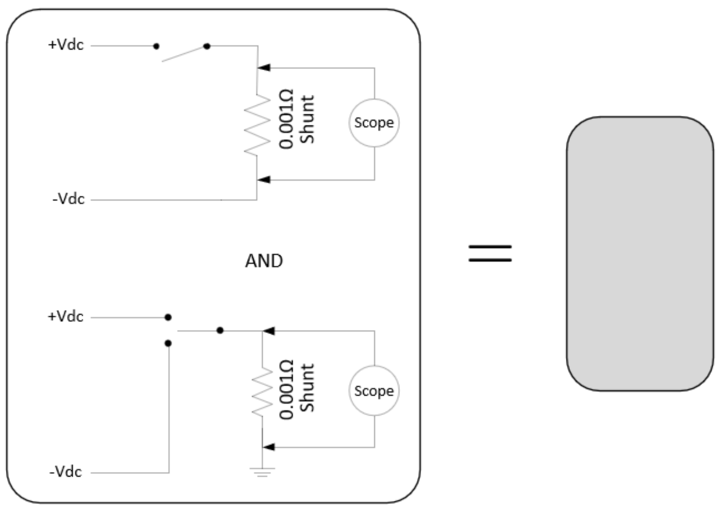


Figure 5.42 – Bus Configuration, Test Circuit Representation

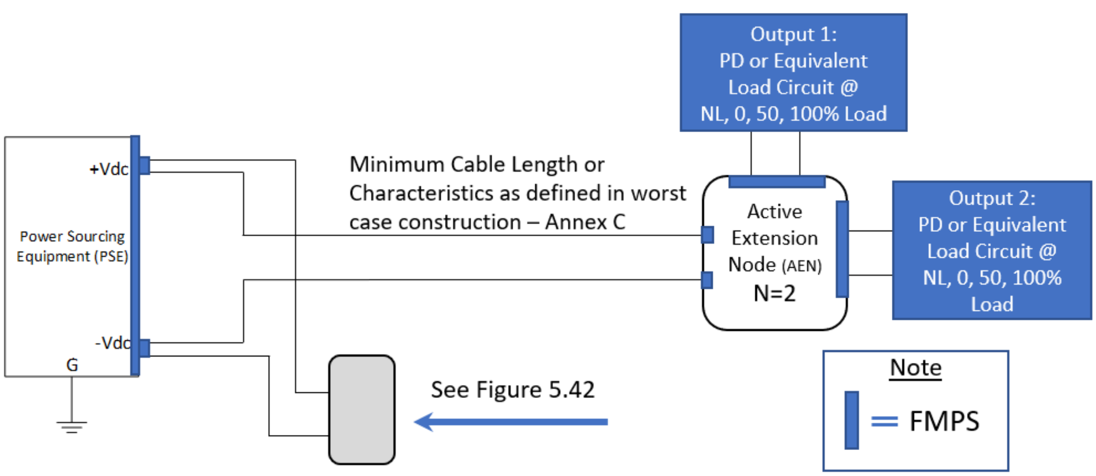


Figure 5.43 – Bus Configuration, Short Circuit Test Setup Line Diagram

5.3.2 Short circuit test data acquisition

For each short circuit test, the short shall be applied to the output terminals of the PSE. PSE output voltage shall be measured and recorded for a period of 100ms prior to insertion of the short using an oscilloscope equipped with a voltage probe meeting the minimum specifications listed in Section 4.6.2. Short circuit voltage and current waveforms shall be measured and recorded across and through the shunt respectively for a minimum period of 1.8 seconds after insertion of the short circuit. See Annex B for CSV data file requirements for recorded time, current and voltage data.

5.3.3 Short circuit data analysis

The short circuit current and voltage waveform data shall be analyzed using the Random Complex Irregular Waveform Analysis (RCIWA) tool provided with this Technical Report in the same manner in which all other simulated human contact fault test data is analyzed. As is the case with simulated human contact fault analysis, any current flow at less than 60 Volts will not be included in the test result. The software-based analysis tool will produce a pass/fail test result and a plot of the short circuit current - time data on the logarithmic graph shown in Figure 5.44. A passing test result will plot to the left of the arc flash limit line as illustrated in Figure 5.44 below. Annex G provides a detailed explanation of the assumptions and rationale behind the development of the short circuit pass/fail threshold depicted in Figure 5.44

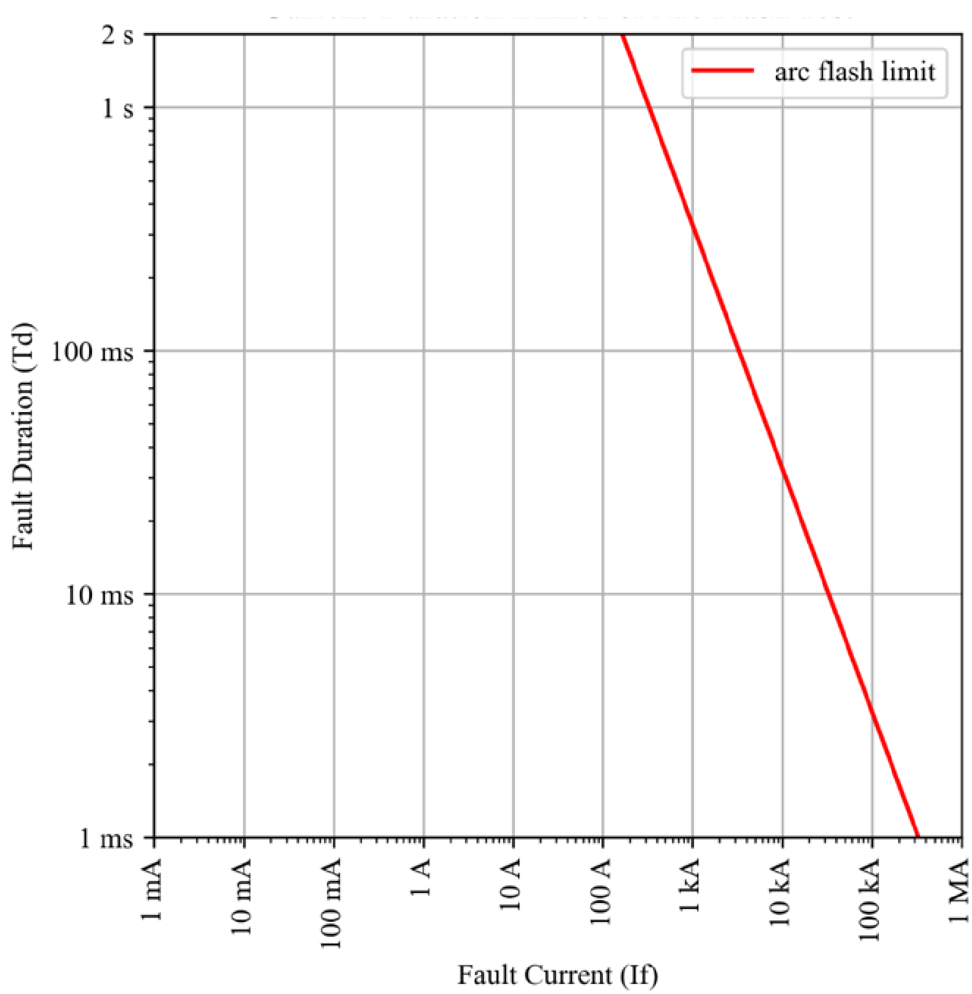


Figure 5.44 – Current Magnitude – Duration Limit for Short Circuit Testing

5.4 Fault Condition Testing – Point to Point Configurations

Point to point fault managed power system circuit configurations consist of a single PSE device connected via a length of two conductor power cable to a single PD device. The power outputs of multiple PD devices can be collected on a common bus to deliver the total magnitude of power required by the remote load. A graphical depiction of a point to point system is shown in Figure 5.2 below.

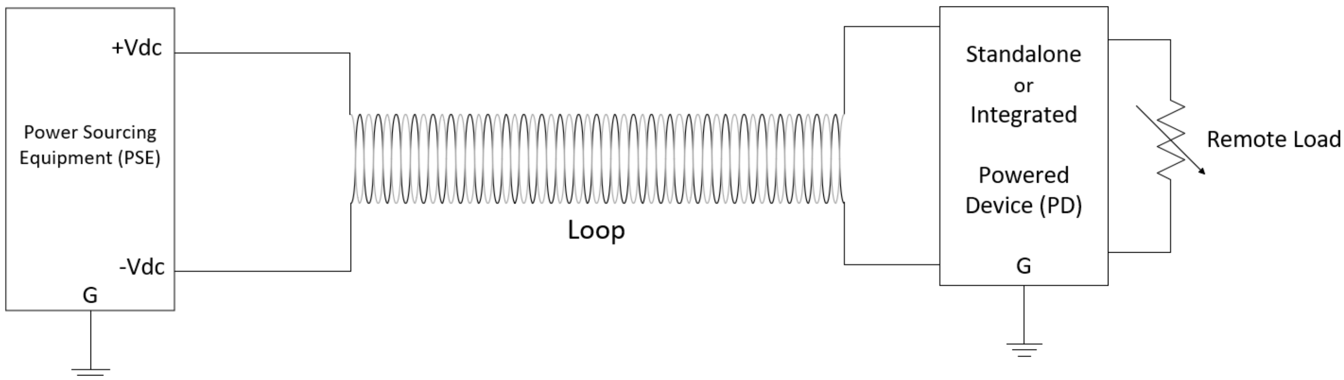


Figure 5.2 – Point to Point System Configuration

5.4.1 Testing Fault Current at the Power Sourcing Equipment output power terminals

5.4.1.1 Simulated human contact applied at the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with no loop, no PD connected

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

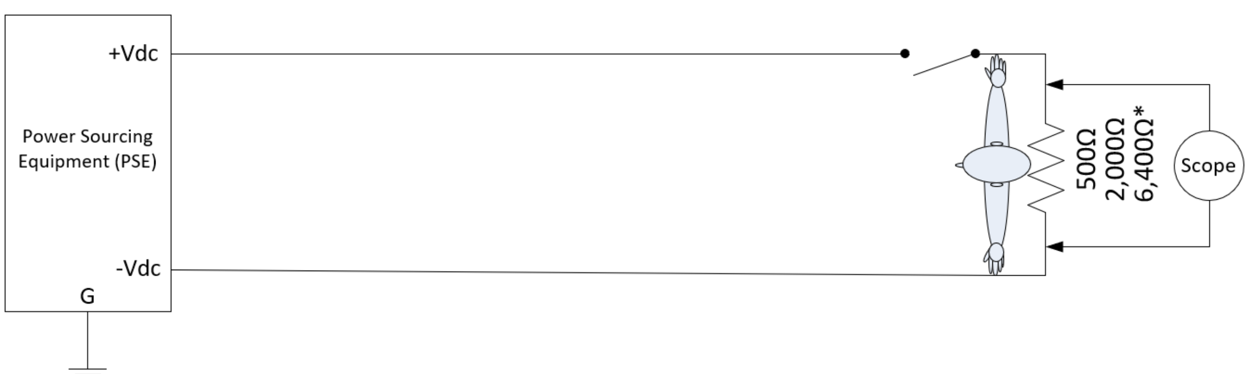


Figure 5.3 – Hand-to-Hand Contact at PSE output terminals, no loop, no PD connected

b) Positive Hand-to-foot human contact (positive line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

c) Negative Hand-to-foot human contact (negative line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

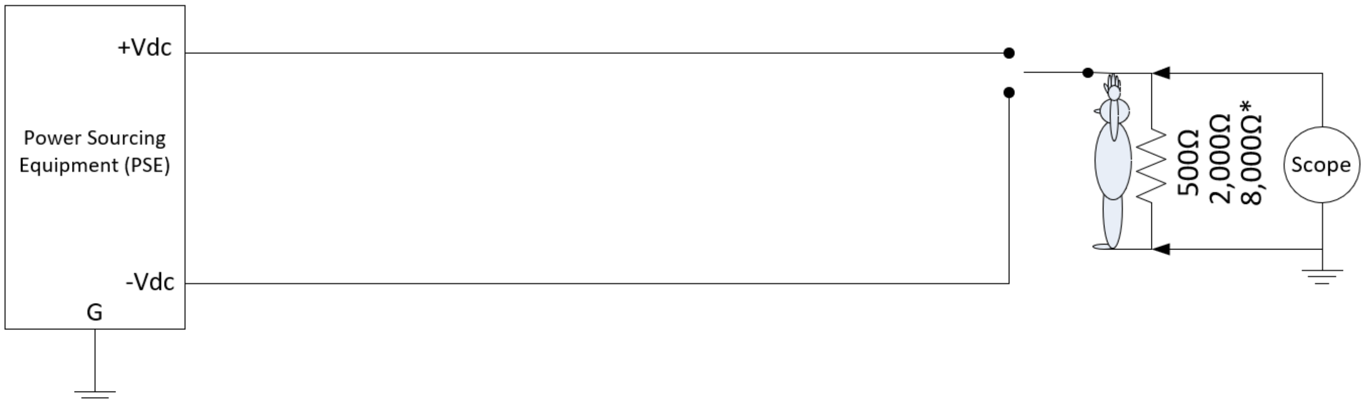


Figure 5.4 – Hand-to-Foot Contact at PSE output terminals, no loop, no PD connected

* Resistance value is touch voltage dependent and corresponds to 25mA of heart current. Refer to Table A.1, in Annex A.

5.4.1.2 Simulated human contact applied at the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with maximum length of loop cable connected, no PD connected

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE energized and stabilized for 5 seconds.

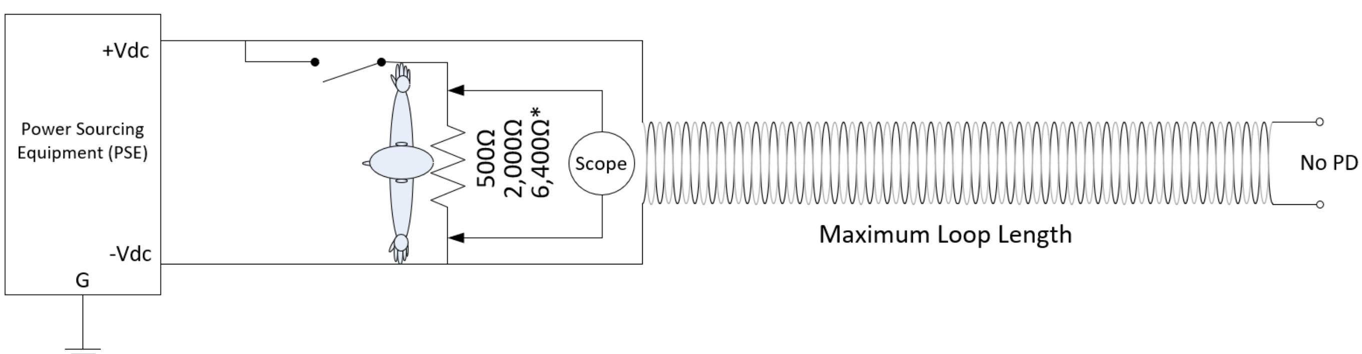


Figure 5.5 – Hand-to-Hand Contact at PSE output terminals, maximum loop, no PD connected

b) Positive hand-to-foot human contact (positive line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

c) Negative hand-to-foot human contact (negative line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

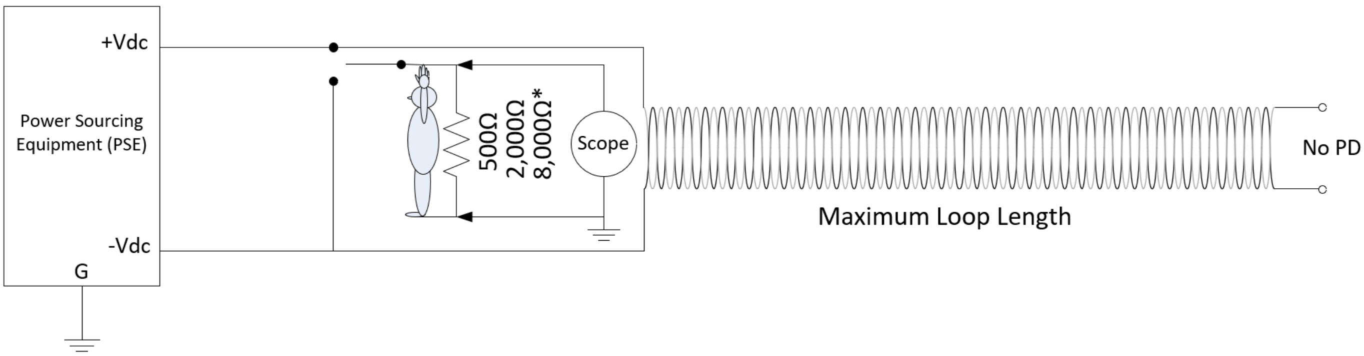


Figure 5.6 – Hand-to-Foot Contact at PSE output terminals, maximum loop, no PD connected

* Resistance value is touch voltage dependent and corresponds to 25mA of heart current. Refer to Table A.1, in Annex A.

5.4.1.3 Simulated human contact applied at the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE energized and stabilized for 5 seconds.

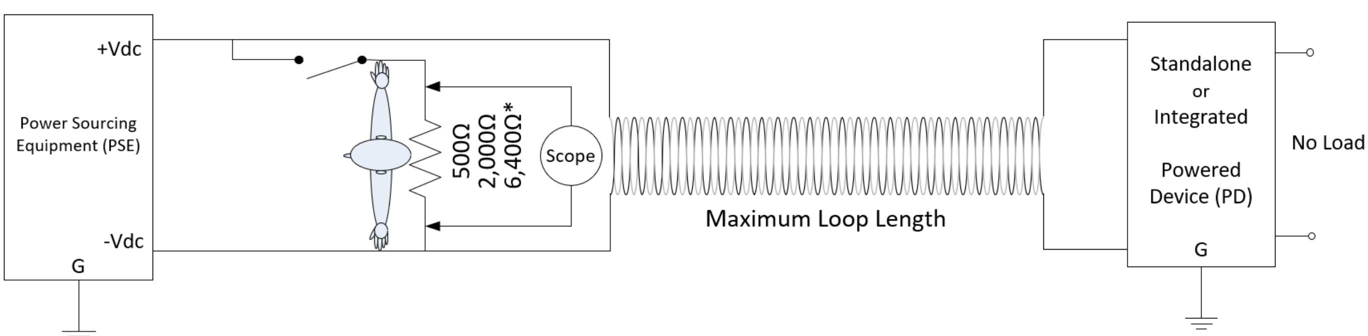


Figure 5.7 – Hand-to-Hand Contact at PSE output terminals, maximum loop, PD connected, no load

b) Positive hand-to-foot human contact (positive line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

c) Negative hand-to-foot human contact (negative line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

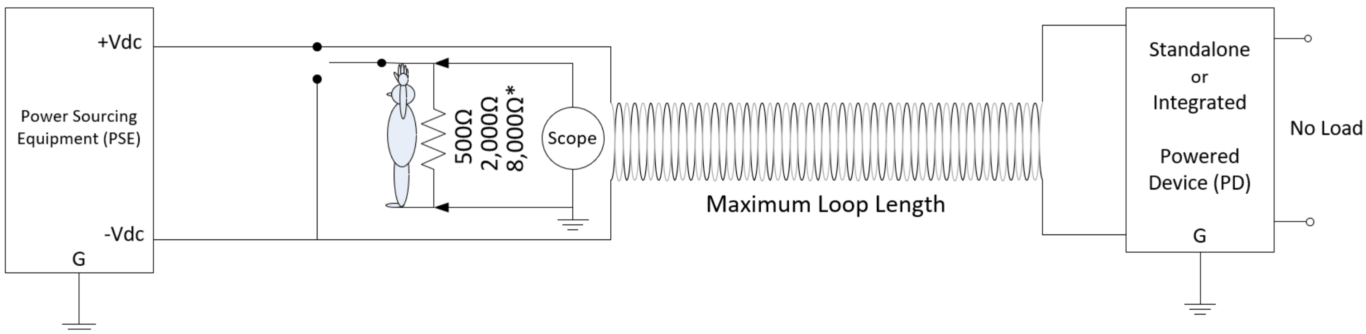


Figure 5.8 – Hand-to-Foot Contact at PSE output terminals, maximum loop, PD connected, no load

* Resistance value is touch voltage dependent and corresponds to 25mA of heart current. Refer to Table A.1, in Annex A.

5.4.1.4 Simulated human contact applied at the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, 50% of maximum load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE energized and stabilized for 5 seconds.

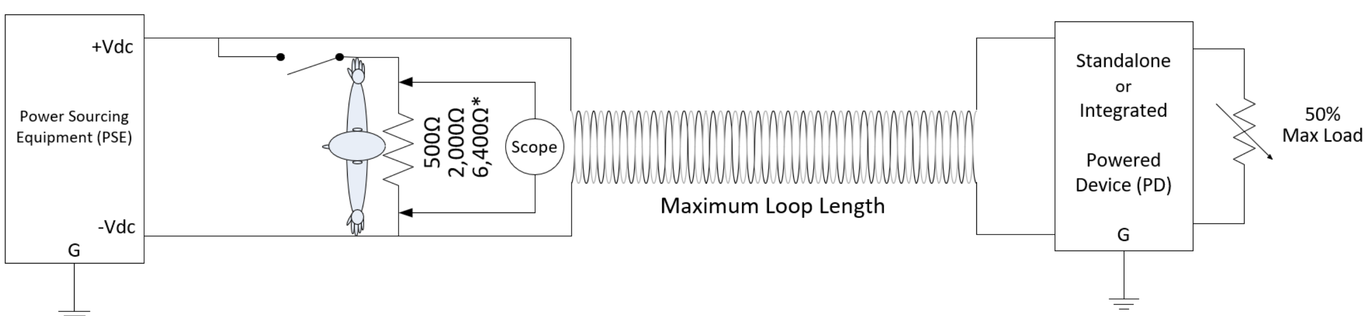


Figure 5.9 – Hand-to-Hand Contact at PSE output terminals, maximum loop, PD connected, 50% load

b) Positive hand-to-foot human contact (positive line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

c) Negative hand-to-foot human contact (negative line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

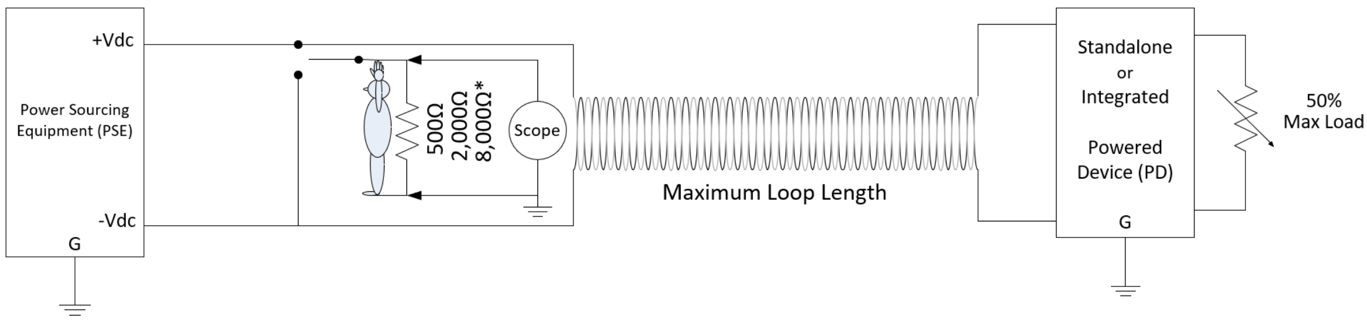


Figure 5.10 – Hand-to-Foot Contact at PSE output terminals, maximum loop, PD connected, 50% load

* Resistance value is touch voltage dependent and corresponds to 25mA of heart current. Refer to Table A.1, in Annex A.

5.4.1.5 Simulated human contact applied at the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, 100% of maximum load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE energized and stabilized for 5 seconds.

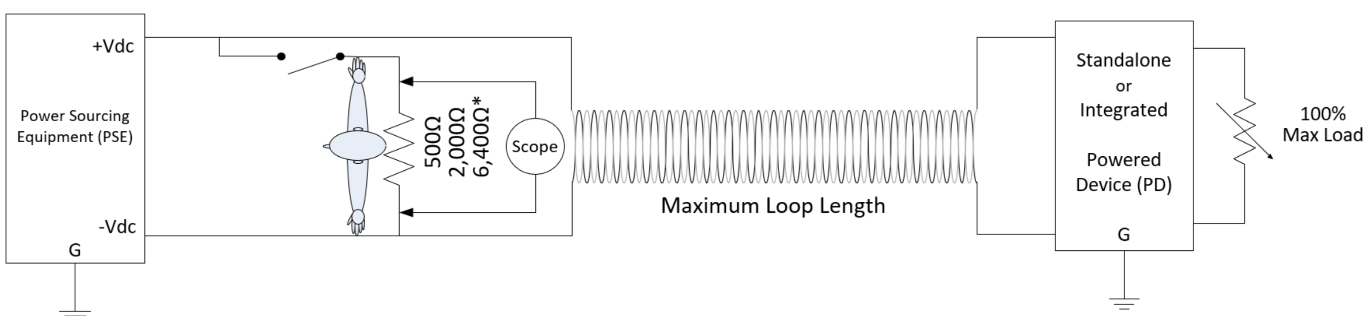


Figure 5.11 – Hand-to-Hand Contact at PSE output terminals, maximum loop, PD connected, 100% load

b) Positive hand-to-foot human contact (positive line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

c) Negative hand-to-foot human contact (negative line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

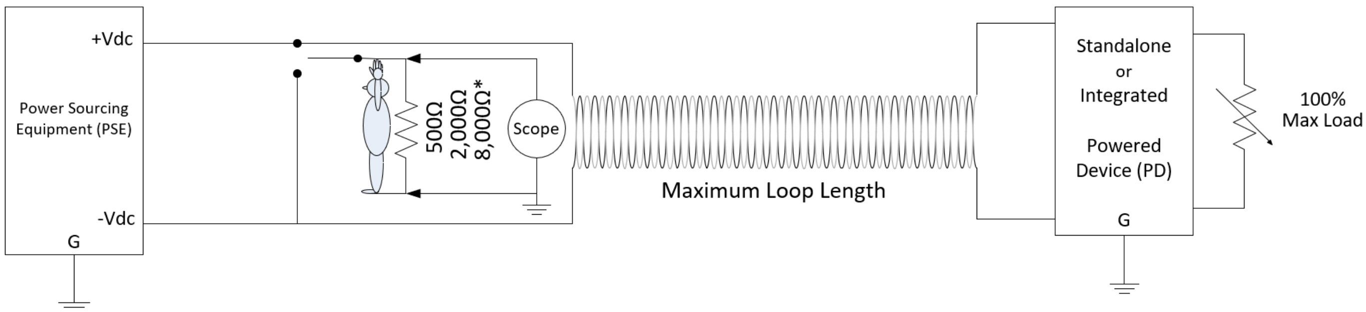


Figure 5.12 – Hand-to-Foot Contact at PSE output terminals, maximum loop, PD connected, 100% load

* Resistance value is touch voltage dependent and corresponds to 25mA of heart current. Refer to Table A.1, in Annex A.

5.4.2 Testing Fault Current, Mid-Span

(33% to 67% of maximum loop length specified by the manufacturer)

5.4.2.1 Simulated human contact applied at Mid-Span via less than 10 ft of test cable with maximum loop length connected, no PD connected

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

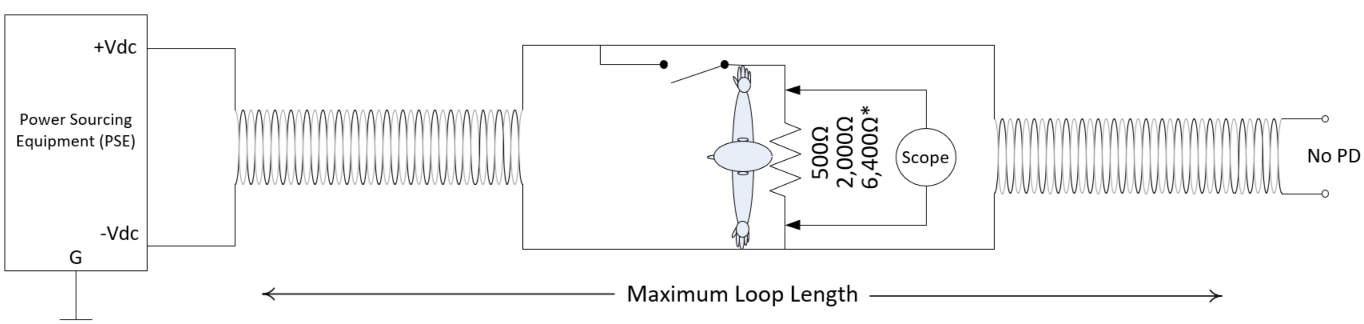


Figure 5.13 – Hand-to-Hand Contact at Mid-Span, maximum loop, no PD connected

b) Positive hand-to-foot human contact (positive line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

c) Negative hand-to-foot human contact (negative line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

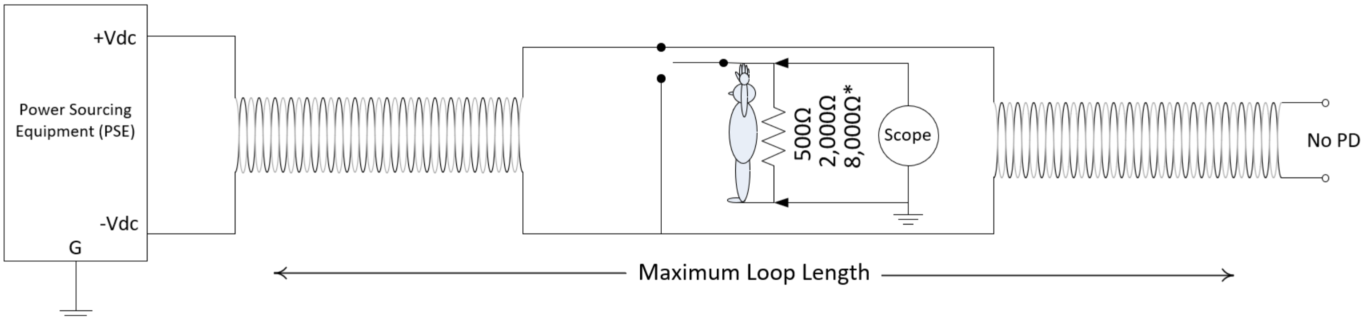


Figure 5.14 – Hand-to-Foot Contact at Mid-Span, maximum loop, no PD connected

* Resistance value is touch voltage dependent and corresponds to 25mA of heart current.
Refer to Table A.1, in Annex A.

5.4.2.2 Simulated human contact applied at Mid-Span via less than 10 ft of test cable with maximum loop length connected, PD connected, no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

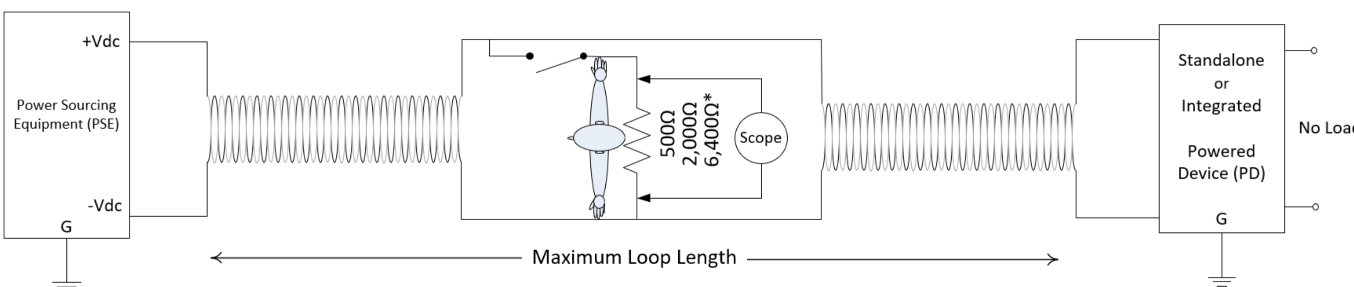


Figure 5.15 – Hand-to-Hand Contact at Mid-Span, maximum loop, PD connected, no load

b) Positive hand-to-foot human contact (positive line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

c) Negative hand-to-foot human contact (negative line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

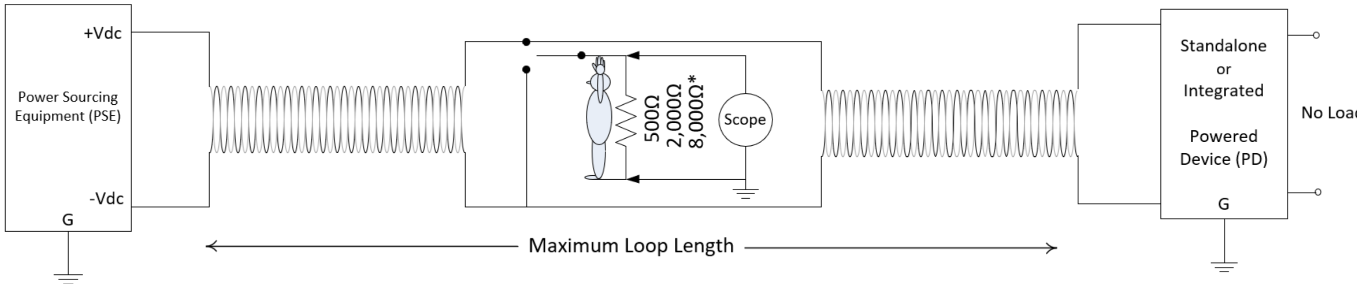


Figure 5.16 – Hand-to-Foot Contact at Mid-Span, maximum loop, PD connected, no load

* Resistance value is touch voltage dependent and corresponds to 25mA of heart current. Refer to Table A.1, in Annex A.

5.4.2.3 Simulated human contact applied at Mid-Span via less than 10 ft of test cable with maximum loop length connected, PD connected, 50% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

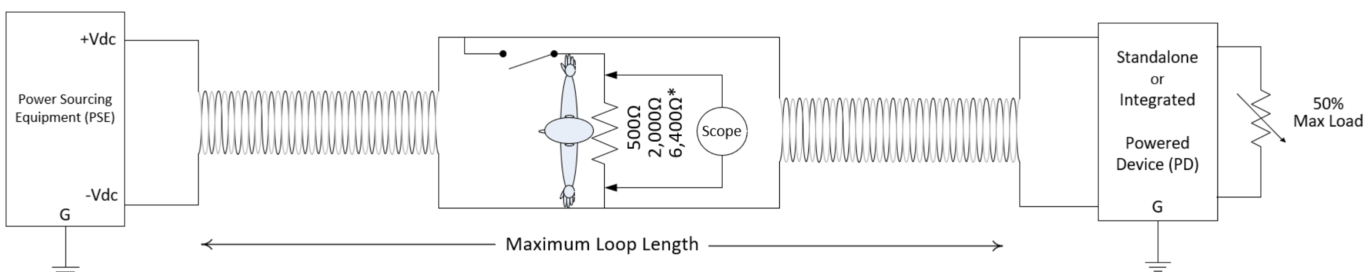


Figure 5.17 – Hand-to-Hand Contact at Mid-Span, maximum loop, PD connected, 50% load

b) Positive hand-to-foot human contact (positive line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

c) Negative hand-to-foot human contact (negative line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

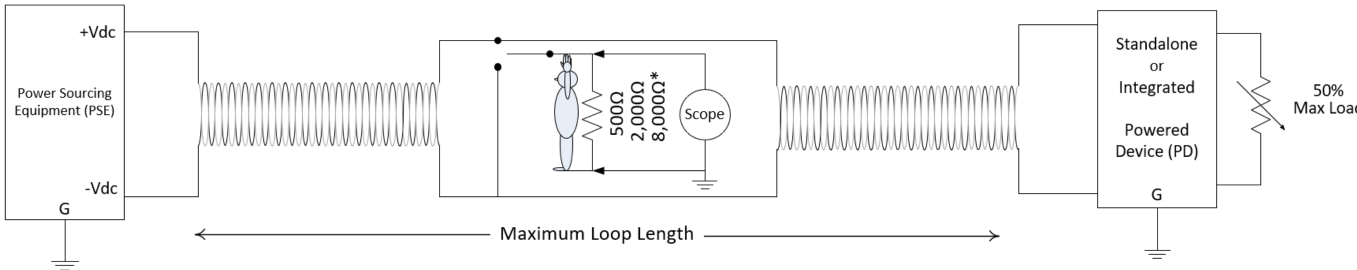


Figure 5.18 – Hand-to-Foot Contact at Mid-Span, maximum loop, PD connected, 50% load

* Resistance value is touch voltage dependent and corresponds to 25mA of heart current. Refer to Table A.1, in Annex A.

5.4.2.4 Simulated human contact applied at Mid-Span via less than 10 ft of test cable with maximum loop length connected, PD connected, 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

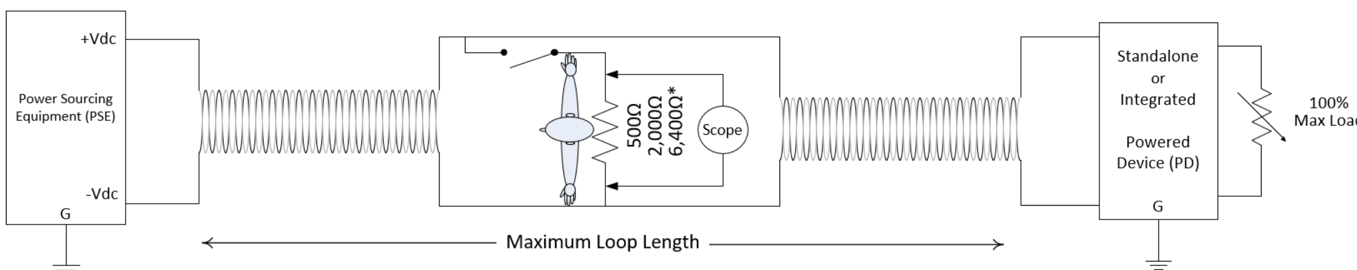


Figure 5.19 – Hand-to-Hand Contact at Mid-Span, maximum loop, PD connected, 100% load

b) Positive hand-to-foot human contact (positive line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

c) Negative hand-to-foot human contact (negative line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

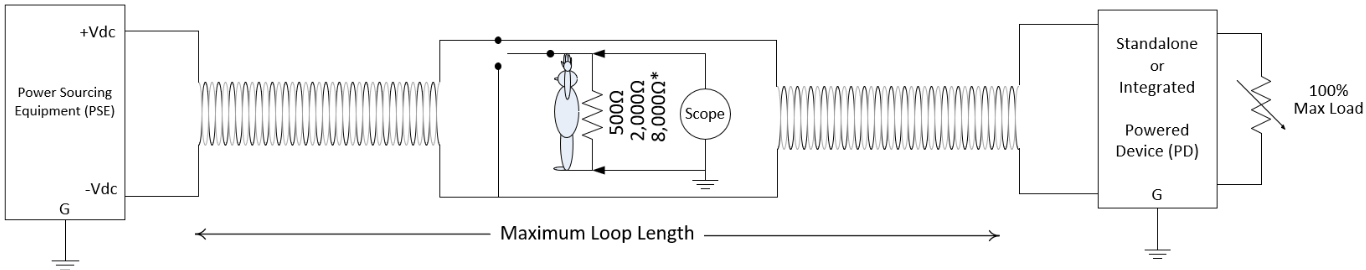


Figure 5.20 – Hand-to-Foot Contact at Mid-Span, maximum loop, PD connected, 100% load

* Resistance value is touch voltage dependent and corresponds to 25mA of heart current. Refer to Table A.1, in Annex A.

5.4.3 Testing Fault Current at the Powered Device input power terminals

5.4.3.1 Simulated human contact applied at remote end of loop via less than 10 ft of test cable with maximum loop length connected, no PD connected

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

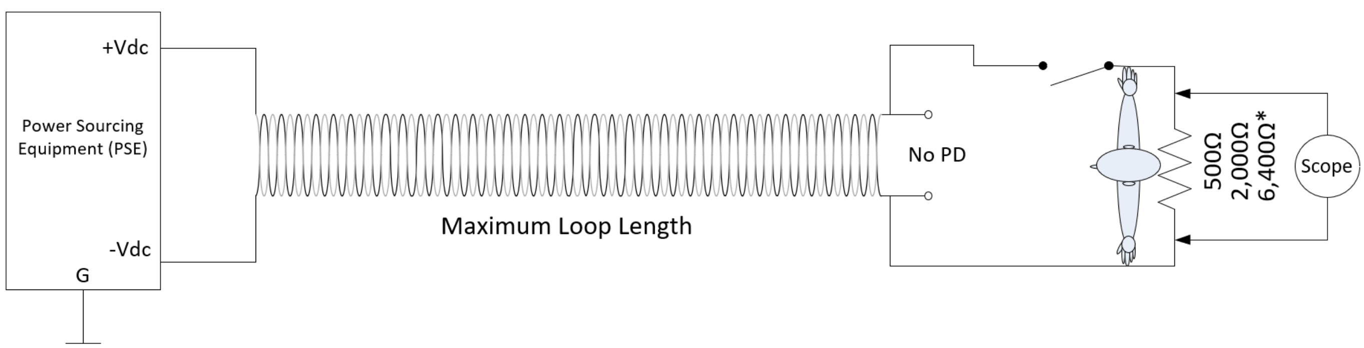


Figure 5.21 – Hand-to-Hand Contact at remote end of maximum loop, no PD

b) Positive hand-to-foot human contact (positive line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

c) Negative hand-to-foot human contact (negative line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

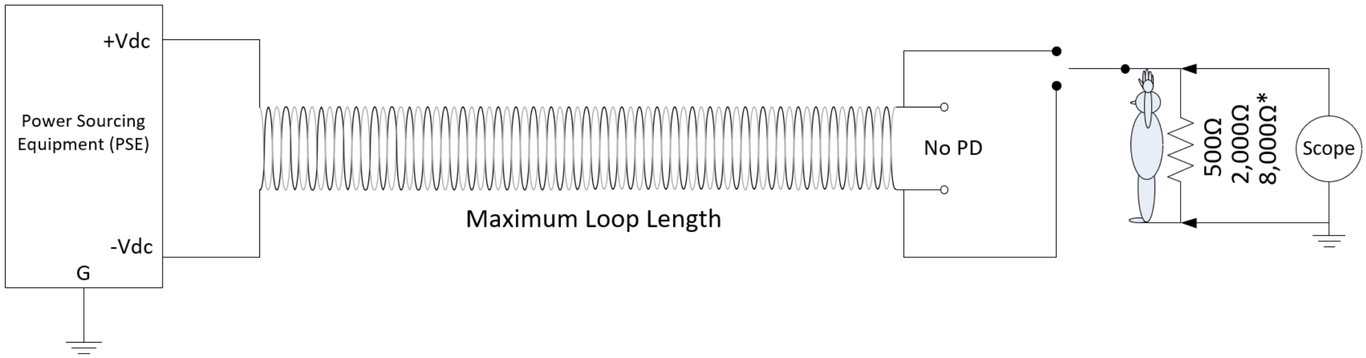


Figure 5.22 – Hand-to-Foot Contact at remote end of maximum loop, no PD

* Resistance value is touch voltage dependent and corresponds to 25mA of heart current.
Refer to Table A.1, in Annex A.

5.4.3.2 Simulated human contact applied at PD input terminals via less than 10 ft of test cable with maximum loop length connected, PD connected, no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

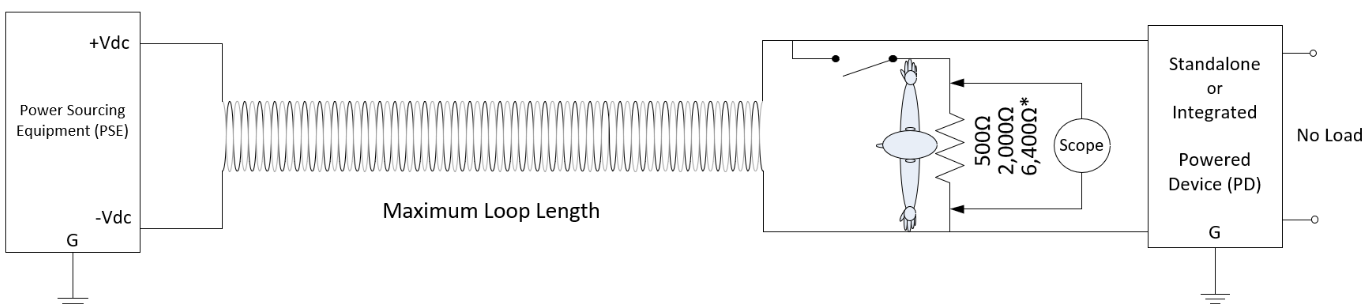


Figure 5.23 – Hand-to-Hand Contact at PD input terminals, maximum loop, PD connected, no load

b) Positive hand-to-foot human contact (positive line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

c) Negative hand-to-foot human contact (negative line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

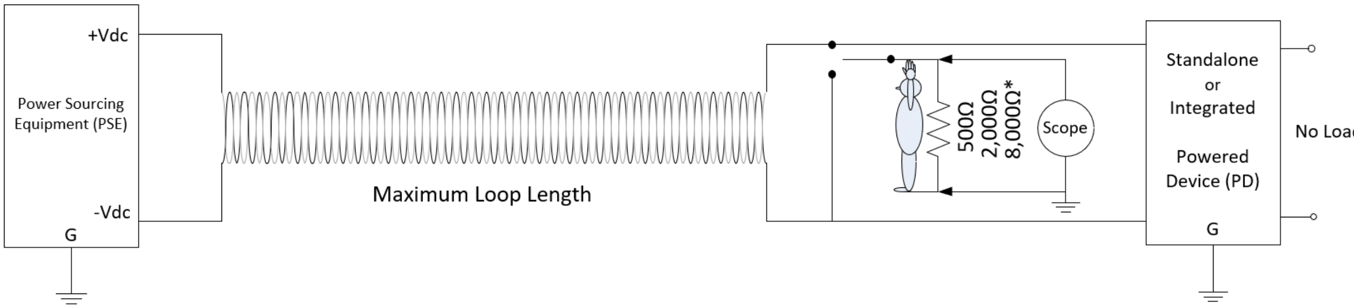


Figure 5.24 – Hand-to-Foot Contact at PD input terminals, maximum loop, PD connected, no load

* Resistance value is touch voltage dependent and corresponds to 25mA of heart current. Refer to Table A.1, in Annex A.

5.4.3.3 Simulated human contact applied at PD input terminals via less than 10 ft of test cable with maximum loop length connected, PD connected, 50% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

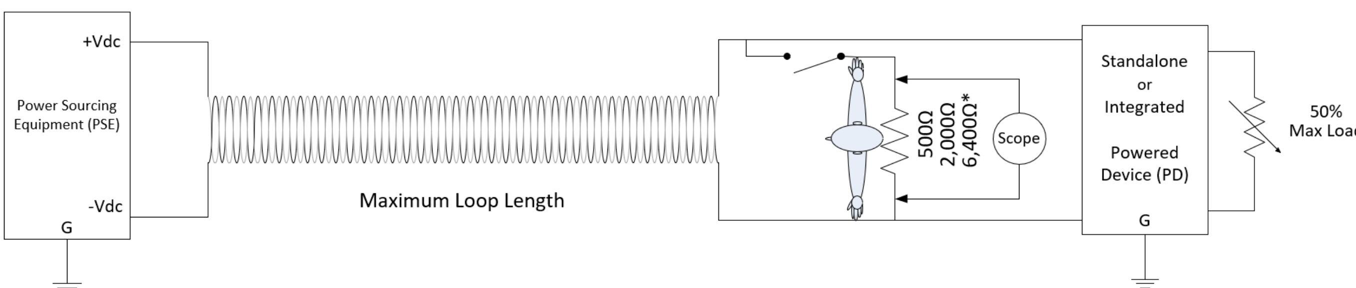


Figure 5.25 – Hand-to-Hand Contact at PD input terminals, maximum loop, PD connected, 50% load

b) Positive hand-to-foot human contact (positive line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

c) Negative hand-to-foot human contact (negative line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

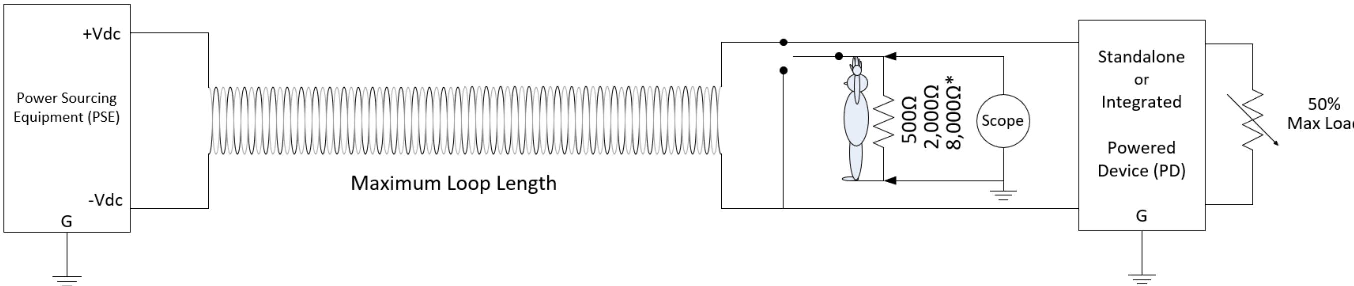


Figure 5.26 – Hand-to-Foot Contact at PD input terminals, maximum loop, PD connected, 50% load

* Resistance value is touch voltage dependent and corresponds to 25mA of heart current.
Refer to Table A.1, in Annex A.

5.4.3.4 Simulated human contact applied at PD input terminals via less than 10 ft of test cable with maximum loop length connected, PD connected, 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

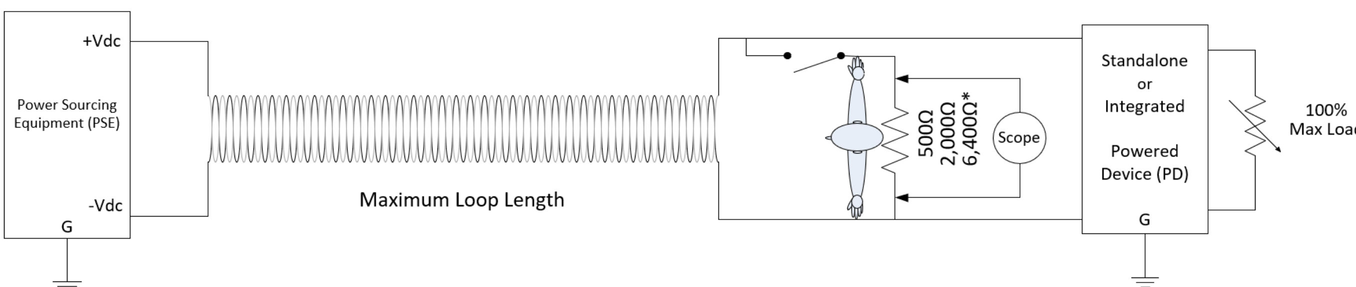


Figure 5.27 – Hand-to-Hand Contact at PD input terminals, maximum loop, PD connected, 100% load

b) Positive hand-to-foot human contact (positive line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

c) Negative hand-to-foot human contact (negative line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

1. Application of total body resistances prior to turn up of PSE.
2. Application of total body resistances after PSE is energized and stabilized for 5 seconds.

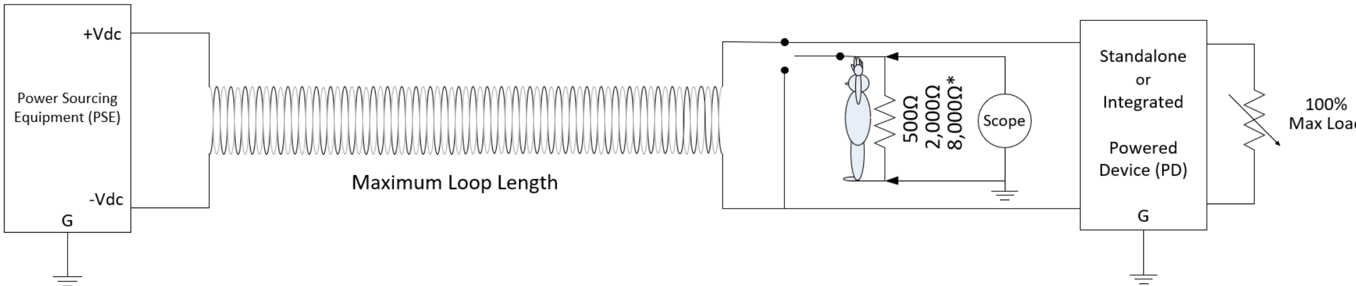


Figure 5.28 – Hand-to-Foot Contact at PD input terminals, maximum loop, PD connected, 100% load

* Resistance value is touch voltage dependent and corresponds to 25mA of heart current. Refer to Table A.1, in Annex A.

5.4.4 Point to Point Fault Test Case Tables

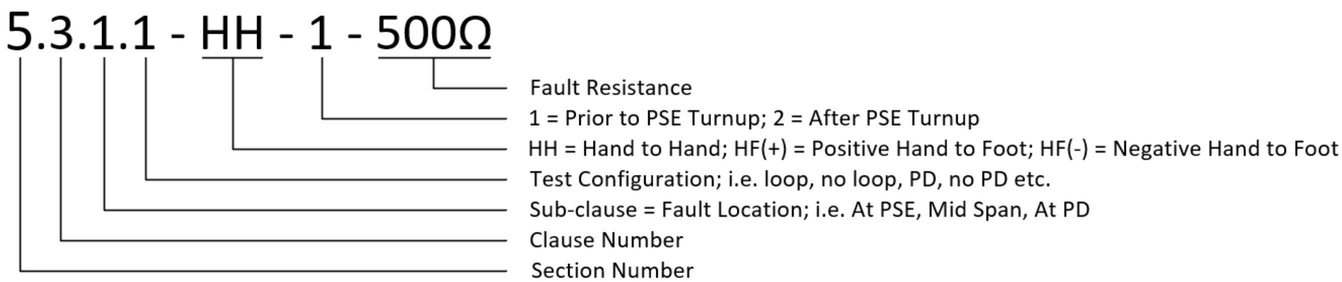


Figure 5.29 – Point to Point Test Case Numbering Convention

Table 5.1 - Fault at PSE - No loop connected

	Faults applied at the PSE - No loop connected					
Test Case	**Hand to Hand** (L to L) **prior to** PSE turn up			**Hand to Hand** (L to L) **after** PSE turn up		
5.3.1.1 - HH - 1 - 500Ω	500Ω					
5.3.1.1 - HH - 1 - 2,000Ω		2,000Ω				
5.3.1.1 - HH - 1 - 6,400Ω			6,400Ω*			
5.3.1.1 - HH - 2 - 500Ω				500Ω		
5.3.1.1 - HH - 2 - 2,000Ω					2,000Ω	
5.3.1.1 - HH - 2 - 6,400Ω						6,400Ω*
Test Case	**Hand to Foot** (+L to G) **prior to** PSE turn up			**Hand to Foot** (+L to G) **after** PSE turn up		
5.3.1.1 - HF(+) - 1 - 500Ω	500Ω					
5.3.1.1 - HF(+) - 1 - 2,000Ω		2,000Ω				
5.3.1.1 - HF(+) - 1 - 8,000Ω			8,000Ω*			
5.3.1.1 - HF(+) - 2 - 500Ω				500Ω		
5.3.1.1 - HF(+) - 2 - 2,000Ω					2,000Ω	
5.3.1.1 - HF(+) - 2 - 8,000Ω						8,000Ω*
Test Case	**Hand to Foot** (-L to G) **prior to** PSE turn up			**Hand to Foot** (-L to G) **after** PSE turn up		
5.3.1.1 - HF(-) - 1 - 500Ω	500Ω					
5.3.1.1 - HF(-) - 1 - 2,000Ω		2,000Ω				
5.3.1.1 - HF(-) - 1 - 8,000Ω			8,000Ω*			
5.3.1.1 - HF(-) - 2 - 500Ω				500Ω		
5.3.1.1 - HF(-) - 2 - 2,000Ω					2,000Ω	
5.3.1.1 - HF(-) - 2 - 8,000Ω						8,000Ω*

Table 5.2 - Fault at PSE - Maximum loop connected, no PD

	Faults applied at the PSE - Maximum loop connected, no PD					
Test Case	**Hand to Hand** (L to L) **prior to** PSE turn up			**Hand to Hand** (L to L) **after** PSE turn up		
5.3.1.2 - HH - 1 - 500Ω	500Ω					
5.3.1.2 - HH - 1 - 2,000Ω		2,000Ω				
5.3.1.2 - HH - 1 - 6,400Ω			6,400Ω*			
5.3.1.2 - HH - 2 - 500Ω				500Ω		
5.3.1.2 - HH - 2 - 2,000Ω					2,000Ω	
5.3.1.2 - HH - 2 - 6,400Ω						6,400Ω*
Test Case	**Hand to Foot** (+L to G) **prior to** PSE turn up			**Hand to Foot** (+L to G) **after** PSE turn up		
5.3.1.2 - HF(+) - 1 - 500Ω	500Ω					
5.3.1.2 - HF(+) - 1 - 2,000Ω		2,000Ω				
5.3.1.2 - HF(+) - 1 - 8,000Ω			8,000Ω*			
5.3.1.2 - HF(+) - 2 - 500Ω				500Ω		
5.3.1.2 - HF(+) - 2 - 2,000Ω					2,000Ω	
5.3.1.2 - HF(+) - 2 - 8,000Ω						8,000Ω*
Test Case	**Hand to Foot** (-L to G) **prior to** PSE turn up			**Hand to Foot** (-L to G) **after** PSE turn up		
5.3.1.2 - HF(-) - 1 - 500Ω	500Ω					
5.3.1.2 - HF(-) - 1 - 2,000Ω		2,000Ω				
5.3.1.2 - HF(-) - 1 - 8,000Ω			8,000Ω*			
5.3.1.2 - HF(-) - 2 - 500Ω				500Ω		
5.3.1.2 - HF(-) - 2 - 2,000Ω					2,000Ω	
5.3.1.2 - HF(-) - 2 - 8,000Ω						8,000Ω*

Table 5.3 - Fault at PSE – Maximum loop & PD connected, no load

	Faults applied at the PSE - Maximum loop & PD connected, no load					
Test Case	**Hand to Hand** (L to L) **prior to** PSE turn up			**Hand to Hand** (L to L) **after** PSE turn up		
5.3.1.3 - HH - 1 - 500Ω	500Ω					
5.3.1.3 - HH - 1 - 2,000Ω		2,000Ω				
5.3.1.3 - HH - 1 - 6,400Ω			6,400Ω*			
5.3.1.3 - HH - 2 - 500Ω				500Ω		
5.3.1.3 - HH - 2 - 2,000Ω					2,000Ω	
5.3.1.3 - HH - 2 - 6,400Ω						6,400Ω*
Test Case	**Hand to Foot** (+L to G) **prior to** PSE turn up			**Hand to Foot** (+L to G) **after** PSE turn up		
5.3.1.3 - HF(+) - 1 - 500Ω	500Ω					
5.3.1.3 - HF(+) - 1 - 2,000Ω		2,000Ω				
5.3.1.3 - HF(+) - 1 - 8,000Ω			8,000Ω*			
5.3.1.3 - HF(+) - 2 - 500Ω				500Ω		
5.3.1.3 - HF(+) - 2 - 2,000Ω					2,000Ω	
5.3.1.3 - HF(+) - 2 - 8,000Ω						8,000Ω*
Test Case	**Hand to Foot** (-L to G) **prior to** PSE turn up			**Hand to Foot** (-L to G) **after** PSE turn up		
5.3.1.3 - HF(-) - 1 - 500Ω	500Ω					
5.3.1.3 - HF(-) - 1 - 2,000Ω		2,000Ω				
5.3.1.3 - HF(-) - 1 - 8,000Ω			8,000Ω*			
5.3.1.3 - HF(-) - 2 - 500Ω				500Ω		
5.3.1.3 - HF(-) - 2 - 2,000Ω					2,000Ω	
5.3.1.3 - HF(-) - 2 - 8,000Ω						8,000Ω*

Table 5.4 - Fault at PSE – Maximum loop & PD connected, 50% load

	Faults applied at the PSE - Maximum loop & PD connected, 50% load					
Test Case	**Hand to Hand** (L to L) **prior to** PSE turn up			**Hand to Hand** (L to L) **after** PSE turn up		
5.3.1.4 - HH - 1 - 500Ω	500Ω					
5.3.1.4 - HH - 1 - 2,000Ω		2,000Ω				
5.3.1.4 - HH - 1 - 6,400Ω			6,400Ω*			
5.3.1.4 - HH - 2 - 500Ω				500Ω		
5.3.1.4 - HH - 2 - 2,000Ω					2,000Ω	
5.3.1.4 - HH - 2 - 6,400Ω						6,400Ω*
Test Case	**Hand to Foot** (+L to G) **prior to** PSE turn up			**Hand to Foot** (+L to G) **after** PSE turn up		
5.3.1.4 - HF(+) - 1 - 500Ω	500Ω					
5.3.1.4 - HF(+) - 1 - 2,000Ω		2,000Ω				
5.3.1.4 - HF(+) - 1 - 8,000Ω			8,000Ω*			
5.3.1.4 - HF(+) - 2 - 500Ω				500Ω		
5.3.1.4 - HF(+) - 2 - 2,000Ω					2,000Ω	
5.3.1.4 - HF(+) - 2 - 8,000Ω						8,000Ω*
Test Case	**Hand to Foot** (-L to G) **prior to** PSE turn up			**Hand to Foot** (-L to G) **after** PSE turn up		
5.3.1.4 - HF(-) - 1 - 500Ω	500Ω					
5.3.1.4 - HF(-) - 1 - 2,000Ω		2,000Ω				
5.3.1.4 - HF(-) - 1 - 8,000Ω			8,000Ω*			
5.3.1.4 - HF(-) - 2 - 500Ω				500Ω		
5.3.1.4 - HF(-) - 2 - 2,000Ω					2,000Ω	
5.3.1.4 - HF(-) - 2 - 8,000Ω						8,000Ω*

Table 5.5 - Fault at PSE - Maximum loop & PD connected, 100% load

	Faults applied at the PSE - Maximum loop & PD connected, 100% load					
Test Case	**Hand to Hand** (L to L) **prior to** PSE turn up			**Hand to Hand** (L to L) **after** PSE turn up		
5.3.1.5 - HH - 1 - 500Ω	500Ω					
5.3.1.5 - HH - 1 - 2,000Ω		2,000Ω				
5.3.1.5 - HH - 1 - 6,400Ω			6,400Ω*			
5.3.1.5 - HH - 2 - 500Ω				500Ω		
5.3.1.5 - HH - 2 - 2,000Ω					2,000Ω	
5.3.1.5 - HH - 2 - 6,400Ω						6,400Ω*
Test Case	**Hand to Foot** (+L to G) **prior to** PSE turn up			**Hand to Foot** (+L to G) **after** PSE turn up		
5.3.1.5 - HF(+) - 1 - 500Ω	500Ω					
5.3.1.5 - HF(+) - 1 - 2,000Ω		2,000Ω				
5.3.1.5 - HF(+) - 1 - 8,000Ω			8,000Ω*			
5.3.1.5 - HF(+) - 2 - 500Ω				500Ω		
5.3.1.5 - HF(+) - 2 - 2,000Ω					2,000Ω	
5.3.1.5 - HF(+) - 2 - 8,000Ω						8,000Ω*
Test Case	**Hand to Foot** (-L to G) **prior to** PSE turn up			**Hand to Foot** (-L to G) **after** PSE turn up		
5.3.1.5 - HF(-) - 1 - 500Ω	500Ω					
5.3.1.5 - HF(-) - 1 - 2,000Ω		2,000Ω				
5.3.1.5 - HF(-) - 1 - 8,000Ω			8,000Ω*			
5.3.1.5 - HF(-) - 2 - 500Ω				500Ω		
5.3.1.5 - HF(-) - 2 - 2,000Ω					2,000Ω	
5.3.1.5 - HF(-) - 2 - 8,000Ω						8,000Ω*

Table 5.6 - Fault at Mid Span - Maximum loop connected, no PD

	Faults applied at Mid Span - Maximum loop connected, no PD					
Test Case	**Hand to Hand** (L to L) **prior to** PSE turn up			**Hand to Hand** (L to L) **after** PSE turn up		
5.3.2.1 - HH - 1 - 500Ω	500Ω					
5.3.2.1 - HH - 1 - 2,000Ω		2,000Ω				
5.3.2.1 - HH - 1 - 6,400Ω			6,400Ω*			
5.3.2.1 - HH - 2 - 500Ω				500Ω		
5.3.2.1 - HH - 2 - 2,000Ω					2,000Ω	
5.3.2.1 - HH - 2 - 6,400Ω						6,400Ω*
Test Case	**Hand to Foot** (+L to G) **prior to** PSE turn up			**Hand to Foot** (+L to G) **after** PSE turn up		
5.3.2.1 - HF(+) - 1 - 500Ω	500Ω					
5.3.2.1 - HF(+) - 1 - 2,000Ω		2,000Ω				
5.3.2.1 - HF(+) - 1 - 8,000Ω			8,000Ω*			
5.3.2.1 - HF(+) - 2 - 500Ω				500Ω		
5.3.2.1 - HF(+) - 2 - 2,000Ω					2,000Ω	
5.3.2.1 - HF(+) - 2 - 8,000Ω						8,000Ω*
Test Case	**Hand to Foot** (-L to G) **prior to** PSE turn up			**Hand to Foot** (-L to G) **after** PSE turn up		
5.3.2.1 - HF(-) - 1 - 500Ω	500Ω					
5.3.2.1 - HF(-) - 1 - 2,000Ω		2,000Ω				
5.3.2.1 - HF(-) - 1 - 8,000Ω			8,000Ω*			
5.3.2.1 - HF(-) - 2 - 500Ω				500Ω		
5.3.2.1 - HF(-) - 2 - 2,000Ω					2,000Ω	
5.3.2.1 - HF(-) - 2 - 8,000Ω						8,000Ω*

Table 5.7 - Fault at Mid Span – Maximum loop & PD connected, no load

	Faults applied at Mid Span - Maximum loop & PD connected, no load					
Test Case	**Hand to Hand** (L to L) **prior to** PSE turn up			**Hand to Hand** (L to L) **after** PSE turn up		
5.3.2.2 - HH - 1 - 500Ω	500Ω					
5.3.2.2 - HH - 1 - 2,000Ω		2,000Ω				
5.3.2.2 - HH - 1 - 6,400Ω			6,400Ω*			
5.3.2.2 - HH - 2 - 500Ω				500Ω		
5.3.2.2 - HH - 2 - 2,000Ω					2,000Ω	
5.3.2.2 - HH - 2 - 6,400Ω						6,400Ω*
Test Case	**Hand to Foot** (+L to G) **prior to** PSE turn up			**Hand to Foot** (+L to G) **after** PSE turn up		
5.3.2.2 - HF(+) - 1 - 500Ω	500Ω					
5.3.2.2 - HF(+) - 1 - 2,000Ω		2,000Ω				
5.3.2.2 - HF(+) - 1 - 8,000Ω			8,000Ω*			
5.3.2.2 - HF(+) - 2 - 500Ω				500Ω		
5.3.2.2 - HF(+) - 2 - 2,000Ω					2,000Ω	
5.3.2.2 - HF(+) - 2 - 8,000Ω						8,000Ω*
Test Case	**Hand to Foot** (-L to G) **prior to** PSE turn up			**Hand to Foot** (-L to G) **after** PSE turn up		
5.3.2.2 - HF(-) - 1 - 500Ω	500Ω					
5.3.2.2 - HF(-) - 1 - 2,000Ω		2,000Ω				
5.3.2.2 - HF(-) - 1 - 8,000Ω			8,000Ω*			
5.3.2.2 - HF(-) - 2 - 500Ω				500Ω		
5.3.2.2 - HF(-) - 2 - 2,000Ω					2,000Ω	
5.3.2.2 - HF(-) - 2 - 8,000Ω						8,000Ω*

Table 5.8 - Fault at Mid Span – Maximum loop & PD connected, 50% load

	Faults applied at Mid Span - Maximum loop & PD connected, 50% load					
Test Case	**Hand to Hand** (L to L) **prior to** PSE turn up			**Hand to Hand** (L to L) **after** PSE turn up		
5.3.2.3 - HH - 1 - 500Ω	500Ω					
5.3.2.3 - HH - 1 - 2,000Ω		2,000Ω				
5.3.2.3 - HH - 1 - 6,400Ω			6,400Ω*			
5.3.2.3 - HH - 2 - 500Ω				500Ω		
5.3.2.3 - HH - 2 - 2,000Ω					2,000Ω	
5.3.2.3 - HH - 2 - 6,400Ω						6,400Ω*
Test Case	**Hand to Foot** (+L to G) **prior to** PSE turn up			**Hand to Foot** (+L to G) **after** PSE turn up		
5.3.2.3 - HF(+) - 1 - 500Ω	500Ω					
5.3.2.3 - HF(+) - 1 - 2,000Ω		2,000Ω				
5.3.2.3 - HF(+) - 1 - 8,000Ω			8,000Ω*			
5.3.2.3 - HF(+) - 2 - 500Ω				500Ω		
5.3.2.3 - HF(+) - 2 - 2,000Ω					2,000Ω	
5.3.2.3 - HF(+) - 2 - 8,000Ω						8,000Ω*
Test Case	**Hand to Foot** (-L to G) **prior to** PSE turn up			**Hand to Foot** (-L to G) **after** PSE turn up		
5.3.2.3 - HF(-) - 1 - 500Ω	500Ω					
5.3.2.3 - HF(-) - 1 - 2,000Ω		2,000Ω				
5.3.2.3 - HF(-) - 1 - 8,000Ω			8,000Ω*			
5.3.2.3 - HF(-) - 2 - 500Ω				500Ω		
5.3.2.3 - HF(-) - 2 - 2,000Ω					2,000Ω	
5.3.2.3 - HF(-) - 2 - 8,000Ω						8,000Ω*

Table 5.9 - Fault at Mid Span – Maximum loop & PD connected, 100% load

	Faults applied at Mid Span - Maximum loop & PD connected, 100% load					
Test Case	**Hand to Hand** (L to L) **prior to** PSE turn up			**Hand to Hand** (L to L) **after** PSE turn up		
5.3.2.4 - HH - 1 - 500Ω	500Ω					
5.3.2.4 - HH - 1 - 2,000Ω		2,000Ω				
5.3.2.4 - HH - 1 - 6,400Ω			6,400Ω*			
5.3.2.4 - HH - 2 - 500Ω				500Ω		
5.3.2.4 - HH - 2 - 2,000Ω					2,000Ω	
5.3.2.4 - HH - 2 - 6,400Ω						6,400Ω*
Test Case	**Hand to Foot** (+L to G) **prior to** PSE turn up			**Hand to Foot** (+L to G) **after** PSE turn up		
5.3.2.4 - HF(+) - 1 - 500Ω	500Ω					
5.3.2.4 - HF(+) - 1 - 2,000Ω		2,000Ω				
5.3.2.4 - HF(+) - 1 - 8,000Ω			8,000Ω*			
5.3.2.4 - HF(+) - 2 - 500Ω				500Ω		
5.3.2.4 - HF(+) - 2 - 2,000Ω					2,000Ω	
5.3.2.4 - HF(+) - 2 - 8,000Ω						8,000Ω*
Test Case	**Hand to Foot** (-L to G) **prior to** PSE turn up			**Hand to Foot** (-L to G) **after** PSE turn up		
5.3.2.4 - HF(-) - 1 - 500Ω	500Ω					
5.3.2.4 - HF(-) - 1 - 2,000Ω		2,000Ω				
5.3.2.4 - HF(-) - 1 - 8,000Ω			8,000Ω*			
5.3.2.4 - HF(-) - 2 - 500Ω				500Ω		
5.3.2.4 - HF(-) - 2 - 2,000Ω					2,000Ω	
5.3.2.4 - HF(-) - 2 - 8,000Ω						8,000Ω*

Table 5.10 - Fault at PD - Maximum loop connected, no PD

	Faults applied at PD location - Maximum loop connected, no PD					
Test Case	**Hand to Hand** (L to L) **prior to** PSE turn up			**Hand to Hand** (L to L) **after** PSE turn up		
5.3.3.1 - HH - 1 - 500Ω	500Ω					
5.3.3.1 - HH - 1 - 2,000Ω		2,000Ω				
5.3.3.1 - HH - 1 - 6,400Ω			6,400Ω*			
5.3.3.1 - HH - 2 - 500Ω				500Ω		
5.3.3.1 - HH - 2 - 2,000Ω					2,000Ω	
5.3.3.1 - HH - 2 - 6,400Ω						6,400Ω*
Test Case	**Hand to Foot** (+L to G) **prior to** PSE turn up			**Hand to Foot** (+L to G) **after** PSE turn up		
5.3.3.1 - HF(+) - 1 - 500Ω	500Ω					
5.3.3.1 - HF(+) - 1 - 2,000Ω		2,000Ω				
5.3.3.1 - HF(+) - 1 - 8,000Ω			8,000Ω*			
5.3.3.1 - HF(+) - 2 - 500Ω				500Ω		
5.3.3.1 - HF(+) - 2 - 2,000Ω					2,000Ω	
5.3.3.1 - HF(+) - 2 - 8,000Ω						8,000Ω*
Test Case	**Hand to Foot** (-L to G) **prior to** PSE turn up			**Hand to Foot** (-L to G) **after** PSE turn up		
5.3.3.1 - HF(-) - 1 - 500Ω	500Ω					
5.3.3.1 - HF(-) - 1 - 2,000Ω		2,000Ω				
5.3.3.1 - HF(-) - 1 - 8,000Ω			8,000Ω*			
5.3.3.1 - HF(-) - 2 - 500Ω				500Ω		
5.3.3.1 - HF(-) - 2 - 2,000Ω					2,000Ω	
5.3.3.1 - HF(-) - 2 - 8,000Ω						8,000Ω*

Table 5.11 - Fault at PD - Maximum loop & PD connected, no load

	Faults applied at PD - Maximum loop & PD connected, no load					
Test Case	**Hand to Hand** (L to L) **prior to** PSE turn up			**Hand to Hand** (L to L) **after** PSE turn up		
5.3.3.2 - HH - 1 - 500Ω	500Ω					
5.3.3.2 - HH - 1 - 2,000Ω		2,000Ω				
5.3.3.2 - HH - 1 - 6,400Ω			6,400Ω*			
5.3.3.2 - HH - 2 - 500Ω				500Ω		
5.3.3.2 - HH - 2 - 2,000Ω					2,000Ω	
5.3.3.2 - HH - 2 - 6,400Ω						6,400Ω*
Test Case	**Hand to Foot** (+L to G) **prior to** PSE turn up			**Hand to Foot** (+L to G) **after** PSE turn up		
5.3.3.2 - HF(+) - 1 - 500Ω	500Ω					
5.3.3.2 - HF(+) - 1 - 2,000Ω		2,000Ω				
5.3.3.2 - HF(+) - 1 - 8,000Ω			8,000Ω*			
5.3.3.2 - HF(+) - 2 - 500Ω				500Ω		
5.3.3.2 - HF(+) - 2 - 2,000Ω					2,000Ω	
5.3.3.2 - HF(+) - 2 - 8,000Ω						8,000Ω*
Test Case	**Hand to Foot** (-L to G) **prior to** PSE turn up			**Hand to Foot** (-L to G) **after** PSE turn up		
5.3.3.2 - HF(-) - 1 - 500Ω	500Ω					
5.3.3.2 - HF(-) - 1 - 2,000Ω		2,000Ω				
5.3.3.2 - HF(-) - 1 - 8,000Ω			8,000Ω*			
5.3.3.2 - HF(-) - 2 - 500Ω				500Ω		
5.3.3.2 - HF(-) - 2 - 2,000Ω					2,000Ω	
5.3.3.2 - HF(-) - 2 - 8,000Ω						8,000Ω*

Table 5.12 - Fault at PD – Maximum loop & PD connected, 50% load

	Faults applied at PD - Maximum loop & PD connected, 50% load					
Test Case	**Hand to Hand** (L to L) **prior to** PSE turn up			**Hand to Hand** (L to L) **after** PSE turn up		
5.3.3.3 - HH - 1 - 500Ω	500Ω					
5.3.3.3 - HH - 1 - 2,000Ω		2,000Ω				
5.3.3.3 - HH - 1 - 6,400Ω			6,400Ω*			
5.3.3.3 - HH - 2 - 500Ω				500Ω		
5.3.3.3 - HH - 2 - 2,000Ω					2,000Ω	
5.3.3.3 - HH - 2 - 6,400Ω						6,400Ω*
Test Case	**Hand to Foot** (+L to G) **prior to** PSE turn up			**Hand to Foot** (+L to G) **afte**r PSE turn up		
5.3.3.3 - HF(+) - 1 - 500Ω	500Ω					
5.3.3.3 - HF(+) - 1 - 2,000Ω		2,000Ω				
5.3.3.3 - HF(+) - 1 - 8,000Ω			8,000Ω*			
5.3.3.3 - HF(+) - 2 - 500Ω				500Ω		
5.3.3.3 - HF(+) - 2 - 2,000Ω					2,000Ω	
5.3.3.3 - HF(+) - 2 - 8,000Ω						8,000Ω*
Test Case	**Hand to Foot** (-L to G) **prior to** PSE turn up			**Hand to Foot** (-L to G) **afte**r PSE turn up		
5.3.3.3 - HF(-) - 1 - 500Ω	500Ω					
5.3.3.3 - HF(-) - 1 - 2,000Ω		2,000Ω				
5.3.3.3 - HF(-) - 1 - 8,000Ω			8,000Ω*			
5.3.3.3 - HF(-) - 2 - 500Ω				500Ω		
5.3.3.3 - HF(-) - 2 - 2,000Ω					2,000Ω	
5.3.3.3 - HF(-) - 2 - 8,000Ω						8,000Ω*

Table 5.13 - Fault at PD – Maximum loop & PD connected, 100% load

	Faults applied at PD - Maximum loop & PD connected, 100% load					
Test Case	**Hand to Hand** (L to L) **prior to** PSE turn up			**Hand to Hand** (L to L) **after** PSE turn up		
5.3.3.4 - HH - 1 - 500Ω	500Ω					
5.3.3.4 - HH - 1 - 2,000Ω		2,000Ω				
5.3.3.4 - HH - 1 - 6,400Ω			6,400Ω*			
5.3.3.4 - HH - 2 - 500Ω				500Ω		
5.3.3.4 - HH - 2 - 2,000Ω					2,000Ω	
5.3.3.4 - HH - 2 - 6,400Ω						6,400Ω*
Test Case	**Hand to Foot** (+L to G) **prior to** PSE turn up			**Hand to Foot** (+L to G) **afte**r PSE turn up		
5.3.3.4 - HF(+) - 1 - 500Ω	500Ω					
5.3.3.4 - HF(+) - 1 - 2,000Ω		2,000Ω				
5.3.3.4 - HF(+) - 1 - 8,000Ω			8,000Ω*			
5.3.3.4 - HF(+) - 2 - 500Ω				500Ω		
5.3.3.4 - HF(+) - 2 - 2,000Ω					2,000Ω	
5.3.3.4 - HF(+) - 2 - 8,000Ω						8,000Ω*
Test Case	**Hand to Foot** (-L to G) **prior to** PSE turn up			**Hand to Foot** (-L to G) **afte**r PSE turn up		
5.3.3.4 - HF(-) - 1 - 500Ω	500Ω					
5.3.3.4 - HF(-) - 1 - 2,000Ω		2,000Ω				
5.3.3.4 - HF(-) - 1 - 8,000Ω			8,000Ω*			
5.3.3.4 - HF(-) - 2 - 500Ω				500Ω		
5.3.3.4 - HF(-) - 2 - 2,000Ω					2,000Ω	
5.3.3.4 - HF(-) - 2 - 8,000Ω						8,000Ω*

* Resistance value is touch voltage dependent and corresponds to 25mA of heart current.
Refer to Table A.1, in Annex A.

5.5 Fault Condition Testing – Bus Configurations

For systems that are architected as a power bus, it is acceptable to qualify a system as a worst-case deployment as it is impractical to test every possible combination of AENs and powered devices (PDs) relating to power levels of each PD and the distances between AENs. The associated testing performed will be documented in a way that maximum component values and system characteristics will be recorded and compared to systems deployed to prove compliance with this standard. This is achieved by recognizing that the maximum energy transferred into a fault is based on maximum energy in the system, in both transient and stored conditions when a fault occurs. Further, simplification methods can be applied if the conditions exist whereby the bus architecture has power take off or tap points that are the same, form-fit-function, across the system. These points can be called AENs where more than one output can be connected to continue providing power to the bus and to PD(s), in the case of a two output port system. Annex C defines the method and procedure for the reduction of a multi-output port bus architecture to an equivalent circuit model, called an Equivalent Load Circuit (ELC) considering all capacitance and resistance values to their maximum equivalent circuit. Annex C will show that a bus architecture can be reduced to a single PSE that transmits power to a single AEN at operational conditions to maximize the energy into any fault. Testing shall be initially performed on actual products, such as active fault energy management devices, power sourcing equipment, power termination devices and cable of the distributed power system to prove that an ELC is electrically equivalent to actual product as it relates to this standard and Fault Energy Management results defined herein. It is important that the manufacturer's manuals and training documentation methods and procedures defined are followed by the test labs to access the equipment and properly perform all tests.

An example is provided with a step by step procedure of how to:

a) build a test model based on maximum component characteristics.
b) test it to show FMPS compliance according to this document.
c) prove compliance with an Equivalent Load Circuit (ELC) that emulates the test model in item “a)” above.
d) build and test an ELC to a worst-case deployment condition.
e) document the solution based on these maximum conditions for certification.

The following figure simplification will be used to represent the test configurations. The grey box represents the test circuits shown to the left of the equal sign in the figure below:

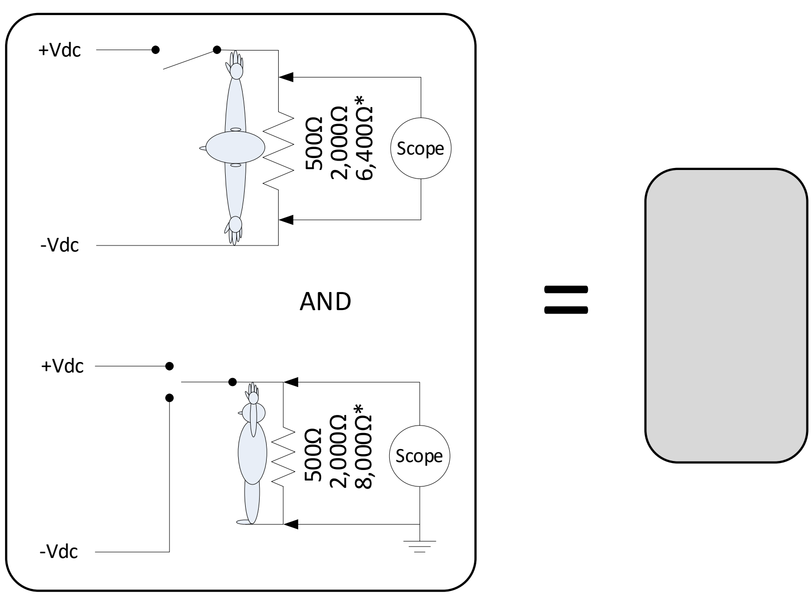


Figure 5.30 – Test Circuit Representation

The 8,000 ohm and 6,400 ohm resistance is voltage dependant and in all cases relates to 25 mA of heart current. See Table A.1 in Annex A.

This next section of tests simulates Hand-to-Hand and Hand-to-Foot faults under all human body resistance and loading conditions. Annex C defines the test conditions with respect to loading and shall be used below to identify the needed tests to be performed based on the appropriate worst-case conditions. The general test setup is:

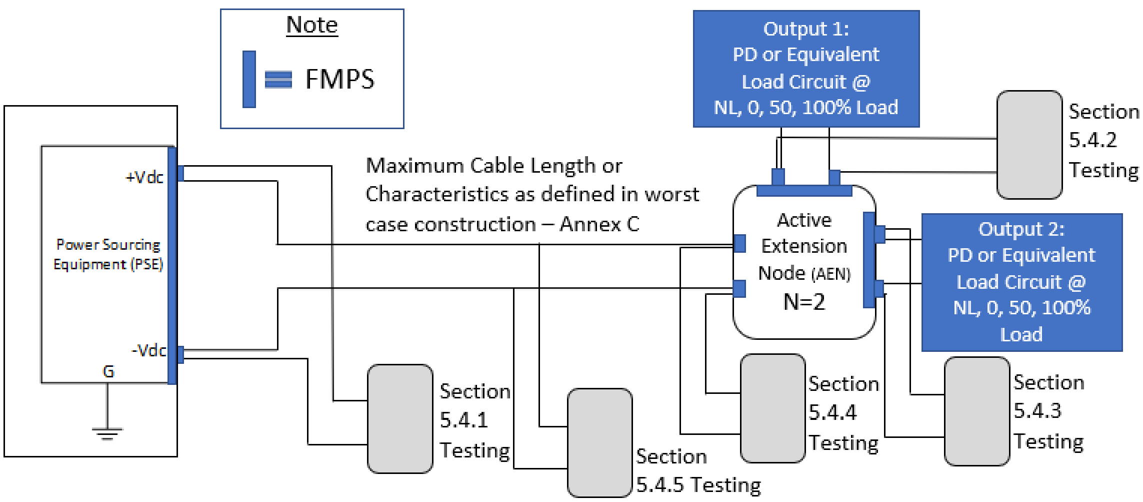


Figure 5.31 – Bus Configuration, General Test Setup Line Diagram with PD/ELC(s)

The table of tests for each output and load condition is:

Table 5.14 - Test Combinations for 2 Output AEN

Possible Load Combinations for Equivalent Load Circuit (ELC) for NB = 2								
Outputs		No Load (No PD)	Based on Maximum PD Power*			Based on Maximum AEN Power*		
2 \ 1			PD @ 0%	PD @ 50%	PD @ 100%	ELC @ 0% or ELC_2 @ 0%	ELC @ 50% or ELC_2 @ 50%	ELC @ 100% or ELC_2 @ 100%
No Load (No PD)		X	X	X	X	X	X	X
Based on Maximum PD Power*	PD @ 0%	X	X	X	X	X	X	X
	PD @ 50%	X	X	X	X	X	X	X
	PD @ 100%	X	X	X	X	X	X	X
Based on Maximum AEN Power*	ELC @ 0% or ELC_2 @ 0%	X	X	X	X	X	X	X
	ELC @ 50% or ELC_2 @ 50%	X	X	X	X	X	X	X
	ELC @ 100% or ELC_2 @ 100%	X	X	X	X	X	X	X

*Notes:
PD - Based on a maximum power in Table C2
ELC - When paired with a PD, based on AEN maximum output current, residual line current, in Table C2
ELC_2 - Used when paired with another ELC, ELC_2 current = PSE maximum current/2

Section 5.5.1 covers the tests at the PSE. Subsection 5.5.1.1 tests the systems with no loop and therefore the no load condition. Subsection 5.4.1.2. adds the equivalent load circuitry, power cable and AEN, however, no load exists. This is to test the system as it would be built out in the field. Section 5.4.1.3 will support the testing at the PSE output and/or AEN input if the conditions in Annex C are met with maximum stored energy and active circuitry that manages the fault. In this case, load is incrementally added to all of the outputs of the system. Testing for the no load condition at both outputs of the AEN is not necessary as it was covered in section 5.5.1.2 tests.

Section 5.5.2 will support the specified testing at output 1 for both deployment variations – terminating load through a PD and then repeated with an ELC if this port can be used as a trunk line or loop. Section 5.5.3 will support the specified testing at output 2, similar to output 1. If the power bus has N output ports, then testing would be repeated for each output port. If the architecture does not meet the condition of equivalent active fault management circuitry in any one of the AENs, that is form, fit and function, then testing would need to be repeated for each occurrence of unique components and their associated outputs in the system.

5.5.1 Testing Fault Current at the PSE Output Power Terminals

5.5.1.1 Simulated human contact applied at the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with no loop, no PD connected

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE is energized and stabilized for 5 seconds.

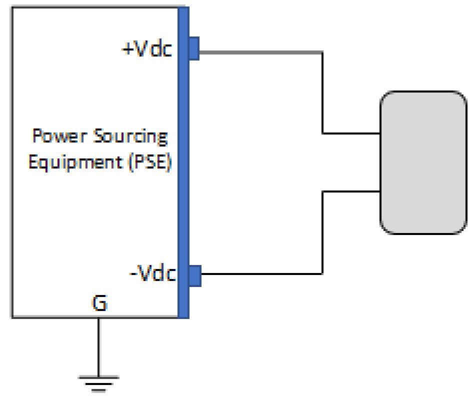


Figure 5.32 – Bus Configuration, PSE Output Terminal, Testing - No Loop

5.5.1.2 Simulated human contact applied at the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with maximum length of loop cable connected, no PD connected

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

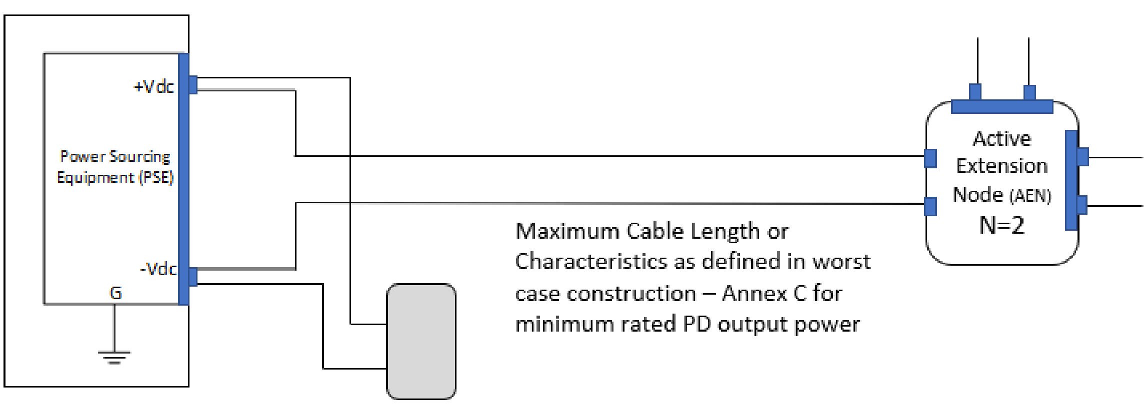


Figure 5.33 – Bus Configuration, PSE Output Terminal, Testing with Loop, AEN and No PD

As load is added to the outputs of the AEN in the system, the following tests are formulated to measure the fault current for every possible load combination. The figure below and subsequent subsections describe where to test the fault and apply the loads.

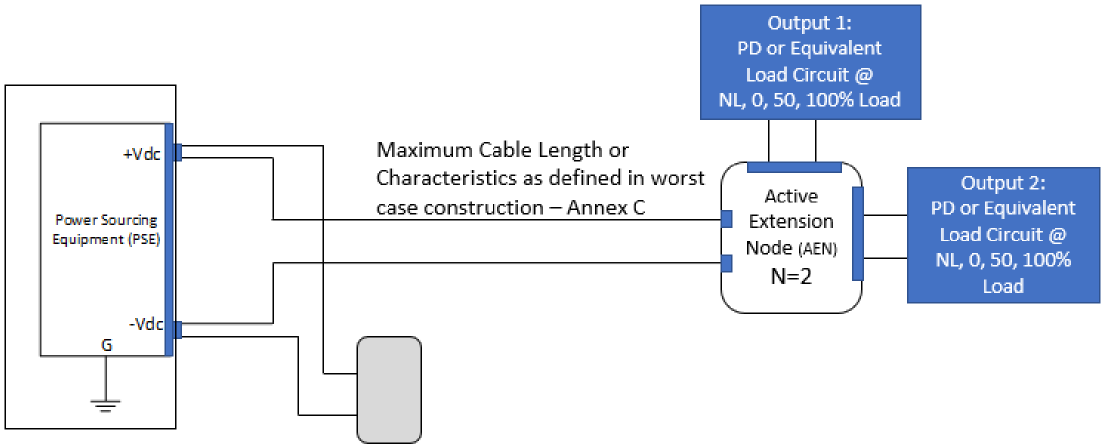


Figure 5.34 – Bus Configuration, PSE Output Terminal, Testing with Loop, AEN and PD/ELC(s), All Load Conditions

5.5.1.3 Simulated human contact applied at the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 0%, Output 2 – no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.1.4 Simulated human contact applied at the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - 50% load and Output 2 – no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.1.5 Simulated human contact applied at the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - 100% load and Output 2 – no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.1.6 Simulated human contact applied at the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - no load, Output 2 – 0% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.1.7 Simulated human contact applied at the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - 0% load and Output 2 – 0% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.1.8 5.4.1.8 – Simulated human contact applied at the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 50% and Output 2 – 0% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.1.9 Simulated human contact applied at the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 100% and Output 2 – 0% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.1.10 Simulated human contact applied at the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - no load, Output 2 – 50% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*

b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.1.11 Simulated human contact applied at the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - 0% load and Output 2 – 50% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.1.12 Simulated human contact applied at the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 50% and Output 2 – 50% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.1.13 Simulated human contact applied at the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 50% and Output 2 – 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.1.14 Simulated human contact applied at the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – no load and Output 2 – 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.1.15 Simulated human contact applied at the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 0% and Output 2 – 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.1.16 Simulated human contact applied at the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 50% and Output 2 – 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.1.17 Simulated human contact applied at the Power Sourcing Equipment (PSE) via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 100% and Output 2 – 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.2 Testing Fault Current, Output 1

This section describes the testing to be performed at output 1 for all load, human body resistances and Hand-to-Hand and Hand-to-Foot conditions. The figure and subsections below will describe where to test the fault energy and the application of the loads.

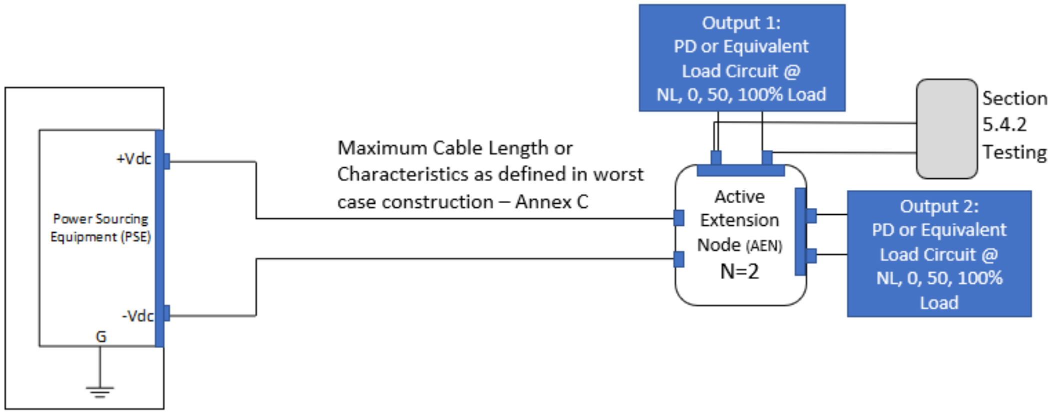


Figure 5.35 – Bus Configuration, AEN Output 1 Testing with PD/ELC(s), All Load Conditions

5.5.2.1 Simulated human contact applied at Output 1 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – no load, Output 2 – no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.2.2 Simulated human contact applied at Output 1 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 0%, Output 2 – no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.2.3 Simulated human contact applied at Output 1 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - 50% load and Output 2 – no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.2.4 Simulated human contact applied at Output 1 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - 100% load and Output 2 – no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.2.5 Simulated human contact applied at Output 1 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - no load, Output 2 – 0% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.2.6 Simulated human contact applied at Output 1 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - 0% load and Output 2 – 0% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.2.7 Simulated human contact applied at Output 1 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 50% and Output 2 – 0% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.2.8 Simulated human contact applied at Output 1 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 100% and Output 2 – 0% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*

b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.2.9 Simulated human contact applied at Output 1 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - no load, Output 2 – 50% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.2.10 Simulated human contact applied at Output 1 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - 0% load and Output 2 – 50% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.2.11 Simulated human contact applied at Output 1 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 50% and Output 2 – 50% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.2.12 Simulated human contact applied at Output 1 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 100% and Output 2 – 50% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.2.13 Simulated human contact applied at Output 1 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – no load and Output 2 – 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.2.14 Simulated human contact applied at Output 1 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 0% and Output 2 – 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.2.15 Simulated human contact applied at Output 1 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 50% and Output 2 – 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.2.16 Simulated human contact applied at Output 1 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 100% and Output 2 – 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.3 Testing Fault Current, Output 2

This section describes the testing to be performed at output 2 for all load, human body resistances and Hand-to-Hand and Hand-to-Foot conditions. The figure and subsections below will describe where to test the fault energy and the application of the loads.

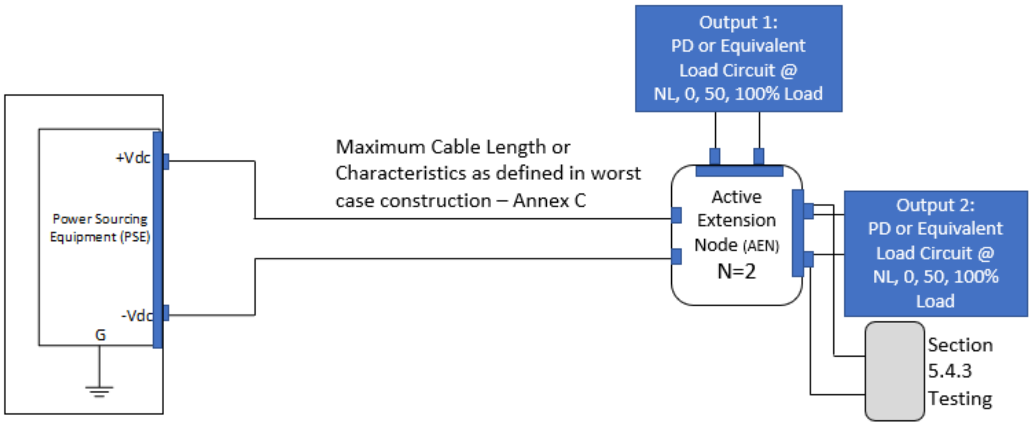


Figure 5.36 – Bus Configuration, AEN Output 2 Testing with PD/ELC(s), All Load Conditions

5.5.3.1 Simulated human contact applied at Output 2 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – no load, Output 2 – no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.3.2 Simulated human contact applied at Output 2 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 0%, Output 2 – no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.3.3 Simulated human contact applied at Output 2 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - 50% load and Output 2 – no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.3.4 Simulated human contact applied at Output 2 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - 100% load and Output 2 – no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.3.5 Simulated human contact applied at Output 2 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - no load, Output 2 – 0% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.3.6 Simulated human contact applied at Output 2 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - 0% load and Output 2 – 0% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.3.7 Simulated human contact applied at Output 2 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 50% and Output 2 – 0% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*

b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.3.8 Simulated human contact applied at Output 2 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 100% and Output 2 – 0% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.3.9 Simulated human contact applied at Output 2 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - no load, Output 2 – 50% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.3.10 Simulated human contact applied at Output 2 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - 0% load and Output 2 – 50% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5. Seconds.

5.5.3.11 Simulated human contact applied at Output 2 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 50% and Output 2 – 50% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.3.12 Simulated human contact applied at Output 2 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 100% and Output 2 – 50% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.3.13 Simulated human contact applied at Output 2 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – no load and Output 2 – 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.3.14 Simulated human contact applied at Output 2 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 0% and Output 2 – 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.3.15 Simulated human contact applied at Output 2 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 50% and Output 2 – 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.3.16 Simulated human contact applied at Output 2 via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 100% and Output 2 – 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*

b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.4 Testing Fault Current, Input Terminals

This section describes the testing to be performed at the AEN Input terminals for all load, human body resistances and Hand-to-Hand and Hand-to-Foot conditions. The figure and subsections below will describe where to test the fault energy and the application of the loads.

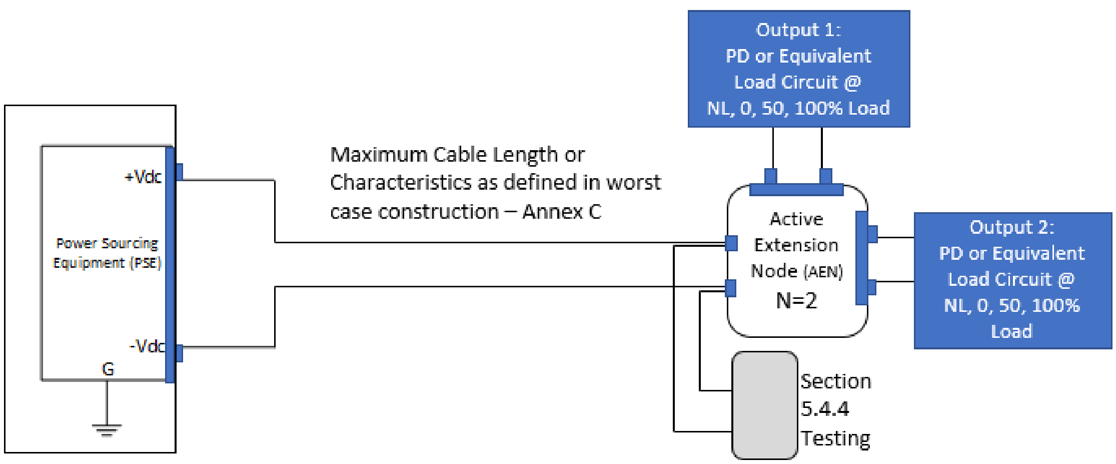


Figure 5.37 – Bus Configuration, AEN Input Terminal Testing with PD/ELC(s), All Load Conditions

5.5.4.1 Simulated human contact applied at the AEN input terminal via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – no load, Output 2 – no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.4.2 Simulated human contact applied at the AEN input terminal via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 0%, Output 2 – no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.4.3 Simulated human contact applied at AEN input terminal via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - 50% load and Output 2 – no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.4.4 Simulated human contact applied at the AEN input terminal via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - 100% load and Output 2 – no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.4.5 Simulated human contact applied at the AEN input terminal via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - no load, Output 2 – 0% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.4.6 Simulated human contact applied at the AEN input terminal via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - 0% load and Output 2 – 0% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*

b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.4.7 Simulated human contact applied at the AEN input terminal via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 50% and Output 2 – 0% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.4.8 Simulated human contact applied at AEN input terminal via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 100% and Output 2 – 0% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.4.9 Simulated human contact applied at the AEN input terminal via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - no load, Output 2 – 50% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.4.10 Simulated human contact applied at the AEN input terminal via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - 0% load and Output 2 – 50% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.4.11 Simulated human contact applied at the AEN input terminal via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 50% and Output 2 – 50% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.4.12 Simulated human contact applied at the AEN input terminal via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 100% and Output 2 – 50% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.4.13 Simulated human contact applied at the AEN input terminal via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – no load and Output 2 – 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.4.14 Simulated human contact applied at the AEN input terminal via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 0% and Output 2 – 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.4.15 Simulated human contact applied at the AEN input terminal via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 50% and Output 2 – 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*

b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.4.16 Simulated human contact applied at the AEN input terminal via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 100% and Output 2 – 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.5 Testing Fault Current, Cable Midspan Cut

This section describes the testing to be performed at the midspan of the cable for all load, human body resistances and Hand-to-Hand and Hand-to-Foot conditions. The figure and subsections below will describe where to test the fault energy and the application of the loads.

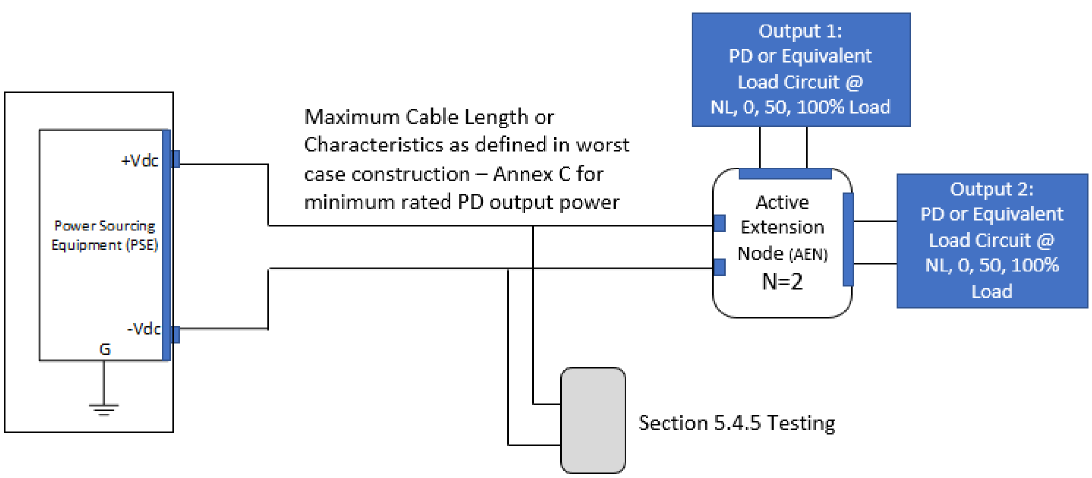


Figure 5.38 – Bus Configuration, Midspan Cable Testing with PD/ELC(s), All Load Conditions

5.5.5.1 Simulated human contact applied at the midspan of the cable via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – no load, Output 2 – no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*

c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.5.2 Simulated human contact applied at the midspan of the cable via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 0%, Output 2 – no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.5.3 Simulated human contact applied at the midspan of the cable via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - 50% load and Output 2 – no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.5.4 Simulated human contact applied at the midspan of the cable via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - 100% load and Output 2 – no load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.5.5 Simulated human contact applied at the midspan of the cable via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - no load, Output 2 – 0% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.5.6 Simulated human contact applied at the midspan of the cable via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - 0% load and Output 2 – 0% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.5.7 Simulated human contact applied at the midspan of the cable via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 50% and Output 2 – 0% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.5.8 Simulated human contact applied at the midspan of the cable via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 100% and Output 2 – 0% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.5.9 Simulated human contact applied at the midspan of the cable via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - no load, Output 2 – 50% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.5.10 Simulated human contact applied at the midspan of the cable via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 - 0% load and Output 2 – 50% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*

b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.5.11 Simulated human contact applied at the midspan of the cable via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 50% and Output 2 – 50% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.5.12 Simulated human contact applied at the midspan of the cable via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 100% and Output 2 – 50% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.5.13 Simulated human contact applied at the midspan of the cable via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – no load and Output 2 – 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.5.14 Simulated human contact applied at the midspan of the cable via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 0% and Output 2 – 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.5.15 Simulated human contact applied at the midspan of the cable via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 50% and Output 2 – 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.5.16 Simulated human contact applied at the midspan of the cable via less than 10 ft of test cable with maximum length of loop cable connected, PD connected, Output 1 – 100% and Output 2 – 100% load

a) Hand-to-hand human contact (line to line) current path. Total body resistance values of 500Ω, 2,000Ω and 6,400Ω*
b) Hand-to-foot human contact (line to ground) current path. Total body resistance values of 500Ω, 2,000Ω and 8,000Ω*
c) Application of total body resistances prior to turn up of PSE.
d) Application of total body resistances after PSE energized and stabilized for 5 seconds.

5.5.6 Fault Test Case Record

Bus test case numbering convention: *

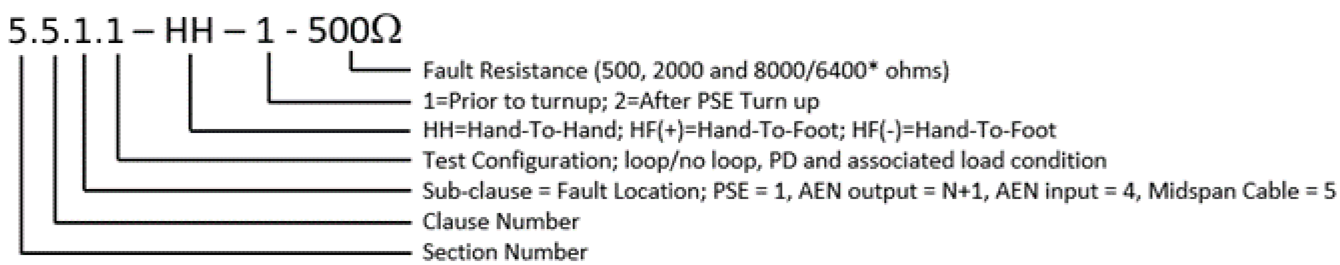


Figure 5.39 – Bus Configuration, Test Case Numbering Convention

*Refer to section 5.5.6 regarding Test Configuration, digit 4 above. Test configurations enumerated in this technical report are exemplary but not necessarily exhaustive.

Each test shall be recorded and plotted as described in this document. The data shall also be recorded and documented in a table that describes the test and its conditions under which the test was conducted.

Table 5.15 - PSE Output Fault Test Record for L-L and L-G Tests

	Test Case	Load Condition		Hand to Hand (L to L) Testing					
				Hand to Hand (L to L) **prior to** PSE turn up			**Hand to Hand** (L to L) **after** PSE turn up		
		Out 1	Out 2	500Ω	2,000Ω	6,400Ω*	500Ω	2,000Ω	6,400Ω*
PSE Test	5.4.1.1 - HH	NA	NA						
	5.4.1.2 - HH	NL	NL						
	5.4.1.3 - HH	0%	NL						
	5.4.1.4 - HH	50%	NL						
	5.4.1.5 - HH	100%	NL						
	5.4.1.6 - HH	NL	0%						
	5.4.1.7 - HH	0%	0%						
	5.4.1.8 - HH	50%	0%						
	5.4.1.9 - HH	100%	0%						
	5.4.1.10 - HH	NL	50%						
	5.4.1.11 - HH	0%	50%						
	5.4.1.12 - HH	50%	50%						
	5.4.1.13 - HH	100%	50%						
	5.4.1.14 - HH	NL	100%						
	5.4.1.15 - HH	0%	100%						
	5.4.1.16 - HH	50%	100%						
	5.4.1.17 - HH	100%	100%						

	Test Case	Load Condition		Hand to Foot (+L to G) Testing					
				Hand to Foot (+L to G) **prior to** PSE turn up			**Hand to Foot** (+L to G) **after** PSE turn up		
		Out 1	Out 2	500Ω	2,000Ω	8,000Ω*	500Ω	2,000Ω	8,000Ω*
PSE Test	5.4.1.1 - HF(+)	NA	NA						
	5.4.1.2 - HF(+)	NL	NL						
	5.4.1.3 - HF(+)	0%	NL						
	5.4.1.4 - HF(+)	50%	NL						
	5.4.1.5 - HF(+)	100%	NL						
	5.4.1.6 - HF(+)	NL	0%						
	5.4.1.7 - HF(+)	0%	0%						
	5.4.1.8 - HF(+)	50%	0%						
	5.4.1.9 - HF(+)	100%	0%						
	5.4.1.10 - HF(+)	NL	50%						
	5.4.1.11 - HF(+)	0%	50%						
	5.4.1.12 - HF(+)	50%	50%						
	5.4.1.13 - HF(+)	100%	50%						
	5.4.1.14 - HF(+)	NL	100%						
	5.4.1.15 - HF(+)	0%	100%						
	5.4.1.16 - HF(+)	50%	100%						
	5.4.1.17 - HF(+)	100%	100%						

	Test Case	Load Condition		Hand to Foot (-L to G) Testing					
				Hand to Foot (-L to G) **prior to** PSE turn up			**Hand to Foot** (-L to G) **after** PSE turn up		
		Out 1	Out 2	500Ω	2,000Ω	8,000Ω*	500Ω	2,000Ω	8,000Ω*
PSE Test	5.4.1.1 - HF(-)	NA	NA						
	5.4.1.2 - HF(-)	NL	NL						
	5.4.1.3 - HF(-)	0%	NL						
	5.4.1.4 - HF(-)	50%	NL						
	5.4.1.5 - HF(-)	100%	NL						
	5.4.1.6 - HF(-)	NL	0%						
	5.4.1.7 - HF(-)	0%	0%						
	5.4.1.8 - HF(-)	50%	0%						
	5.4.1.9 - HF(-)	100%	0%						
	5.4.1.10 - HF(-)	NL	50%						
	5.4.1.11 - HF(-)	0%	50%						
	5.4.1.12 - HF(-)	50%	50%						
	5.4.1.13 - HF(-)	100%	50%						
	5.4.1.14 - HF(-)	NL	100%						
	5.4.1.15 - HF(-)	0%	100%						
	5.4.1.16 - HF(-)	50%	100%						
	5.4.1.17 - HF(-)	100%	100%						

* Resistance value is touch voltage dependent and corresponds to 25mA of heart current.

Refer to Table A.1, in Annex A.

Table 5.16 - AEN Output 1 Fault Test Record for L-L and L-G Tests

	Test Case	Load Condition		Hand to Hand (L to L) Testing					
				Hand to Hand (L to L) **prior to** PSE turn up			**Hand to Hand** (L to L) **after** PSE turn up		
		Out 1	Out 2	500Ω	2,000Ω	6,400Ω*	500Ω	2,000Ω	6,400Ω*
AEN Output 1 Tests	5.4.2.1 - HH	NL	NL						
	5.4.2.2 - HH	0%	NL						
	5.4.2.3 - HH	50%	NL						
	5.4.2.4 - HH	100%	NL						
	5.4.2.5 - HH	NL	0%						
	5.4.2.6 - HH	0%	0%						
	5.4.2.7 - HH	50%	0%						
	5.4.2.8 - HH	100%	0%						
	5.4.2.9 - HH	NL	50%						
	5.4.2.10 - HH	0%	50%						
	5.4.2.11 - HH	50%	50%						
	5.4.2.12 - HH	100%	50%						
	5.4.2.13 - HH	NL	100%						
	5.4.2.14 - HH	0%	100%						
	5.4.2.15 - HH	50%	100%						
	5.4.2.16 - HH	100%	100%						

	Test Case	Load Condition		Hand to Foot (+L to G) Testing					
				Hand to Foot (+L to G) **prior to** PSE turn up			**Hand to Foot** (+L to G) **afte**r PSE turn up		
		Out 1	Out 2	500Ω	2,000Ω	8,000Ω*	500Ω	2,000Ω	8,000Ω*
AEN Output 1 Tests	5.4.2.1 - HF(+)	NL	NL						
	5.4.2.2 - HF(+)	0%	NL						
	5.4.2.3 - HF(+)	50%	NL						
	5.4.2.4 - HF(+)	100%	NL						
	5.4.2.5 - HF(+)	NL	0%						
	5.4.2.6 - HF(+)	0%	0%						
	5.4.2.7 - HF(+)	50%	0%						
	5.4.2.8 - HF(+)	100%	0%						
	5.4.2.9 - HF(+)	NL	50%						
	5.4.2.10 - HF(+)	0%	50%						
	5.4.2.11 - HF(+)	50%	50%						
	5.4.2.12 - HF(+)	100%	50%						
	5.4.2.13 - HF(+)	NL	100%						
	5.4.2.14 - HF(+)	0%	100%						
	5.4.2.15 - HF(+)	50%	100%						
	5.4.2.16 - HF(+)	100%	100%						

	Test Case	Load Condition		Hand to Foot (-L to G) Testing					
				Hand to Foot (-L to G) **prior to** PSE turn up			**Hand to Foot** (-L to G) **afte**r PSE turn up		
		Out 1	Out 2	500Ω	2,000Ω	8,000Ω*	500Ω	2,000Ω	8,000Ω*
AEN Output 1 Tests	5.4.2.1 - HF(-)	NL	NL						
	5.4.2.2 - HF(-)	0%	NL						
	5.4.2.3 - HF(-)	50%	NL						
	5.4.2.4 - HF(-)	100%	NL						
	5.4.2.5 - HF(-)	NL	0%						
	5.4.2.6 - HF(-)	0%	0%						
	5.4.2.7 - HF(-)	50%	0%						
	5.4.2.8 - HF(-)	100%	0%						
	5.4.2.9 - HF(-)	NL	50%						
	5.4.2.10 - HF(-)	0%	50%						
	5.4.2.11 - HF(-)	50%	50%						
	5.4.2.12 - HF(-)	100%	50%						
	5.4.2.13 - HF(-)	NL	100%						
	5.4.2.14 - HF(-)	0%	100%						
	5.4.2.15 - HF(-)	50%	100%						
	5.4.2.16 - HF(-)	100%	100%						

* Resistance value is touch voltage dependent and corresponds to 25mA of heart current.
Refer to Table A.1, in Annex A.

Table 5.17 - AEN Output 2 Fault Test Record for L-L and L-G Tests

				Hand to Hand (L to L) Testing					
	Test Case	Load Condition		**Hand to Hand** (L to L) **prior to** PSE turn up			**Hand to Hand** (L to L) **after** PSE turn up		
		Out 1	Out 2	500Ω	2,000Ω	6,400Ω*	500Ω	2,000Ω	6,400Ω*
AEN Output 2 Tests	5.4.3.1 - HH	NL	NL						
	5.4.3.2 - HH	0%	NL						
	5.4.3.3 - HH	50%	NL						
	5.4.3.4 - HH	100%	NL						
	5.4.3.5 - HH	NL	0%						
	5.4.3.6 - HH	0%	0%						
	5.4.3.7 - HH	50%	0%						
	5.4.3.8 - HH	100%	0%						
	5.4.3.9 - HH	NL	50%						
	5.4.3.10 - HH	0%	50%						
	5.4.3.11 - HH	50%	50%						
	5.4.2.12 - HH	100%	50%						
	5.4.2.13 - HH	NL	100%						
	5.4.2.14 - HH	0%	100%						
	5.4.2.15 - HH	50%	100%						
	5.4.2.16 - HH	100%	100%						

				Hand to Foot (+L to G) Testing					
	Test Case	Load Condition		**Hand to Foot** (+L to G) **prior to** PSE turn up			**Hand to Foot** (+L to G) **after** PSE turn up		
		Out 1	Out 2	500Ω	2,000Ω	8,000Ω*	500Ω	2,000Ω	8,000Ω*
AEN Output 2 Tests	5.4.3.1 - HF(+)	NL	NL						
	5.4.3.2 - HF(+)	0%	NL						
	5.4.3.3 - HF(+)	50%	NL						
	5.4.3.4 - HF(+)	100%	NL						
	5.4.3.5 - HF(+)	NL	0%						
	5.4.3.6 - HF(+)	0%	0%						
	5.4.3.7 - HF(+)	50%	0%						
	5.4.3.8 - HF(+)	100%	0%						
	5.4.3.9 - HF(+)	NL	50%						
	5.4.3.10 - HF(+)	0%	50%						
	5.4.3.11 - HF(+)	50%	50%						
	5.4.2.12 - HF(+)	100%	50%						
	5.4.2.13 - HF(+)	NL	100%						
	5.4.2.14 - HF(+)	0%	100%						
	5.4.2.15 - HF(+)	50%	100%						
	5.4.2.16 - HF(+)	100%	100%						

				Hand to Foot (-L to G) Testing					
	Test Case	Load Condition		**Hand to Foot** (-L to G) **prior to** PSE turn up			**Hand to Foot** (-L to G) **after** PSE turn up		
		Out 1	Out 2	500Ω	2,000Ω	8,000Ω*	500Ω	2,000Ω	8,000Ω*
AEN Output 2 Tests	5.4.3.1 - HF(-)	NL	NL						
	5.4.3.2 - HF(-)	0%	NL						
	5.4.3.3 - HF(-)	50%	NL						
	5.4.3.4 - HF(-)	100%	NL						
	5.4.3.5 - HF(-)	NL	0%						
	5.4.3.6 - HF(-)	0%	0%						
	5.4.3.7 - HF(-)	50%	0%						
	5.4.3.8 - HF(-)	100%	0%						
	5.4.3.9 - HF(-)	NL	50%						
	5.4.3.10 - HF(-)	0%	50%						
	5.4.3.11 - HF(-)	50%	50%						
	5.4.2.12 - HF(-)	100%	50%						
	5.4.2.13 - HF(-)	NL	100%						
	5.4.2.14 - HF(-)	0%	100%						
	5.4.2.15 - HF(-)	50%	100%						
	5.4.2.16 - HF(-)	100%	100%						

* Resistance value is touch voltage dependent and corresponds to 25mA of heart current.
Refer to Table A.1, in Annex A.

Table 5.18 - AEN Input Fault Test Record for L-L and L-G Tests

				Hand to Hand (L to L) Testing					
	Test Case	Load Condition		**Hand to Hand** (L to L) **prior to** PSE turn up			**Hand to Hand** (L to L) **after** PSE turn up		
		Out 1	Out 2	500Ω	2,000Ω	6,400Ω*	500Ω	2,000Ω	6,400Ω*
AEN Input Tests	5.4.4.1 - HH	NL	NL						
	5.4.4.2 - HH	0%	NL						
	5.4.4.3 - HH	50%	NL						
	5.4.4.4 - HH	100%	NL						
	5.4.4.5 - HH	NL	0%						
	5.4.4.6 - HH	0%	0%						
	5.4.4.7 - HH	50%	0%						
	5.4.4.8 - HH	100%	0%						
	5.4.4.9 - HH	NL	50%						
	5.4.4.10 - HH	0%	50%						
	5.4.4.11 - HH	50%	50%						
	5.4.2.12 - HH	100%	50%						
	5.4.2.13 - HH	NL	100%						
	5.4.2.14 - HH	0%	100%						
	5.4.2.15 - HH	50%	100%						
	5.4.2.16 - HH	100%	100%						

				Hand to Foot (+L to G) Testing					
	Test Case	Load Condition		**Hand to Foot** (+L to G) **prior to** PSE turn up			**Hand to Foot** (+L to G) **after** PSE turn up		
		Out 1	Out 2	500Ω	2,000Ω	8,000Ω*	500Ω	2,000Ω	8,000Ω*
AEN Input Tests	5.4.4.1 - HF(+)	NL	NL						
	5.4.4.2 - HF(+)	0%	NL						
	5.4.4.3 - HF(+)	50%	NL						
	5.4.4.4 - HF(+)	100%	NL						
	5.4.4.5 - HF(+)	NL	0%						
	5.4.4.6 - HF(+)	0%	0%						
	5.4.4.7 - HF(+)	50%	0%						
	5.4.4.8 - HF(+)	100%	0%						
	5.4.4.9 - HF(+)	NL	50%						
	5.4.4.10 - HF(+)	0%	50%						
	5.4.4.11 - HF(+)	50%	50%						
	5.4.2.12 - HF(+)	100%	50%						
	5.4.2.13 - HF(+)	NL	100%						
	5.4.2.14 - HF(+)	0%	100%						
	5.4.2.15 - HF(+)	50%	100%						
	5.4.2.16 - HF(+)	100%	100%						

				Hand to Foot (-L to G) Testing					
	Test Case	Load Condition		**Hand to Foot** (-L to G) **prior to** PSE turn up			**Hand to Foot** (-L to G) **after** PSE turn up		
		Out 1	Out 2	500Ω	2,000Ω	8,000Ω*	500Ω	2,000Ω	8,000Ω*
AEN Input Tests	5.4.4.1 - HF(-)	NL	NL						
	5.4.4.2 - HF(-)	0%	NL						
	5.4.4.3 - HF(-)	50%	NL						
	5.4.4.4 - HF(-)	100%	NL						
	5.4.4.5 - HF(-)	NL	0%						
	5.4.4.6 - HF(-)	0%	0%						
	5.4.4.7 - HF(-)	50%	0%						
	5.4.4.8 - HF(-)	100%	0%						
	5.4.4.9 - HF(-)	NL	50%						
	5.4.4.10 - HF(-)	0%	50%						
	5.4.4.11 - HF(-)	50%	50%						
	5.4.2.12 - HF(-)	100%	50%						
	5.4.2.13 - HF(-)	NL	100%						
	5.4.2.14 - HF(-)	0%	100%						
	5.4.2.15 - HF(-)	50%	100%						
	5.4.2.16 - HF(-)	100%	100%						

* Resistance value is touch voltage dependent and corresponds to 25mA of heart current. Refer to Table A.1, in Annex A.

Table 5.19 - Cable Midspan Fault Test Record for L-L and L-G Tests

	Test Case	Load Condition		Hand to Hand (L to L) Testing					
				Hand to Hand (L to L) **prior to** PSE turn up			**Hand to Hand** (L to L) **after** PSE turn up		
		Out 1	Out 2	500Ω	2,000Ω	6,400Ω*	500Ω	2,000Ω	6,400Ω*
Cable Midspan Tests	5.4.5.1 - HH	NL	NL						
	5.4.5.2 - HH	0%	NL						
	5.4.5.3 - HH	50%	NL						
	5.4.5.4 - HH	100%	NL						
	5.4.5.5 - HH	NL	0%						
	5.4.5.6 - HH	0%	0%						
	5.4.5.7 - HH	50%	0%						
	5.4.5.8 - HH	100%	0%						
	5.4.5.9 - HH	NL	50%						
	5.4.5.10 - HH	0%	50%						
	5.4.5.11 - HH	50%	50%						
	5.4.2.12 - HH	100%	50%						
	5.4.2.13 - HH	NL	100%						
	5.4.2.14 - HH	0%	100%						
	5.4.2.15 - HH	50%	100%						
	5.4.2.16 - HH	100%	100%						

	Test Case	Load Condition		Hand to Foot (+L to G) Testing					
				Hand to Foot (+L to G) **prior to** PSE turn up			**Hand to Foot** (+L to G) **afte**r PSE turn up		
		Out 1	Out 2	500Ω	2,000Ω	8,000Ω*	500Ω	2,000Ω	8,000Ω*
Cable Midspan Tests	5.4.5.1 - HF(+)	NL	NL						
	5.4.5.2 - HF(+)	0%	NL						
	5.4.5.3 - HF(+)	50%	NL						
	5.4.5.4 - HF(+)	100%	NL						
	5.4.5.5 - HF(+)	NL	0%						
	5.4.5.6 - HF(+)	0%	0%						
	5.4.5.7 - HF(+)	50%	0%						
	5.4.5.8 - HF(+)	100%	0%						
	5.4.5.9 - HF(+)	NL	50%						
	5.4.5.10 - HF(+)	0%	50%						
	5.4.5.11 - HF(+)	50%	50%						
	5.4.2.12 - HF(+)	100%	50%						
	5.4.2.13 - HF(+)	NL	100%						
	5.4.2.14 - HF(+)	0%	100%						
	5.4.2.15 - HF(+)	50%	100%						
	5.4.2.16 - HF(+)	100%	100%						

	Test Case	Load Condition		Hand to Foot (-L to G) Testing					
				Hand to Foot (-L to G) **prior to** PSE turn up			**Hand to Foot** (-L to G) **afte**r PSE turn up		
		Out 1	Out 2	500Ω	2,000Ω	8,000Ω*	500Ω	2,000Ω	8,000Ω*
Cable Midspan Tests	5.4.5.1 - HF(-)	NL	NL						
	5.4.5.2 - HF(-)	0%	NL						
	5.4.5.3 - HF(-)	50%	NL						
	5.4.5.4 - HF(-)	100%	NL						
	5.4.5.5 - HF(-)	NL	0%						
	5.4.5.6 - HF(-)	0%	0%						
	5.4.5.7 - HF(-)	50%	0%						
	5.4.5.8 - HF(-)	100%	0%						
	5.4.5.9 - HF(-)	NL	50%						
	5.4.5.10 - HF(-)	0%	50%						
	5.4.5.11 - HF(-)	50%	50%						
	5.4.2.12 - HF(-)	100%	50%						
	5.4.2.13 - HF(-)	NL	100%						
	5.4.2.14 - HF(-)	0%	100%						
	5.4.2.15 - HF(-)	50%	100%						
	5.4.2.16 - HF(-)	100%	100%						

* Resistance value is touch voltage dependent and corresponds to 25mA of heart current.
Refer to Table A.1, in Annex A.

Test List and Test Configuration Parameters:

Each test is run H-H and H-F, pre and post energizing, and at all human body resistance values.

- Test Configuration 5.5.1.1 – Fault at PSE – No loop connected
- Test Configuration 5.5.1.2 – Fault at PSE – Maximum Equivalent Circuit, no PD (NL
- Test Configuration 5.5.1.3 – Fault at PSE – Maximum Equivalent Circuit, N1=0%, N2 = NL
- Test Configuration 5.5.1.4 – Fault at PSE – Maximum Equivalent Circuit, N1=50%, N2 = NL
- Test Configuration 5.5.1.5 – Fault at PSE Maximum Equivalent Circuit, N1=100%, N2 = NL
- Test Configuration 5.5.1.6 – Fault at PSE – Maximum Equivalent Circuit, N1=NL, N2 = 0%
- Test Configuration 5.5.1.7 – Fault at PSE – Maximum Equivalent Circuit, N1=0%, N2 = 0%
- Test Configuration 5.5.1.8 – Fault at PSE – Maximum Equivalent Circuit, N1=50%, N2 = 0%
- Test Configuration 5.5.1.9 – Fault at PSE – Maximum Equivalent Circuit, N1=100%, N2 = 0%
- Test Configuration 5.5.1.10 – Fault at PSE – Maximum Equivalent Circuit, N1=NL, N2 = 50%
- Test Configuration 5.5.1.11 – Fault at PSE – Maximum Equivalent Circuit, N1=0%, N2 = 50%
- Test Configuration 5.5.1.12 – Fault at PSE – Maximum Equivalent Circuit, N1=50%, N2 = 50%
- Test Configuration 5.5.1.13 – Fault at PSE – Maximum Equivalent Circuit, N1=100%, N2 = 50%
- Test Configuration 5.5.1.14 – Fault at PSE – Maximum Equivalent Circuit, N1=NL, N2 = 100%
- Test Configuration 5.5.1.15 – Fault at PSE – Maximum Equivalent Circuit, N1=0%, N2 = 100%
- Test Configuration 5.5.1.16 – Fault at PSE – Maximum Equivalent Circuit, N1=50%, N2 = 100%
- Test Configuration 5.5.1.17 – Fault at PSE – Maximum Equivalent Circuit, N1=100%, N2 = 100%
- Test Configuration 5.5.2.1 – Fault at Output 1 – Maximum Equivalent Circuit, N1=NL, N2 = NL
- Test Configuration 5.5.2.2 – Fault at Output 1 – Maximum Equivalent Circuit, N1=0%, N2 = NL
- Test Configuration 5.5.2.3 – Fault at Output 1 – Maximum Equivalent Circuit, N1=50%, N2 = NL
- Test Configuration 5.5.2.4 – Fault at Output 1 – Maximum Equivalent Circuit, N1=100%, N2 = NL
- Test Configuration 5.5.2.5 – Fault at Output 1 – Maximum Equivalent Circuit, N1=NL, N2 = 0%
- Test Configuration 5.5.2.6 – Fault at Output 1 – Maximum Equivalent Circuit, N1=0%, N2 = 0%
- Test Configuration 5.5.2.7 – Fault at Output 1 – Maximum Equivalent Circuit, N1=50%, N2 = 0%
- Test Configuration 5.5.2.8 – Fault at Output 1 – Maximum Equivalent Circuit, N1=100%, N2 = 0%
- Test Configuration 5.5.2.9 – Fault at Output 1 – Maximum Equivalent Circuit, N1=NL, N2 = 50%
- Test Configuration 5.5.2.10 – Fault at Output 1 – Maximum Equivalent Circuit, N1=0%, N2 = 50%
- Test Configuration 5.5.2.11 – Fault at Output 1 – Maximum Equivalent Circuit, N1=50%, N2 = 50%
- Test Configuration 5.5.2.12 – Fault at Output 1 – Maximum Equivalent Circuit, N1=100%, N2 = 50%
- Test Configuration 5.5.2.13 – Fault at Output 1 – Maximum Equivalent Circuit, N1=NL, N2 = 100%
- Test Configuration 5.5.2.14 – Fault at Output 1 – Maximum Equivalent Circuit, N1=0%, N2 = 100
- Test Configuration 5.5.2.15 – Fault at Output 1 – Maximum Equivalent Circuit, N1=50%, N2 = 100%
- Test Configuration 5.5.2.16 – Fault at Output 1 – Maximum Equivalent Circuit, N1=100%, N2 = 100
- Test Configuration 5.5.3.1 – Fault at Output 2 – Maximum Equivalent Circuit, N1=NL, N2 = NL
- Test Configuration 5.5.3.2 – Fault at Output 2 – Maximum Equivalent Circuit, N1=0%, N2 = NL
- Test Configuration 5.5.3.3 – Fault at Output 2 – Maximum Equivalent Circuit, N1=50%, N2 = NL
- Test Configuration 5.5.3.4 – Fault at Output 2 – Maximum Equivalent Circuit, N1=100%, N2 = NL
- Test Configuration 5.5.3.5 – Fault at Output 2 – Maximum Equivalent Circuit, N1=NL, N2 = 0%
- Test Configuration 5.5.3.6 – Fault at Output 2 – Maximum Equivalent Circuit, N1=0%, N2 = 0%
- Test Configuration 5.5.3.7 – Fault at Output 2 – Maximum Equivalent Circuit, N1=50%, N2 = 0%
- Test Configuration 5.5.3.8 – Fault at Output 2 – Maximum Equivalent Circuit, N1=100%, N2 = 0%
- Test Configuration 5.5.3.9 – Fault at Output 2 – Maximum Equivalent Circuit, N1=NL, N2 = 50%
- Test Configuration 5.5.3.10 – Fault at Output 2 – Maximum Equivalent Circuit, N1=0%, N2 = 50%
- Test Configuration 5.5.3.11 – Fault at Output 2 – Maximum Equivalent Circuit, N1=50%, N2 = 50%
- Test Configuration 5.5.3.12 – Fault at Output 2 – Maximum Equivalent Circuit, N1=100%, N2 = 50%
- Test Configuration 5.5.3.13 – Fault at Output 2 – Maximum Equivalent Circuit, N1=NL, N2 = 100%
- Test Configuration 5.5.3.14 – Fault at Output 2 – Maximum Equivalent Circuit, N1=0%, N2 = 100%
- Test Configuration 5.5.3.15 – Fault at Output 2 – Maximum Equivalent Circuit, N1=50%, N2 = 100%
- Test Configuration 5.5.3.16 – Fault at Output 2 – Maximum Equivalent Circuit, N1=100%, N2 = 100%

- Test Configuration 5.5.4.1 – Fault at Input Terminal – Maximum Equivalent Circuit, N1=NL, N2 = NL
- Test Configuration 5.5.4.2 – Fault at Input Terminal – Maximum Equivalent Circuit, N1=0%, N2 = NL
- Test Configuration 5.5.4.3 – Fault at Input Terminal – Maximum Equivalent Circuit, N1=50%, N2 = NL
- Test Configuration 5.5.4.4 – Fault at Input Terminal – Maximum Equivalent Circuit, N1=100%, N2 = NL
- Test Configuration 5.5.4.5 – Fault at Input Terminal – Maximum Equivalent Circuit, N1=NL, N2 = 0%
- Test Configuration 5.5.4.6 – Fault at Input Terminal – Maximum Equivalent Circuit, N1=0%, N2 = 0%
- Test Configuration 5.5.4.7 – Fault at Input Terminal – Maximum Equivalent Circuit, N1=50%, N2 = 0%
- Test Configuration 5.5.4.8 – Fault at Input Terminal – Maximum Equivalent Circuit, N1=100%, N2 = 0%
- Test Configuration 5.5.4.9 – Fault at Input Terminal – Maximum Equivalent Circuit, N1=NL, N2 = 50%
- Test Configuration 5.5.4.10 – Fault at Input Terminal – Maximum Equivalent Circuit, N1=0%, N2 = 50%
- Test Configuration 5.5.4.11 – Fault at Input Terminal – Maximum Equivalent Circuit, N1=50%, N2 = 50%
- Test Configuration 5.5.4.12 – Fault at Input Terminal – Maximum Equivalent Circuit, N1=100%, N2 = 50%
- Test Configuration 5.5.4.13 – Fault at Input Terminal – Maximum Equivalent Circuit, N1=NL, N2 = 100%
- Test Configuration 5.5.4.14 – Fault at Input Terminal – Maximum Equivalent Circuit, N1=0%, N2 = 100%
- Test Configuration 5.5.4.15 – Fault at Input Terminal – Maximum Equivalent Circuit, N1=50%, N2 = 100%
- Test Configuration 5.5.4.16 – Fault at Input Terminal – Maximum Equivalent Circuit, N1=100%, N2 = 100%
- Test Configuration 5.5.5.1 – Fault at Midspan of Cable – Maximum Equivalent Circuit, N1=NL, N2 = NL
- Test Configuration 5.5.5.2 – Fault at Midspan of Cable – Maximum Equivalent Circuit, N1=0%, N2 = NL
- Test Configuration 5.5.5.3 – Fault at Midspan of Cable – Maximum Equivalent Circuit, N1=50%, N2 = NL
- Test Configuration 5.5.5.4 – Fault at Midspan of Cable – Maximum Equivalent Circuit, N1=100%, N2 = NL
- Test Configuration 5.5.5.5 – Fault at Midspan of Cable – Maximum Equivalent Circuit, N1=NL, N2 = 0%
- Test Configuration 5.5.5.6 – Fault at Midspan of Cable – Maximum Equivalent Circuit, N1=0%, N2 = 0%
- Test Configuration 5.5.5.7 – Fault at Midspan of Cable – Maximum Equivalent Circuit, N1=50%, N2 = 0%
- Test Configuration 5.5.5.8 – Fault at Midspan of Cable – Maximum Equivalent Circuit, N1=100%, N2 = 0%
- Test Configuration 5.5.5.9 – Fault at Midspan of Cable – Maximum Equivalent Circuit, N1=NL, N2 = 50%
- Test Configuration 5.5.5.10 – Fault at Midspan of Cable – Maximum Equivalent Circuit, N1=0%, N2 = 50%
- Test Configuration 5.5.5.11 – Fault at Midspan of Cable – Maximum Equivalent Circuit, N1=50%, N2 = 50%
- Test Configuration 5.5.5.12 – Fault at Midspan of Cable – Maximum Equivalent Circuit, N1=100%, N2 = 50%
- Test Configuration 5.5.5.13 – Fault at Midspan of Cable – Maximum Equivalent Circuit, N1=NL, N2 = 100%
- Test Configuration 5.5.5.14 – Fault at Midspan of Cable – Maximum Equivalent Circuit, N1=0%, N2 = 100%
- Test Configuration 5.5.5.15 – Fault at Midspan of Cable – Maximum Equivalent Circuit, N1=50%, N2 = 100%
- Test Configuration 5.5.5.16 – Fault at Midspan of Cable – Maximum Equivalent Circuit, N1=100%, N2 = 100%

***Refer to section 5.5.6 regarding Test Configuration, digit 4 above. Test configurations enumerated in this standard are exemplary but not necessarily exhaustive.**

6 Transient Tolerance, Fault Management Functionality & Service Continuity

Fault managed power systems shall continue to operate without service interruption when the line voltage terminals are subjected to certain transient voltages. Such transients experienced in field applications could result in fault management system failures or service interruptions for telecommunications equipment served by fault managed power systems.

To assess the susceptibility of fault managed power systems to transients, testing shall be conducted to Telcordia GR-1089-CORE [Ref 4] *Electromagnetic Compatibility (EMC) and Electrical Safety - Generic Criteria for Network Telecommunications Equipment*, including:

1. Section 4 Lightning and Power Fault
   - Where GR-1089-CORE [Ref 4] specifies, tip, ring and ground- for use with fault managed power systems, Line 1 and Line 2 shall be considered Tip and Ring as appropriate for the application. The Test Report shall clearly identify the type of each equipment port evaluated in accordance with Appendix B.
2. Section 5.2 Longitudinal Induction Criteria

During First Level lightning surge and power fault testing, the fault management system shall not be impaired from maintaining fault detection and shut down capability and shock hazard protection . Following First Level lightning surge and power fault testing, the fault managed systems shall not be damaged or create a fire, fragmentation or shock hazard. Fault managed power systems must remain fully functional following first level lightning surge and power fault testing.

After the First Level lightning surge and/or power fault application, additional testing and analysis shall be conducted to Section 5.4 Fault Condition Testing – Point to Point Configurations or Section 5.5 Fault Condition Testing – Bus Configurations as appropriate to verify proper fault management functionality. This can be demonstrated by retesting the worst case line to line and line to ground fault test configurations with the highest time-current fault level plotted, based on prior fault test analysis results. Fault testing performed before and after First Level lightning surge and power fault testing must result in system response to the left of "b" line shock hazard threshold shown in Figure 5.1. If proper fault management functionality verification testing is performed at a third-party test lab, the FMPS system manufacturer shall provide the testing laboratory with any additional equipment and/or cables as well as instructions to determine proper operation of the FMPS. Proper system functionality may be verified using minimal cable length to connect the PSE to the PD or AEN/PD combination. The third-party testing lab shall provide the manufacturer with screen captures of all PSE output voltage and current waveforms as well as the time, voltage and current CSV data files. Additionally, the third-party test lab shall provide the manufacturer with the results of the Random Complex Irregular Waveform Analysis (RCIWA) report. See Annex B of this Technical Report for details pertaining to use of the RCIWA tool and CSV data file requirements. All other conformance criteria of GR 1089 First Level testing shall be met.

Following Second Level lightning surge and power fault testing, the fault managed systems shall not create a fire, fragmentation or shock hazard and may not provide any hazardous power output if still providing power as described below.

The test system shall be powered as intended during testing. The surge and power fault test condition shall be applied at the output of the PSE for point-to-point systems and at the output of the PSE and input and output of the AEN for bus configured systems. Any output port that supports fault managed power shall be tested.

To determine if the fault management functionality of the fault managed power system has not been impaired after being subjected to simulated Second Level transient events, the system shall meet the following requirements:

There shall be no potentially hazardous PSE power output (greater than 60 Vdc and/or 50 Vac) following Second Level lightning surge and power fault testing. If still providing potentially hazardous power output there shall be no failure of fault management functionality.

a) If after the Second Level lightning surge and/or power fault application, the system does not provide any output power, no additional testing is needed.

b) If after the Second Level lightning surge and/or power fault application, the system does provide output power with a voltage of ≤60 Vdc and/or ≤50 Vac, no additional testing is needed.

c) If after the Second Level lightning surge and/or power fault application, the system does provide output power at greater than 60 Vdc and/or 50 Vac, additional testing and analysis shall be conducted to Section 5.4 Fault Condition Testing – Point to Point Configurations or Section 5.5 Fault Condition Testing – Bus Configurations as appropriate in order to verify proper fault management functionality. This can be demonstrated by retesting the fault test configuration with the highest time-current fault level plotted based on the prior fault test analysis results. Fault testing performed before and after Second Level lightning surge and power fault testing must result in system response to the left of "b" line shock hazard threshold shown in Figure 5.1.

7 Discussion of Thermal Exposure and Thermal Management

Proper operation of FMPS fault detection and source shutdown shall be reviewed for installation environment. The harshness of the Outside Plant (OSP) environment needs to be understood and appreciated during the design of fault managed power systems and their sub-components and devices. Key variables to successfully design equipment include heat dissipation (internal load) and design (ventilation scheme) for the equipment assembly, as well as systems criteria such as outdoor conditions (external load) and enclosure design (envelope, heat exchangers, etc.).

The PSE and the AEN shall be subjected to the various environmental conditions and verified to review that the system maintains fault management functionality.

It is recommended that fault managed power systems be reviewed to GR-3108, *Generic Requirements for Network Equipment in the Outside Plant (OSP)* or ATIS-0600010.01 *Temperature, Humidity, Altitude, and Salt Fog Requirements for Information and Communications Technology (ICT) Equipment Utilized in Outside Plant Environments.* When exposed to the various operating conditions specified in GR-3108 or ATIS-0600010.01, the FMPS fault detection shall function as intended and provide power to the load.

8 Discussion of Software and Hardware Analysis & Functional Safety Standard Compliance

Proper operation of FMPS fault detection and source shut down circuitry, software/firmware and related components are critical to the safe operation of fault managed power distribution systems. Testing and compliance to the applicable functional safety standards is essential to ensure that no single point of failure can result in a failure of the fault detection and source shut down functionality of the system while still allowing the PSE to provide power to the PD(s).

The fault managed power system may use physical protection safeguards and software algorithms to monitor and control the system with the intent to keep it in a safe operating condition. This ATIS document does not review the software algorithms or physical protection safeguards used in fault managed power systems and this section is provided for informational purposes only. Since safety is provided through monitoring and control, and physical protection, including basic cable insulation, a review focusing on the electronic circuits, firmware, and software fault/error detection/mitigation strategies and mechanical protection and disconnecting means are required. The test plans in this TR shall apply to areas of the system where the requirements of other accepted industry standards are not met. This TR is intended to review the safe installation, operation and maintenance of the system. For example, if the system is deployed and operated with exposed terminals and metallic conductors that have voltage levels and currents defined in this TR, they shall be tested in accordance with this TR.

This physical protection review will be part of the Listing of the system. The following standard can be used in the physical protection evaluation.

IEC/UL/CSA 62368-1 [Ref 13], Ed. 3*, Audio/Video, Information and Communication Technology Equipment- Part 1:*

Safety Requirements.

1. This standard is a product safety standard that prescribes physical safeguards for the protection of three categories of persons as it relates to energy levels. A safeguard is defined as a scheme that reduces the likelihood of energy being transferred to a body part. The standard provides a method for:
    a. Evaluating such safeguards.
    b. Defining skill levels of personnel.
    c. Determining the safety of a system based on the safeguard and skill level – risk analysis.

This software review will be part of the Listing of the system. The following is a summary of standards that can be used in the software evaluation:

UL 1998 Standard for Software in Programmable Components

1. This standard covers the risks unique to product hardware controlled by software in programmable components by evaluating:
    - Risk Analysis
    - Qualification of Design, Implementation, and Verification Tools
    - Software Design
    - Measures to Address Microelectronic Hardware Failure Modes
    - Software Analysis and Testing
    - Documentation and Software change control
2. These requirements are intended to supplement applicable product or component standards and requirements and are not intended to serve as the sole basis for investigating the risk of fire, electric shock, or injury to persons.
3. These requirements are intended to address risks that occur in the software or in the process used to develop and maintain the software.

UL 5500 Remote Software Updates

1. This standard covers REMOTE software updates taking into account the manufacturer's recommended process. It is limited to software elements having an influence on safety and on compliance with the particular end product safety standard.
2. This standard additionally covers hardware compatibility necessary for safety of the REMOTE software update.

IEC 61508-1 Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems - Part 1: General Requirements

1. This standard applies to safety-related systems when one or more of such systems incorporates electrical/electronic/programmable electronic elements.
2. This is generically - based and applicable to all E/E/PE safety-related systems irrespective of the application.
3. This standard provides the allocate Safety Integrity Level (SIL) 1, 2, 3, 4 on the probability of failure per hour of operation

IEC 61508-2 Requirements for electrical/electronic/programmable electronic safety-related systems

This standard applies to any safety-related system, as defined by IEC 61508-1, that contains at least:

1. One electrical, electronic or programmable electronic element,
2. Applies to all elements within an E/E/PE safety-related system,
3. Specifies how to refine the E/E/PE system safety requirements specification, developed in accordance with IEC 61508-1, into the E/E/PE system design requirements specification,
4. Specifies the requirements for activities that are to be applied during the design and manufacture of the E/E/PE safety-related systems except software, which is dealt with in IEC 61508-3.

IEC 61508-3 Functional safety of electrical safety-related systems – Part 3: Software requirements

This part of the IEC 61508 series:

1. Is intended to be utilized only after a thorough understanding of IEC 61508-1 and IEC 61508-2,
2. Applies to any software forming part of a safety-related system or used to develop a safety-related system within the scope of IEC 61508-1 and IEC 61508-2. Such software is termed safety-related software (including operating systems, system software, software in communication networks, human-computer interface functions, and firmware as well as application software),
3. Provides specific requirements applicable to support tools used to develop and configure a safety-related system within the scope of IEC 61508-1 and IEC 61508-2,
4. Requires that the software safety functions and software systematic capability are specified.

UL 60730-1 Safety for Automatic Electrical Controls

1. This standard applies to automatic electrical controls for use in, on or in association with equipment for household and similar use. The equipment may use electricity, gas, oil, solid fuel, solar thermal energy, etc., or a combination thereof. It also applies to automatic electrical controls for equipment that may be

used by the public, such as equipment intended to be used in shops, offices, hospitals, farms and commercial and industrial applications.

2. This standard applies to the inherent safety, to the operating values, operating times, and operating sequences where such are associated with equipment safety, and to the testing of automatic electrical control devices used in, or in association with, equipment.
3. This standard is also appliable to the Functional Safety of Low Complexity Safety Related Systems and Controls.
4. This standard applies to automatic electrical controls, mechanically or electrically operated, responsive to or controlling such characteristics as temperature, pressure, passage of time, humidity, light, electrostatic effects, flow, or liquid level, current, voltage, acceleration, or combinations thereof.
5. This standard applies to ac. or dc. powered controls with a rated voltage not exceeding 690V ac. or 600V dc. It applies to the electrical and Functional Safety of controls capable of receiving and responding to communications signals, including signals for power billing rate and demand response. The signals may be transmitted to or received from external units being part of the control (wired), or to and from external units which are not part of the control (wireless) under test. This standard does not address the integrity of the output signal to the network devices, such as interoperability with other devices unless it has been evaluated as part of the control system.

Note: Beside these standards, electrical safety will be covered per UL/CSA/IEC 62368-1 [Ref 13] or proposed UL desk standards (or references) 1400-1 and 1400-2 that are under development at the time of this ATIS Technical Report publication.

Functional Safety is an additional step beyond the traditional product safety assessment as per applicable product standards for electrical safety such as UL 62368-1 [Ref 13] or UL 60950-1 [Ref 12] etc. and tackles increasingly complex programmable technologies and the hazards they can create. It is the part of the overall safety of a system or piece of equipment that depends on the system or equipment operating correctly in response to its inputs, including the safe management of likely operator errors, hardware and software failures and environmental changes.

For specific functional and software safety requirements of electronic safety-related systems, refer to IEC 61508 (Series) or UL 1998 or UL 5500 or UL 60730-1 or another applicable functional safety standard.

- **IEC 61508** series generally applicable to all Electrical/Electronic/Programable Electronic safety-related systems irrespective of the application.
- **UL 1998** intended to address risks that occur in the software or in the process used to develop and maintain the software.
- **UL 5500** covers remote software updates taking into account the manufacturer's recommended process. It is limited to software elements having an influence on safety and on compliance with the particular end-product safety standard.
- **UL 60730-1** covers safety evaluation of automatic electrical controls of equipment that provides protection against electrical shock and mechanical hazards. Moreover, this standard also covers the functional safety aspect of electrical controls by evaluating internal faults or risks that can create a hazard for the end-user. This process of functional safety evaluation includes extensive software fault analysis of automatic electrical controls to ensure that end-user hazard exposure is minimal.

Annex A
(normative)

A Human body resistance model

A.1 Definition & Assumptions

1. Maximum source voltages for fault managed power distribution systems in scope for this ATIS standard are limited to 200 Vdc line to ground and 400 Vdc line to line. Therefore, the highest hand to foot (ground fault) touch voltage that a person can be subjected to is 200 Vdc. From Table 1 shown below, total hand to foot body resistances of 500Ω, 2,000Ω and 8,000Ω shall be used when performing fault tests for a worst-case touch voltage of 200 Vdc. Hand to foot resistance values of 500Ω and 2,000Ω for touch voltages of 60 – 200 Vdc listed in Table 1 are derived from the lowest and highest total body resistance values consistent with the human body impedance network defined in IEC 60990 [Ref 3]. The resistance values listed in the right-most hand to foot total resistance column of Table 1 for touch voltages of 60 – 200 Vdc correspond to a body current of 25mA which represents the DC-2 / DC-3 boundary line of IEC 60479-1 [Ref 1] Figure 22, Conventional Time/Current Zones for body current durations ≥ 2 seconds. Heart current is assumed to be equal to body current for a hand to foot current path through the body.
2. Dual polarity +/-200 Vdc fault managed power distribution systems can subject a person to a maximum of 400 Vdc in the event of a hand to hand (line to line) contact situation. From Table 1 shown below, total hand to hand body resistance values of 500Ω and 2,000Ω shall be used for line to line contact scenarios for touch voltages of 60 – 400 Vdc. The resistance values listed in the right-most hand to hand total resistance column of Table 1 correspond to a heart current of 25mA which represents the DC-2 / DC-3 boundary line of IEC 60479-1 [Ref 1] Figure 22, Conventional Time/Current Zones for body current durations ≥ 2 seconds. Heart current is assumed to be 40% of total body current for a hand to hand current path through the body.
3. Hand to hand and hand to foot resistance values of 500Ω and 2,000Ω are chosen for touch voltages of 60 – 400 Vdc and 60 – 200 Vdc respectively to ensure that the highest and lowest total body resistance values consistent with the human body model defined in IEC 60990 [Ref 3] are covered. In one case, the lower the resistance value that the human body presents to the Power Sourcing Equipment (PSE), the higher the magnitude of conducted body current. In the other case, the higher the resistance value that the human body presents to the PSE, the more discriminatory the source fault detection circuitry must be in order to react to human contact thereby limiting the duration of current flow through the body. The total body resistance value of 500Ω assumes that skin has been compromised and no longer offers any resistance to current flow. This very conservative approach allows for evaluation of worst-case physiological effects under a wide range of human fault conditions such as large surface area of contact with saltwater-wet skin and/or open wounds.
4. The hand to hand and hand to foot resistance values listed in the right-most two columns of Table 1 for touch voltages of 60 - 400 Vdc and 60 - 200 Vdc respectively correspond to a heart current value of 25mA which represents the DC-2 / DC-3 boundary line of IEC 60479-1 [Ref 1] Figure 22, Conventional Time/Current Zones for body current durations ≥ 2 seconds. These total body resistance values represent the highest fault resistance values that a fault managed power distribution system is required to detect in order to ensure that exposure to electric shock is confined to DC zone 2 for continuous contact with live parts.

Table A.1 - Total Body Resistance

Total body resistance values R_T for specified d.c. current path i.e. *hand to hand* & *hand to foot*						
	Total body resistance values assuming no skin impedance IEC 60990 Body Impedance Network		Total body resistance values assuming 1,500Ω skin impedance IEC 60990 Body Impedance Network		Total body resistance values corresponding to 25mA magnitude of body current*	
Touch Voltage (volts)	R_T hand-hand (Ω)	R_T hand-foot (Ω)	R_T hand-hand (Ω)	R_T hand-foot (Ω)	R_T hand-hand** (Ω)	R_T hand-foot (Ω)
400	500	***	2,000	***	6,400	***
380	500	***	2,000	***	6,080	***
225	500	***	2,000	***	3,600	***
200	500	500	2,000	2,000	3,200	8,000
190	500	500	2,000	2,000	3,040	7,600
175	500	500	2,000	2,000	2,800	7,000
150	500	500	2,000	2,000	2,400	6,000
125	500	500	2,000	2,000	2,000	5,000
100	500	500	2,000	2,000	1,600	4,000
75	500	500	2,000	2,000	1,200	3,000
60	500	500	2,000	2,000	960	2,400

* 25mA of body current represents the DC-2/DC-3 boundary line of IEC 60479-1 Figure 22, Conventional Time/Current Zones for durations ≥ 2 seconds

** The heart factor of 0.4 has been applied to total body current to account for heart current based on a hand to hand current path through the body

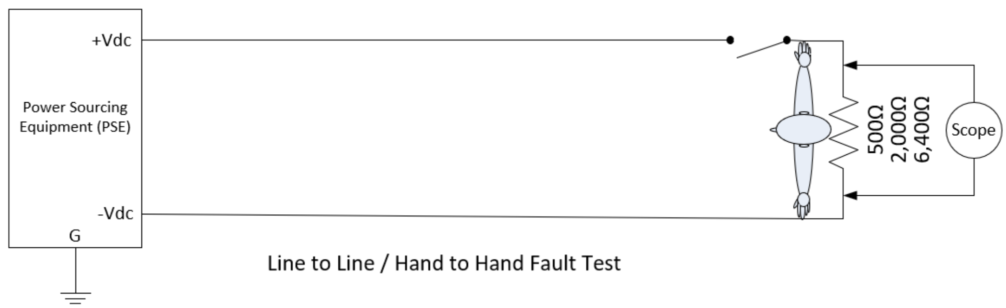
5. This human body resistance model shall consist of a single resistor connected between points of contact with fault managed power distribution system voltages to simulate various human hand to hand and hand to foot contact scenarios.

   Power distribution system fault testing shall be performed at 500Ω for touch voltages of 60 - 400Vdc, which represents the lowest expected hand to hand and hand to foot total body resistances where skin impedance is eliminated from the total body resistance calculation. Therefore, skin capacitance has been eliminated from this human body model.

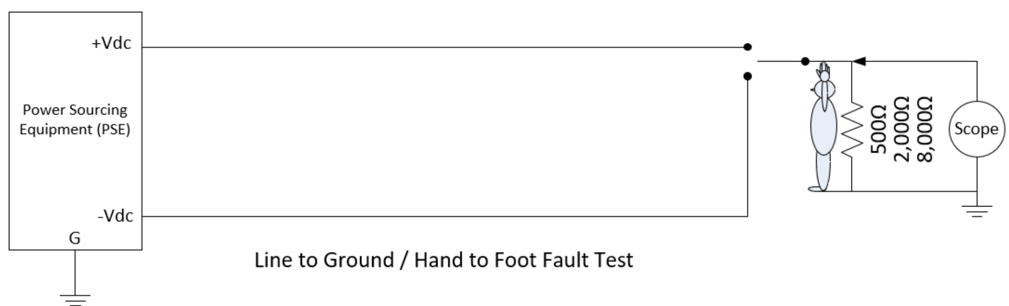
   As previously stated, additional power distribution system fault testing shall be performed at 2,000Ω and resistance values corresponding to 25mA of heart current for touch voltages of 60 - 400Vdc

   It is assumed that the body is insulated from ground for hand-to-hand contact scenarios and that one or both feet are grounded for hand to foot contact scenarios.

   The following diagrams depict line to line / hand to hand and line to ground / hand to foot fault test setups:



Line to Line / Hand to Hand Fault Test



Line to Ground / Hand to Foot Fault Test

6. The physiological effects of various magnitudes and durations of current flow through the human body shall be assessed using the following graph and tabular information from IEC 60479-1 [Ref 1]. For fault managed power distribution systems that present fault current as a series of pulses or waveforms of different shapes, a methodology to equate the measured RMS value of fault current to a "plottable" dc value based on information published in IEC 60479-1 [Ref 1] and IEC 60479-2 [Ref 2] shall be provided in this ATIS standard.

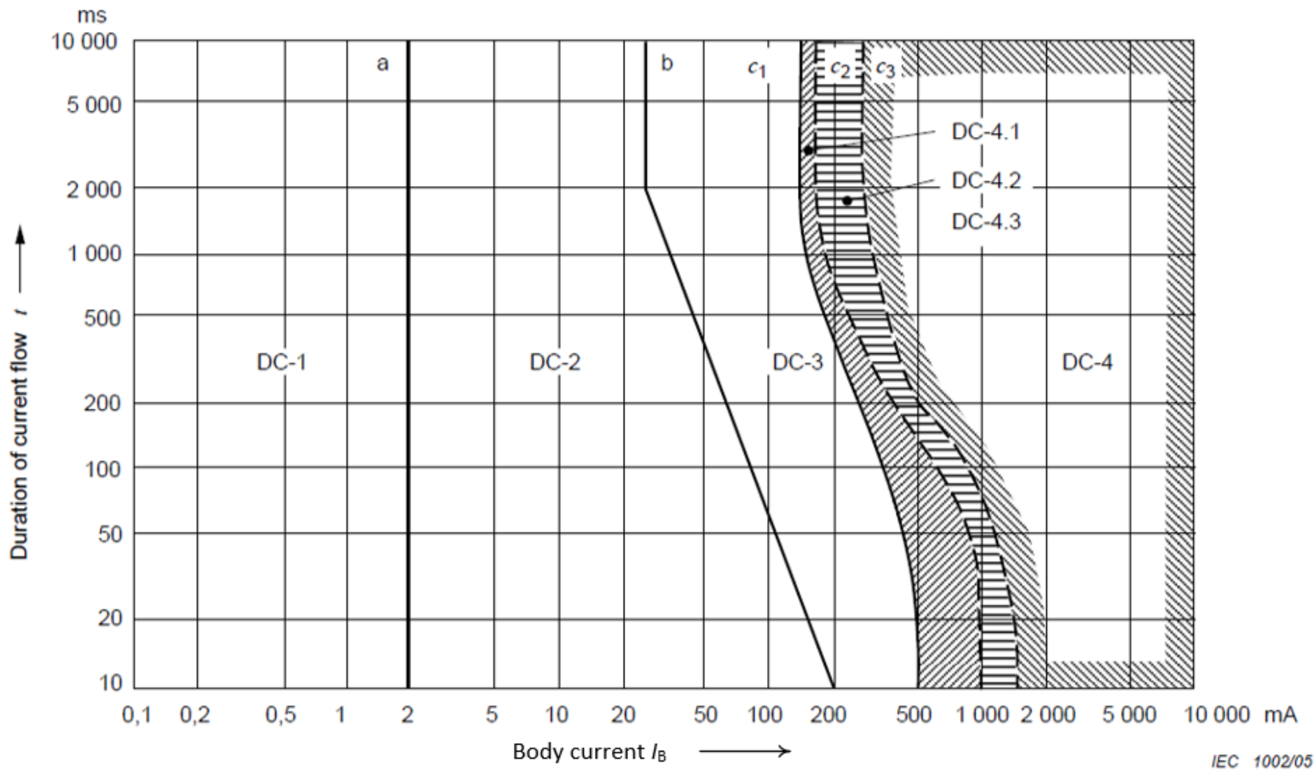


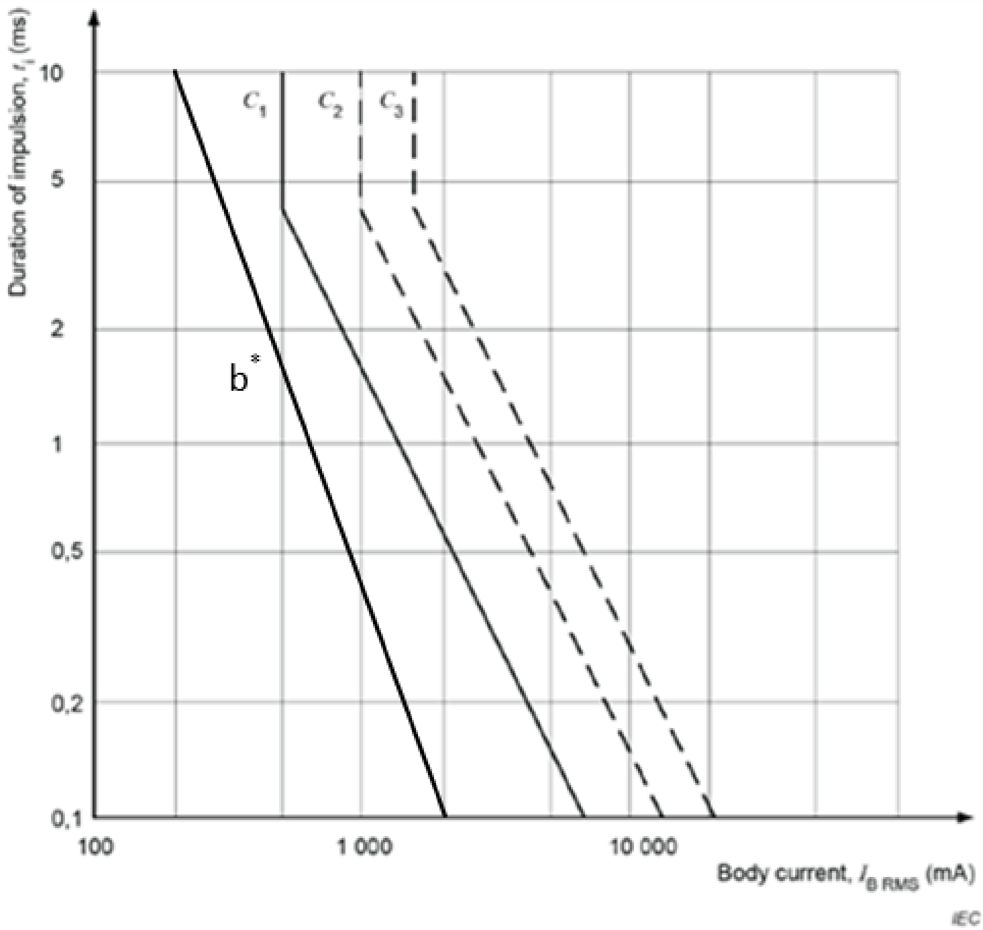
Figure 22 – Conventional time/current zones of effects of d.c. currents on persons for a longitudinal upward current path (for explanation see Table 13)

Table 13 – Time/current zones for d.c. for hand to feet pathway – Summary of zones of Figure 22

Zones	Boundaries	Physiological effects
DC-1	Up to 2 mA curve a	Slight pricking sensation possible when making, breaking or rapidly altering current flow
DC-2	2 mA up to curve b	Involuntary muscular contractions likely especially when making, breaking or rapidly altering current flow but usually no harmful electrical physiological effects
DC-3	Curve b and above	Strong involuntary muscular reactions and reversible disturbances of formation and conduction of impulses in the heart may occur, increasing with current magnitude and time. Usually no organic damage to be expected
DC-4 [1)]	Above curve c_1	Patho-physiological effects may occur such as cardiac arrest, breathing arrest, and burns or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time
	c_1-c_2	DC-4.1 Probability of ventricular fibrillation increasing up to about 5 %
	c_2-c_3	DC-4.2 Probability of ventricular fibrillation up to about 50 %
	Beyond curve c_3	DC-4.3 Probability of ventricular fibrillation above 50 %

1) For durations of current flow below 200 ms, ventricular fibrillation is only initiated within the vulnerable period if the relevant thresholds are surpassed. As regards ventricular fibrillation this figure relates to the effects of current which flows in the path left hand to feet and for upward current. For other current paths the heart current factor has to be considered.

7. Alternatively, if a fault managed power distribution system reacts to a human fault condition and reduces source voltage to a safe level in less than 10 milliseconds, the following graph based on Figure 23 from IEC 60479-2 [Ref 2] shall be used to assess the probability of fibrillation risk to the human body. A hypothetical "b" line similar to that which is shown in IEC 60479-1 [Ref 1], Figure 22 has been plotted onto IEC 60479-2 [Ref 2], Figure 23 shown below based on the assumptions and theory described in the whitepaper, "On Extending the $Td{-}Ib$ Curve b Limit For Td Shorter Than 10ms" Rev. A0.4. 11/23/2020 published by Dr. Francisco Paz [Ref 22].



The curves indicate the probability of fibrillation risks for current flowing in the path left hand to feet. For other current paths, see IEC 60479-1:2018, 5.9.

Below C_1:	no fibrillation,
Above C_1 up to C_2:	low risk of fibrillation (up to 5 % probability),
Above C_2 up to C_3:	average risk of fibrillation (up to 50 % probability),
Above C_3:	high risk of fibrillation (more than 50 % probability).

Figure 23 – Probability of fibrillation risks for current flowing in the path left hand to feet

* Extension of "b" line below 10ms. Reference:

On Extending the $Td{-}Ib$ Curve b Limit For Td Shorter Than 10ms. Rev. A0.4. 11/23/2020

By *Dr. Francisco Paz (*franciscopaz@ieee.org*)*

8. When assessing the probability of fibrillation risk to the human body for hand-to-hand contact situations, a heart-current factor *F* of 0.4 must be applied to the magnitude of body current per Table 12 from IEC 60479-1 [Ref 1] shown below:

Table 12 – Heart-current factor *F* for different current paths

Current path	Heart-current factor *F*
Left hand to left foot, right foot or both feet	1,0
Both hands to both feet	1,0
Left hand to right hand	0,4
Right hand to left foot, right foot or to both feet	0,8
Back to right hand	0,3
Back to left hand	0,7
Chest to right hand	1,3
Chest to left hand	1,5
Seat to left hand, right hand or to both hands	0,7
Left foot to right foot	0,04

EXAMPLE A current of 225 mA hand to hand has the same likelihood of producing ventricular fibrillation as a current of 90 mA left hand to both feet.

A.2 Rationale

In order to determine both the highest and the lowest total body resistance values that are likely to be presented by the vast majority of the population under a wide range of circumstances, the following data from IEC 60479-1 [Ref 1], “Effects of current on human beings and livestock – Part 1: General aspects” was compiled and analyzed.

A.2.1 Lowest total body resistance

To determine the lowest known total body resistance values, data presented in IEC 60479-1 Table 3 corresponding to large surface areas of contact in saltwater-wet skin conditions was chosen. To capture the absolute lowest body resistance values, the total body impedance data listed in the “not exceeded for 5% of the population” column of Table 3 which covers more than 95 % of the population was selected. Table 3, which lists body impedance data for a current path hand to hand for AC 50/60 Hz was used based on the following statement from IEC 60479-1 [Ref 1] Section 4.6.5 “Direct Current”:

> “For large surface areas of contact in water-wet and saltwater-wet conditions the total body resistance *R*T may be determined with sufficient accuracy from Tables 2 and 3, while neglecting small differences of *Z*T between alternating current and direct current which may exist in the voltage range below 100 V. For all other cases, the tables for alternating current can be used for a conservative estimate.”

Table A.2 – Lowest Total Body Resistance, shown below is based on data presented in IEC 60479-1 [Ref 1] Table 3. Asymptotic impedance values (no skin resistance) were chosen for all touch voltages above 200 volts to take into consideration, the potential for skin damage at elevated touch voltages. Hand to foot resistance values were calculated at 70% of hand-to-hand resistance values based on information provided in Note 1 of Table 3.

Table A.2 - Lowest Total Body Resistance

Table A.2 – Lowest Total Body Resistance

Total body resistance values R_T for specified d.c. current path for **large surface areas of contact in saltwater-wet conditions** i.e. *hand to hand* or *hand to foot*

	Total body resistance values that are not exceeded for 5% of the population.		Total body resistance values that are not exceeded for 95% of the population.	
Touch Voltage (volts)	R_T hand-hand (Ω)	R_T hand-foot (Ω)	R_T hand-hand (Ω)	R_T hand-foot (Ω)
25	960	672	1,755	1,229
50	940	658	1,720	1,204
75	920	644	1,685	1,180
100	880	616	1,655	1,159
125	850	595	1,620	1,134
150	830	581	1,590	1,113
175	810	567	1,560	1,092
200	790	553	1,530	1,071
225	575	403	1,050	735
400	575	403	1,050	735
500	575	403	1,050	735
700	575	403	1,050	735
1000	575	403	1,050	735

Based on 60479-1 table 3. H-F values are 70% of H-H values from table 3.
Asymptotic values presented for touch voltages > 200 volts (no skin resistance)

Table 3 – Total body impedances Z_T for a current path hand to hand AC 50/60 Hz, for large surface areas of contact in saltwater-wet conditions

Touch voltage V	Values for the total body impedances Z_T (Ω) that are not exceeded for		
	5 % of the population	50 % of the population	95 % of the population
25	960	1 300	1 755
50	940	1 275	1 720
75	920	1 250	1 685
100	880	1 225	1 655
125	850	1 200	1 620
150	830	1 180	1 590
175	810	1 155	1 560
200	790	1 135	1 530
225	770	1 115	1 505
400	700	950	1 275
500	625	850	1 150
700	575	775	1 050
1 000	575	775	1 050
Asymptotic value = internal impedance	575	775	1 050

NOTE 1 Some measurements indicate that the total body impedance for the current path hand to foot is somewhat lower than for a current path hand to hand (10 % to 30 %).

NOTE 2 Due to low skin impedances in this case it can be assumed that Z_T depends little on the duration of current flow; Z_T approaches the internal body impedance Z_i.

NOTE 3 For the standard value of the voltage 230 V (network-system 3N ~ 230/400 V) it can be assumed that the values of the total body impedance are the same as for a touch voltage of 225 V.

NOTE 4 Values of Z_T are rounded to 5 Ω.

A.2.2 Highest total body resistance

To determine the highest known total body resistance values, data presented in IEC 60479-1 [Ref 1] Table 7 corresponding to small surface areas of contact in dry skin conditions for touch voltages up to 200 volts was used to develop Table 3 – Highest Total Body Resistance, shown below. For touch voltages above 200 volts, total body resistance values based on 60479-1 [Ref 1] Table 10 resistance values adjusted for small area of contact were developed. For a current path hand to hand, Table 10 resistance values were adjusted upward by 1,000Ω to approximate an index finger to thumb contact with both hands. For a current path hand to foot, Table 10 hand to hand resistance values were adjusted upward by 500Ω to approximate an index finger to thumb contact with one hand. Additionally, the hand to foot total body resistance values were calculated at 90% of the adjusted hand to hand resistance values. The value of 500Ω per index finger to thumb contact with one hand is based on the following statement in Section 4.3 "Body Impedance" of IEC 60479-5:

> "NOTE 2 A finger can be assumed to have a resistance of approximately 1,000Ω. Therefore, contact with a finger-tip rather than with the palm of the hand will significantly increase the body impedance."

Contact with an index finger and thumb is considered to be two 1,000Ω resistors in parallel, hence 500Ω.

Table A.3 - Highest Total Body Resistance

Table A.3 – Highest Total Body Resistance

Total body resistance values R_T for specified d.c. current path for **small surface areas of contact in dry conditions** i.e. hand to hand or hand to foot				
	Total body resistance values that are not exceeded for 5% of the population.		Total body resistance values that are not exceeded for 95% of the population.	
Touch Voltage (volts)	R_T hand-hand (Ω)	R_T hand-foot (Ω)	R_T hand-hand (Ω)	R_T hand-foot (Ω)
25	91,250	82,125	317,725	285,953
50	74,800	67,320	250,250	225,225
75	42,550	38,295	133,200	119,880
100	23,000	20,700	70,400	63,360
125	12,875	11,588	37,850	34,065
150	7,200	6,480	20,225	18,203
175	4,000	3,600	10,725	9,653
200	3,500	3,150	8,650	7,785
225	1,775	1,148	2,900	2,160
400	1,700	1,080	2,275	1,598
500	1,625	1,013	2,150	1,485
700	1,575	968	2,050	1,395
1000	1,575	968	2,050	1,395

Based on 60479-1 table 7 resistance values for touch voltages 25-200 volts
Based on 60479-1 table 10 resistance values adjusted for small area of contact for touch voltages >200 volts
Table 10 H to H resistance values adjusted upward by 1,000Ω, index finger to thumb contact with both hands
Table 10 H to F resistance values adjusted upward by 500Ω, index finger to thumb contact with one hand
Hand to foot resistance values are calculated at 90% of hand to hand resistance values

Table 10 – Total body resistances R_T for a current path hand to hand, direct current, for large surface areas of contact in dry conditions

Touch voltage V	Values for the total body resistance R_T (Ω) that are not exceeded for		
	5 % of the population	50 % of the population	95 % of the population
25	2 100	3 875	7 275
50	1 600	2 900	5 325
75	1 275	2 275	4 100
100	1 100	1 900	3 350
125	975	1 675	2 875
150	875	1 475	2 475
175	825	1 350	2 225
200	800	1 275	2 050
225	775	1 225	1 900
400	700	950	1 275
500	625	850	1 150
700	575	775	1 050
1 000	575	775	1 050
Asymptotic value	575	775	1 050

NOTE 1 Some measurements indicate that the total body resistance R_T for the current path hand to foot is somewhat lower than for a current path hand to hand (10 % to 30 %).

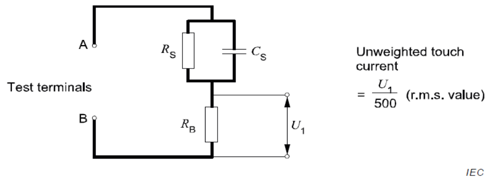
NOTE 2 For living persons, the values of R_T correspond to a duration of current flow of about 0,1 s. For longer durations R_T values can decrease (about 10 % to 20 %) and after complete rupture of the skin R_T approaches the initial body resistance R_0.

NOTE 3 Values of R_T are rounded to 25 Ω.

Table 7 – Total body impedances Z_T for a current path hand to hand for small surface areas of contact in dry conditions at touch voltages U_T = 25 V to 200 V AC 50/60 Hz (values rounded to 25 Ω)

Touch voltage V	Values for the total body impedances Z_T (Ω) that are not exceeded for		
	5 % of the population	50 % of the population	95 % of the population
25	91 250	169 000	317 725
50	74 800	136 000	250 250
75	42 550	74 000	133 200
100	23 000	40 000	70 400
125	12 875	22 000	37 850
150	7 200	12 000	20 225
175	4 000	6 500	10 725
200	3 500	5 400	8 650

A.2.3 Human body model defined in IEC 60990



R_S	1 500 Ω
R_B	500 Ω
C_S	0,22 μF

Figure 3 – Measuring network, unweighted touch current

E.2 Body impedance network – Figure 3

The purpose of the network of Figure 3 is to

– simulate the impedance of the human body,

– provide a measurement indicating the level of current which can flow through a human body if the body contacts the EQUIPMENT in a like manner.

R_B models the internal impedance of the human body.

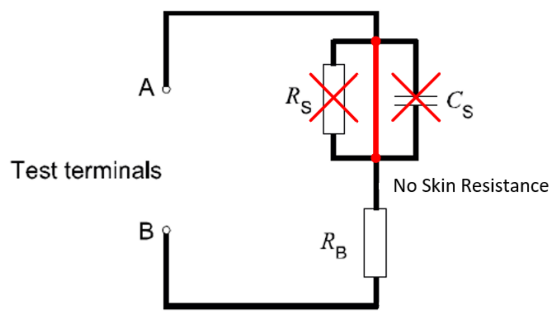
R_S and C_S model the total skin impedance of two points of contact. The value of C_S is determined from the area of skin contact. For larger areas of contact, a larger value (for example, 0,33 μF) may be used.

NOTE The human body model of Figure 3 with the R and C values used herein has traditionally been used in product safety standards for 50 years or more; it has a long history of adequacy for this measurement.

A.2.4 IEC 60990 Body Impedance Network

Upon analysis of the lowest total body resistance values developed in Table 2 - Lowest Total Body Resistance shown above, a high correlation with the human body model defined in IEC 60990 [Ref 3] becomes apparent. When skin resistance and capacitance is removed from the model, total remaining body resistance is defined as 500Ω. Lowest hand to hand and hand to foot resistance values form Table 2 are 575Ω and 553Ω respectively.

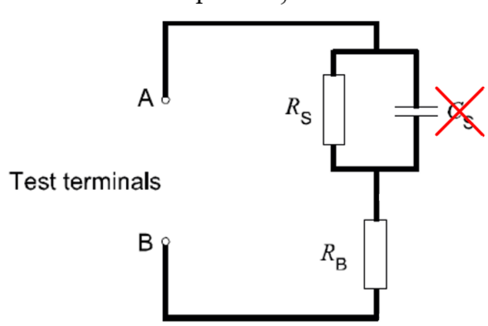
$$R_T = 500\ \Omega$$



$R_S = 0\ \Omega$ $R_B = 500\ \Omega$ $C_S = 0$ uF

Once the short-term effect of capacitance associated with skin impedance is removed from the model, total remaining body resistance is defined as 2,000Ω. Capacitance can be ignored in this case because fault managed power distribution system fault testing shall be performed at 500Ω for touch voltages of 60 - 400 Vdc, which represents worst case conditions where skin impedance is eliminated from the total body resistance calculation.

$$R_T = 2{,}000\ \Omega$$



$R_S = 1{,}500\ \Omega$ $R_B = 500\ \Omega$ $C_S = 0{,}22$ uF

This ATIS body model adopts both the 500Ω and 2,000Ω boundary conditions of the IEC 60990 [Ref 3] model. 500Ω represents a worst-case scenario where skin impedance is eliminated, assuming an open wound or damaged skin contact with live parts. "The human body model of Figure 3 with the *R* and *C* values used herein has traditionally been used in product safety standards for 50 years or more; it has a long history of adequacy for this measurement".

In order to verify that a fault managed power distribution system is capable of detecting and reacting to the highest total body resistance values required to ensure that exposure to electric shock is confined to DC zone 2 for continuous contact with live parts, total body resistance values corresponding to a heart current magnitude of 25mA have been included in this human body model. The 25mA heart current value represents the DC-2 / DC-3 boundary line (the "b line") of IEC 60479-1 [Ref 1] Figure 22, Conventional Time/Current Zones for body current flow durations ≥ 2 seconds.

Hand to foot resistance values are calculated by simple application of ohm's law for each touch voltage. (R_T = touch voltage divided by 25mA) For a hand to foot current path through the body, total body current is assumed to be equal to heart current. Hand to hand resistance values are also calculated by application of ohm's law for each touch voltage, however, a heart-current factor of 0.4 must be applied due to the hand to hand current path through the body. (R_T = touch voltage divided by 62.5mA, where 62.5mA of body current x 0.4 = 25mA of heart current)

The total body resistance values corresponding to 25mA of heart current are more representative of total body resistance values associated with various areas of contact with dry skin conditions for various percentiles of the population. If actual total body resistance values presented by a person exceed the resistance values associated with 25mA of heart current, then the magnitude of heart current that the person sustains is inherently confined to DC zone 1 or 2.

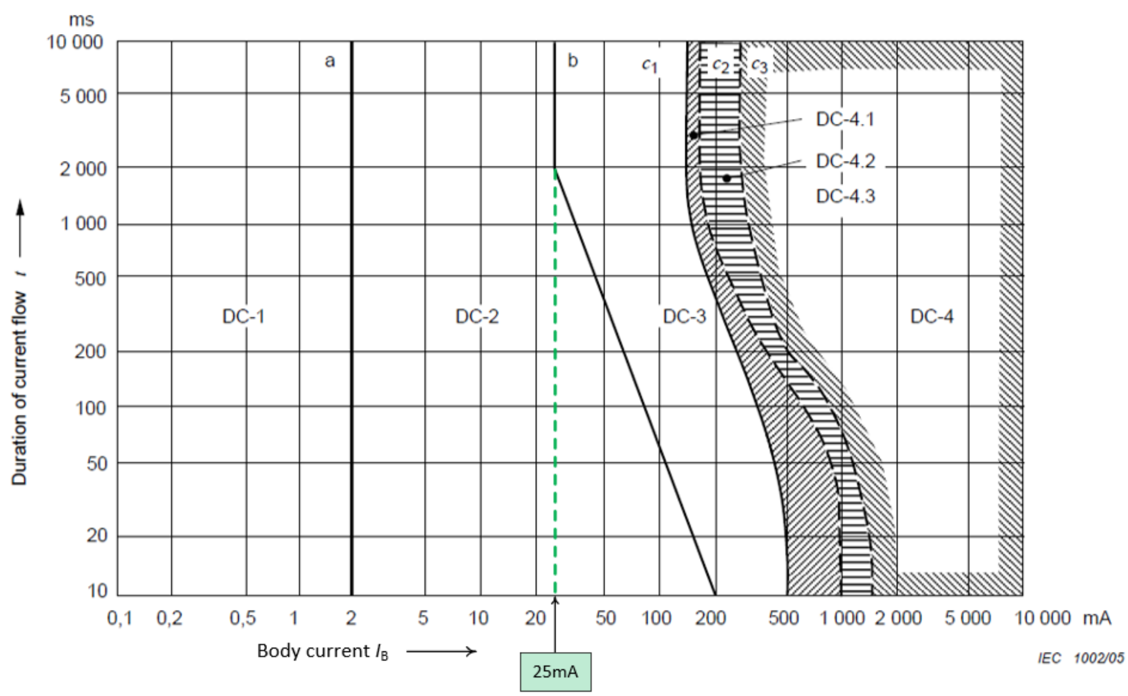


Figure 22 – Conventional time/current zones of effects of d.c. currents on persons for a longitudinal upward current path (for explanation see Table 13)

A.3 Conclusion

This human body resistance model is based on resistance values specified for various touch voltages sourced from Tables 3, 5, 7 and 10 of IEC 60479-1 [Ref 1], “Effects of current on human beings and livestock – Part 1: General aspects”. Upon analysis of the tabular total body resistance data compiled for lowest and highest total body resistances covering more than 95% of the population, it was decided to adopt the boundary resistance values of 500Ω and 2,000Ω defined in the IEC 60990 [Ref 3] Body Impedance Network for touch voltages from 60 to 400 Vdc. Additionally, total body resistance values corresponding to a heart current value of 25mA, which represent the DC-2 / DC-3 boundary line of IEC 60479-1 [Ref 1] Figure 22, Conventional Time/Current Zones for body current flow durations ≥ 2 seconds have been included in this model. These total body resistance values represent the highest fault resistance values that a fault managed power distribution system is required to detect in order to ensure that exposure to electric shock is confined to DC zone 2 for continuous contact with live parts for various surface areas of contact under a wide range of skin conditions.

The human body resistance model presented here is intended to be used in conjunction with a well-defined set of line to line and line to ground fault test cases designed to evaluate fault managed power distribution system response to various simulated human hand to hand and hand to foot contact scenarios. For fault current durations in excess of 10 milliseconds, test results in the form of current magnitude and duration shall be plotted on the conventional time / current zones graph defined in Figure 22 of IEC 60479-1 [Ref 1] to determine the relative safety level of the power distribution system under test. For human fault current events less than 10 milliseconds in duration, the magnitude of current shall be plotted on the graph illustrated in Figure 23 of IEC 60479-2 [Ref 2] to assess the probability of fibrillation risk to the human body.

Annex B

(Normative)

B Application of IEC 60479-1 & IEC 60479-2 - Analysis of Fault Current Waveforms not explicitly covered under IEC 60479-2

B.1 Introduction

IEC 60479-1 [Ref 1] and IEC 60479-2 [Ref 2] are very clear on how to plot unidirectional square wave dc current waveforms. In order to plot an arbitrary unidirectional dc current waveform, produced by some FMPSs, a method of relating the effective energy of the arbitrary pulse to an equivalent dc pulse is needed. After thorough examination of IEC 60479-2 [Ref 2] it has been determined that Section 11 uses the RMS value of current when comparing the risk of ventricular fibrillation for waveforms of different shapes for durations up to 10ms. Example 1 from Section 11 describes a capacitor discharge with a 3ms duration and Example 2 describes a similar discharge with a 30ms duration. Based upon the examples provided, coupled with the content of IEC 60479-2 [Ref 2] Section 9, it is concluded that the RMS value of current may be used to relate the amplitude of an arbitrary unidirectional dc current pulse to a unidirectional square wave dc pulse, which can be plotted using the method identified in the flowchart shown in Figure B.1 below.

The method described in IEC 60479-2 [Ref 2] equates the measured RMS value of current to a dc value that can be used to plot a fault current duration and magnitude on the merged IEC duration – magnitude graph depicted in Figure 5.1 (of this TR) according to the flowchart in Figure B.1 below. This flowchart is a decision-making guide that describes the process for plotting simple line-powering fault current waveforms based on IEC 60479-1 [Ref 1] and IEC 60479-2 [Ref 2] standards. This manual fault current analysis method is provided for informational purposes only. This TR includes a software-based Random Complex Irregular Waveform Analysis (RCIWA) tool for use in analysis of all simulated human body current fault test results produced by test cases defined in this TR. Instructions for use of the tool and example plots are shown later in this Annex. Details regarding theory of RCIWA methodology are explained in Annex E.

It is apparent from IEC 60479-2 [Ref 2], Section 9 that pulses of current with a repetitive nature may present an increased risk of ventricular fibrillation. Section 9.2 addresses possible cumulative effects associated with a series of pulse bursts of human body current in situations when there is less than 300msec of off time between pulse bursts when the first pulse in a series of pulses plots to the right of the b line. Note that any fault current magnitude – duration event that plots to the right of the b line would immediately disqualify a FMPS as being deemed acceptable for inadvertent human contact by this TR. The software-based fault current analysis tool included with this TR takes into consideration, all possible combinations of fault current magnitude, duration and the cumulative effects that may occur when a FMPS produces a complex fault current waveform. Results of the analysis are automatically and accurately plotted as a trace on the merged IEC duration – current graph shown in Figure 5.1 by the software tool.

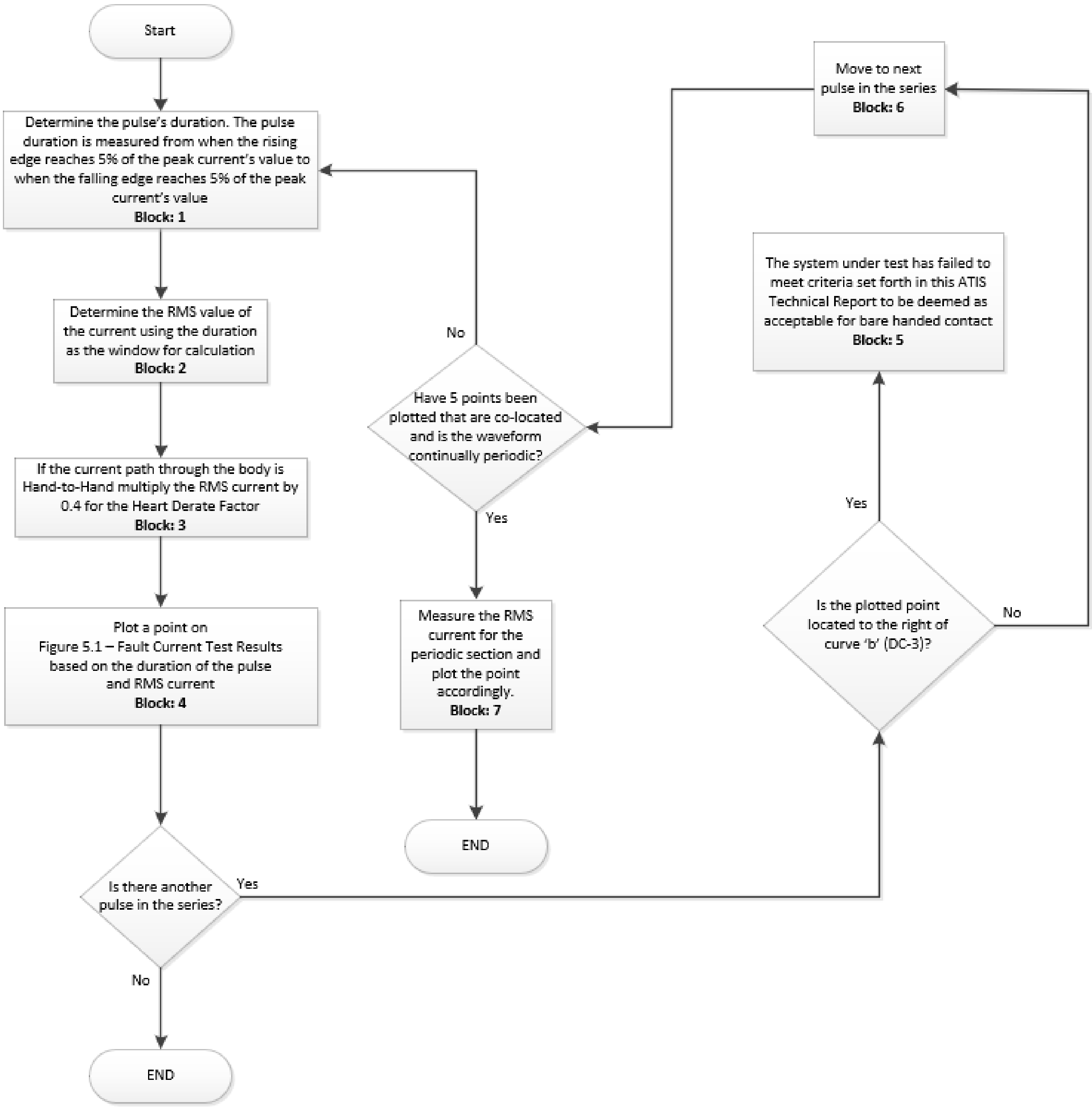


Figure B.1 – Clause 5.3 / 5.4 Test Results Plotting Flowchart (Informational Only)

B.2 Random Complex Irregular Waveform Analysis (RCIWA)

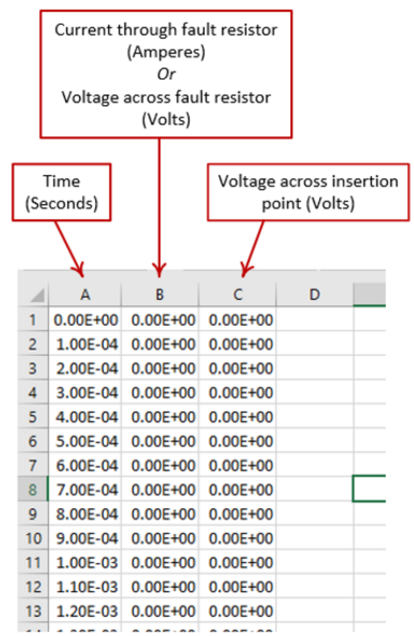
B.2.1 Software-Based Tool Background

Complex irregular fault current waveforms produced by some fault managed power systems in response to human contact fault events can require time consuming and computationally intensive processing to convert raw digital oscilloscope captured waveform data to plottable fault current magnitude and duration data. To ensure that the fault current waveform data captured when performing the test cases defined in this TR is accurately and efficiently plotted on the merged IEC current-duration graph depicted in Figure 5.1, a software-based Random Complex Irregular Waveform Analysis tool has been developed and is included with this TR. The software-based tool takes various waveform properties into consideration during the analysis and processing of the raw waveform data to include interaction between random current pulses. The tool can be configured to analyze both hand to hand and hand to foot current paths through the human body. Upon completion of fault current waveform analysis, the software-based tool produces a test result report in pdf file format. Plotted test results are presented as a continuous trace on the merged IEC current-duration graph depicted in Figure 5.1. Pass / Fail results are indicated for both the 0.1 to 10msec region of the graph (left of the extended b curve) as well as for the 10ms to 10 second region of the graph (DC Zone 1 or 2).

B.2.2 Instructions for use of the Random Complex Irregular Waveform Analysis Tool

#1 - CSV File Requirements

- The CSV file requirements are very simple:
  - A single CSV file for the whole waveform capture from the oscilloscope.
  - The CSV file should have only 3 columns, with the following order, left to right:
    - ➢ Time (in Seconds)
    - ➢ Current through the fault resistor (in Amperes or Volts*)
    - ➢ Voltage across the insertion point** (in Volts)
  - The CSV shall have no header, with the data starting on row 1

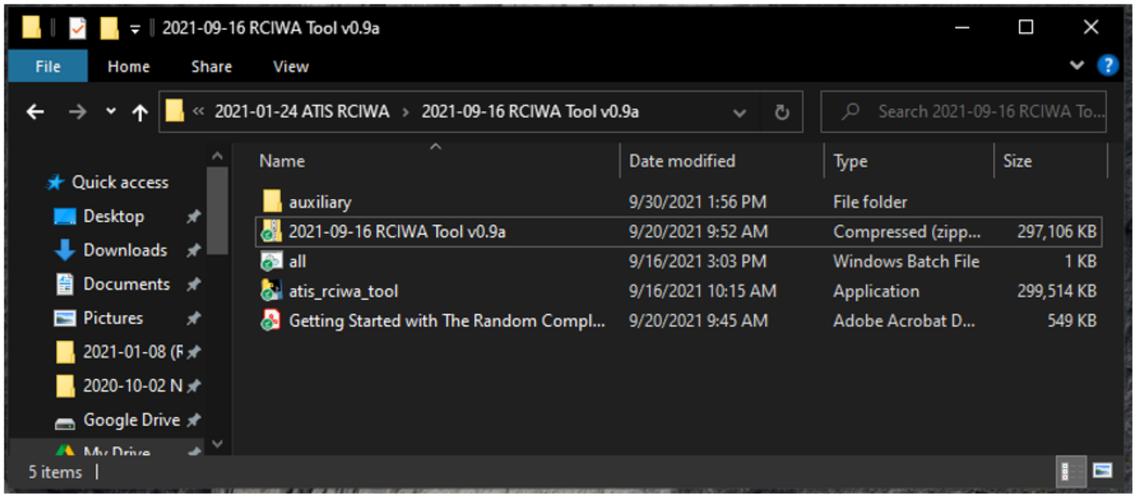


	A	B	C	D
1	0.00E+00	0.00E+00	0.00E+00	
2	1.00E-04	0.00E+00	0.00E+00	
3	2.00E-04	0.00E+00	0.00E+00	
4	3.00E-04	0.00E+00	0.00E+00	
5	4.00E-04	0.00E+00	0.00E+00	
6	5.00E-04	0.00E+00	0.00E+00	
7	6.00E-04	0.00E+00	0.00E+00	
8	7.00E-04	0.00E+00	0.00E+00	
9	8.00E-04	0.00E+00	0.00E+00	
10	9.00E-04	0.00E+00	0.00E+00	
11	1.00E-03	0.00E+00	0.00E+00	
12	1.10E-03	0.00E+00	0.00E+00	
13	1.20E-03	0.00E+00	0.00E+00	

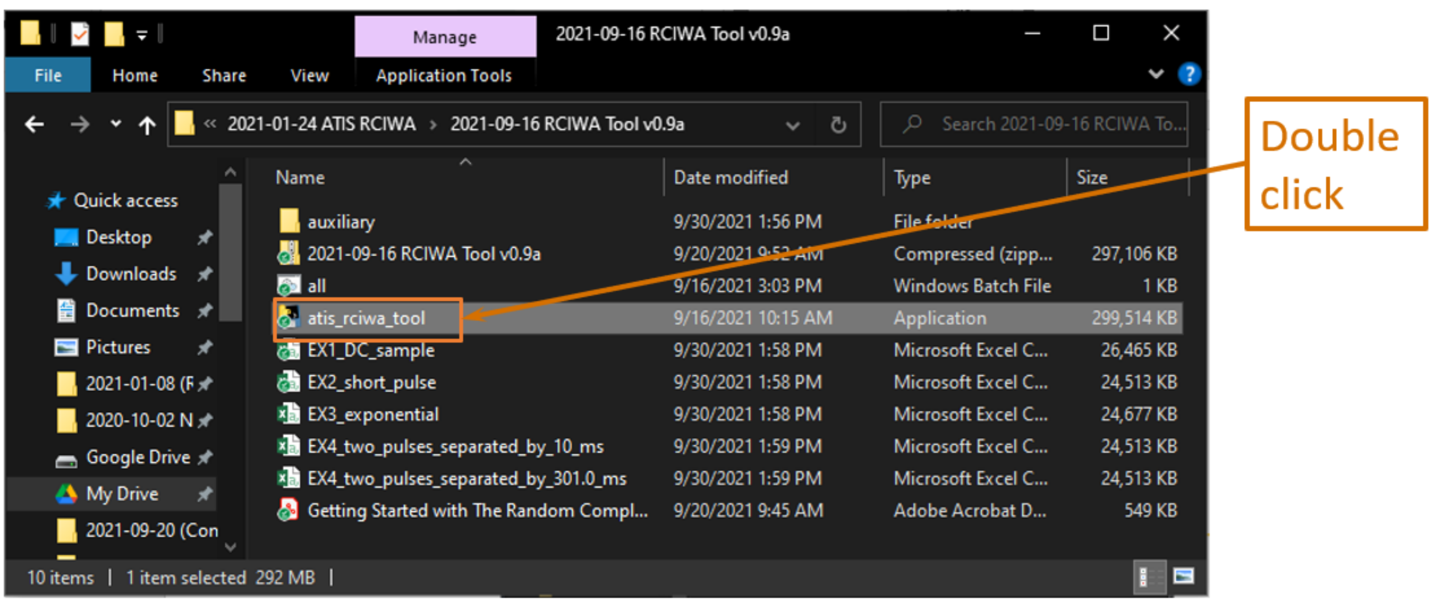
* If the current was measured with a current probe, then the units for the current trace should be Amperes. If the current is measured as the voltage across a resistor, then its units should be Volts; the tool will convert the unit to amperes by dividing by the resistor value specified in ohms.

** The insertion point consists of both the fault resistor and the solid-state switch used to insert the fault resistance into the circuit under test. The voltage measurement across the insertion point includes voltage drop across both the fault resistor and the switch (MOSFET or IGBT).

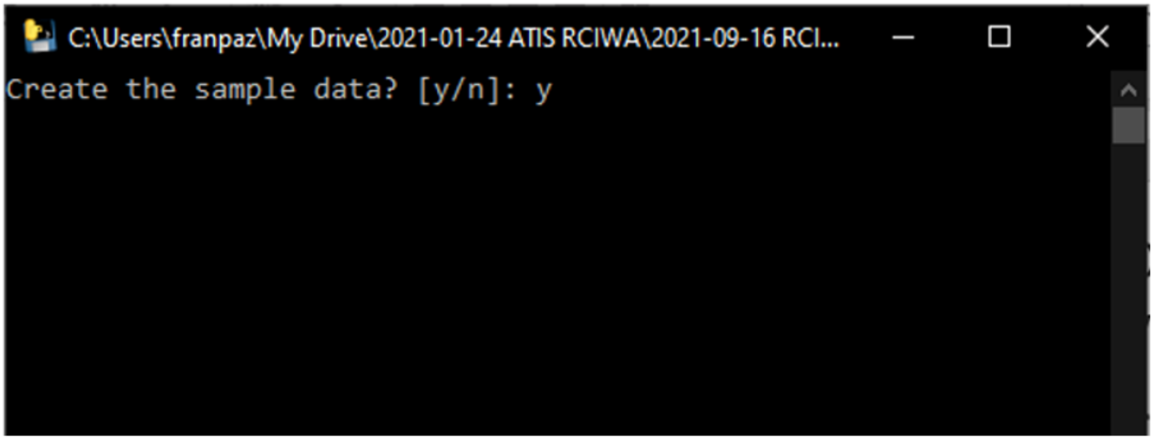
#2 - Unzip the package to a folder of your choice



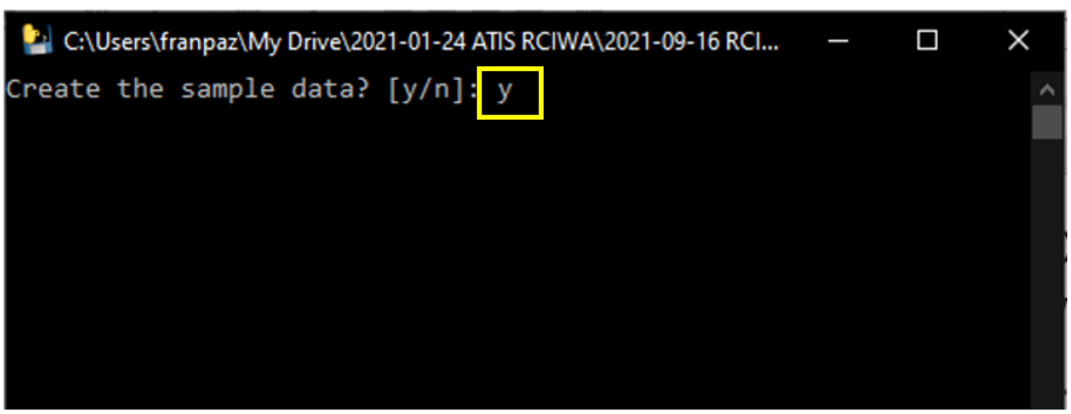
#3 - Double click the executable file



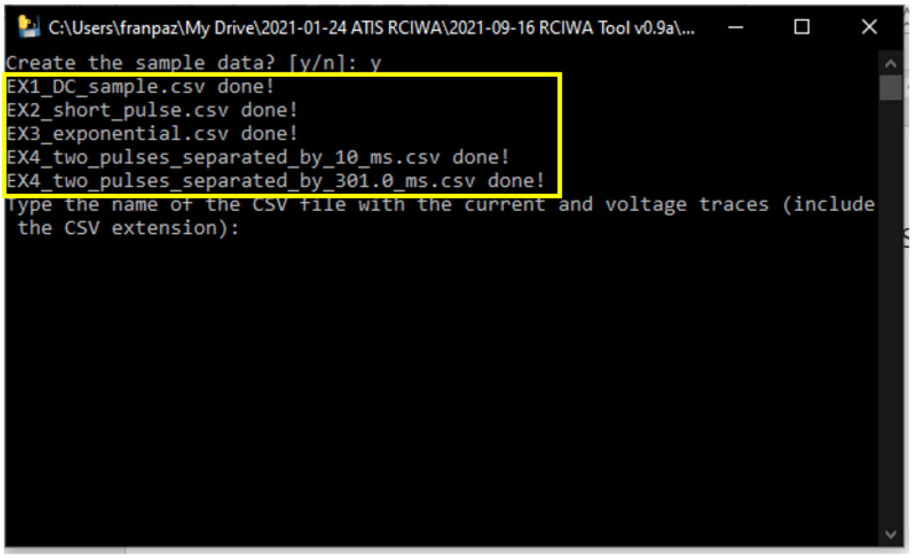
#4 - A command line window will pop up. Wait a few seconds for the program to load.



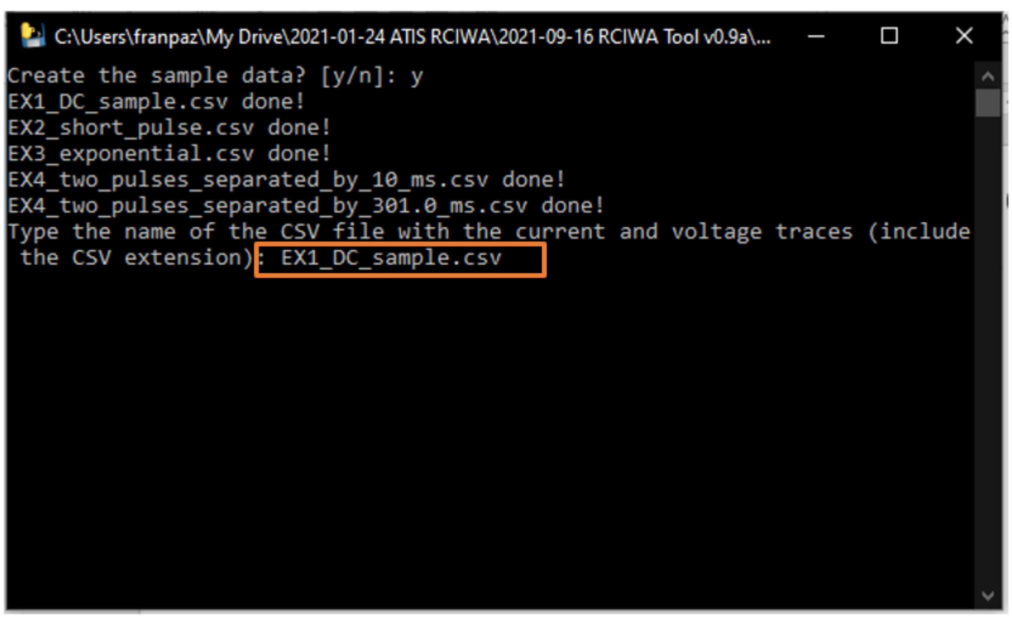
#5 - The program will prompt users to create a set of sample CSV files: Type “y” to create the samples or you can type “n” to skip this step if the samples were previously created or you want to analyze your own CSV files.



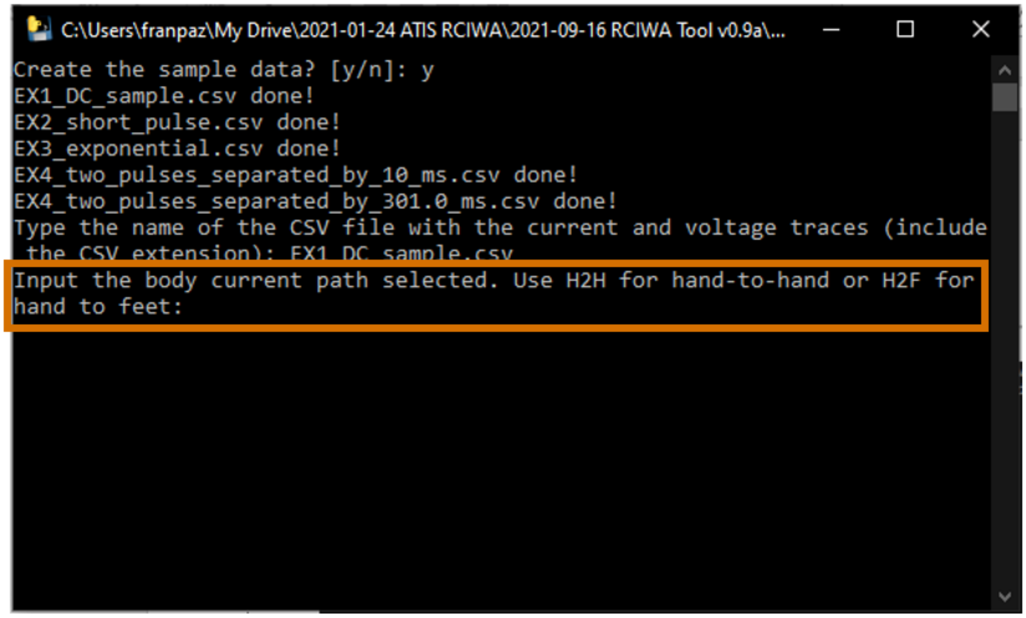
#6 – If “y”, the program will confirm the samples were created before prompting the user to enter the name of a CSV file. If “n”, the user is simply prompted to enter the name of the CSV file to be analyzed.



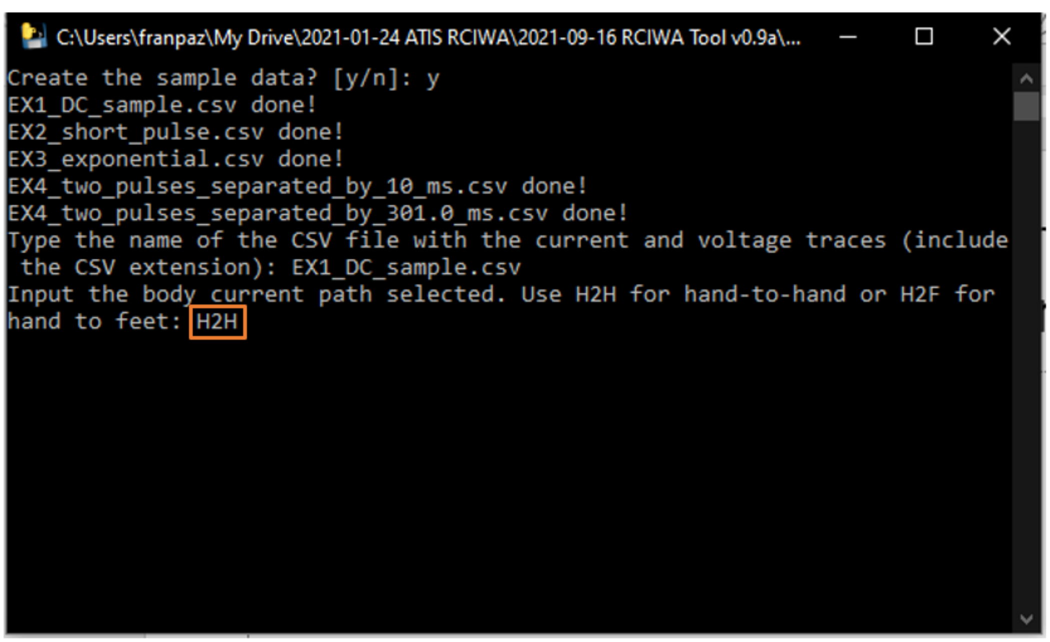
#7 - To analyze a waveform, type the name of the CSV file in the folder (remember to include the .CSV extension). Press enter.



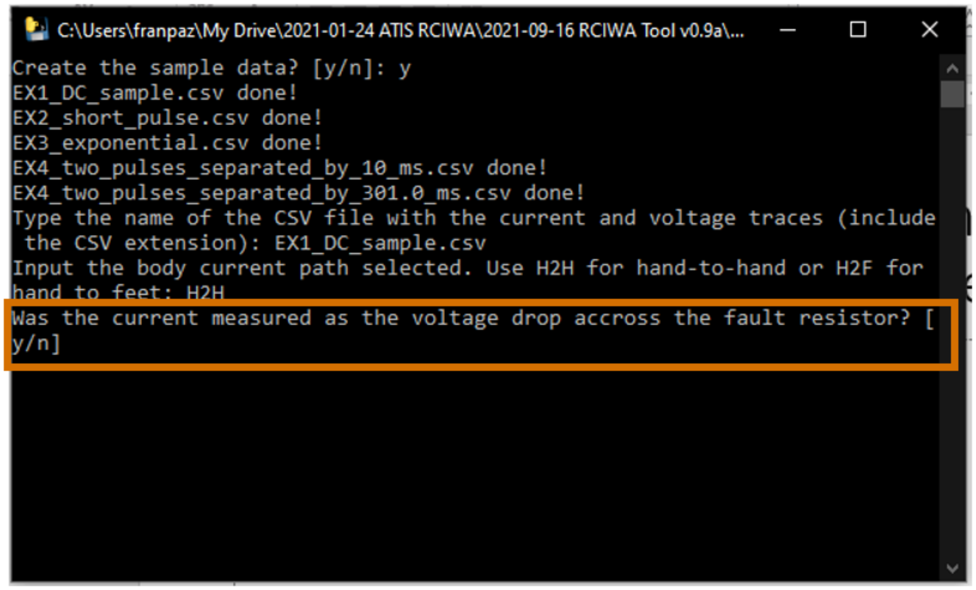
#8 - You will be prompted to enter the body current path for analysis.



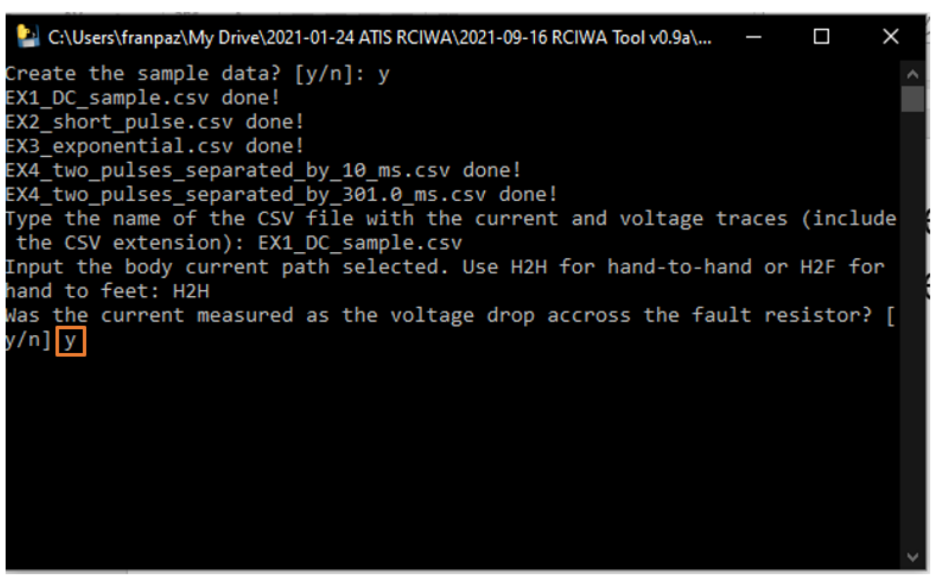
#9 - Type **H2H** for Hand-To-Hand current path or **H2F** for Hand-To-Foot current path. Then press enter.



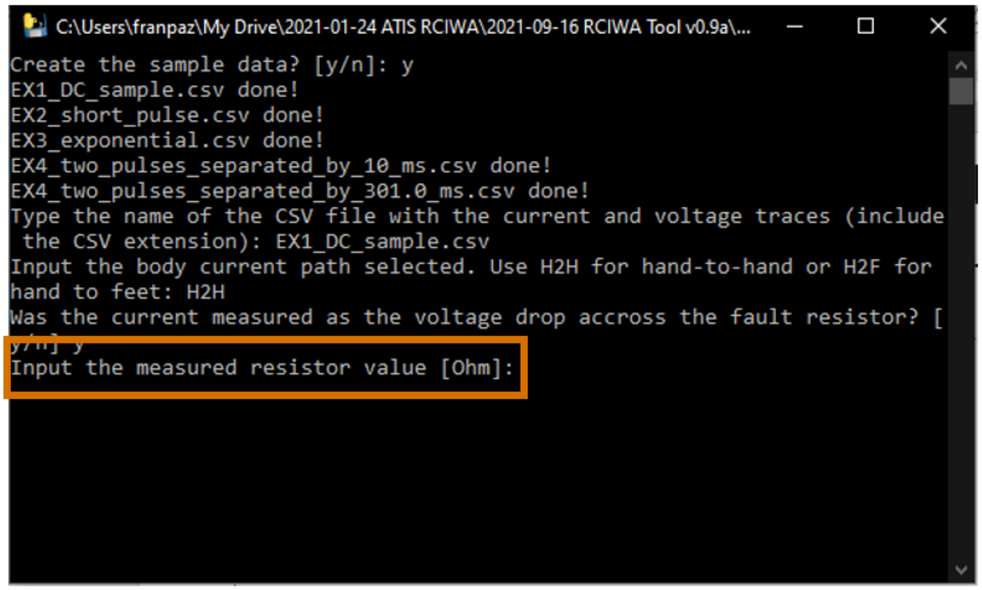
#10 - The program asks if the current is to be calculated based on a voltage drop waveform measurement across the fault resistor.



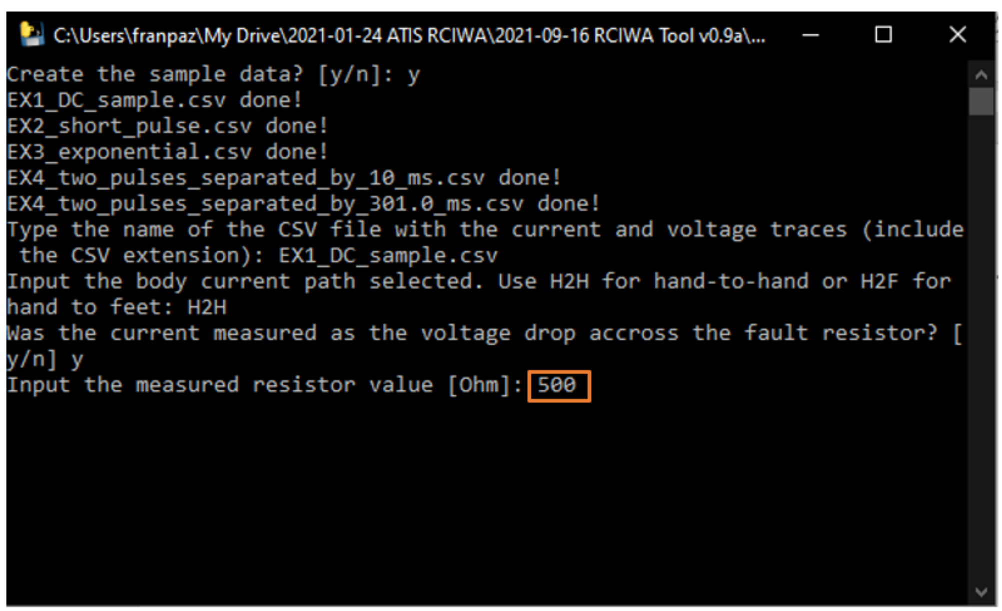
#11 - Type “y” if the current measurement is to be calculated based on a voltage drop waveform measurement across the fault resistor, or else type “n” and go to step #14.



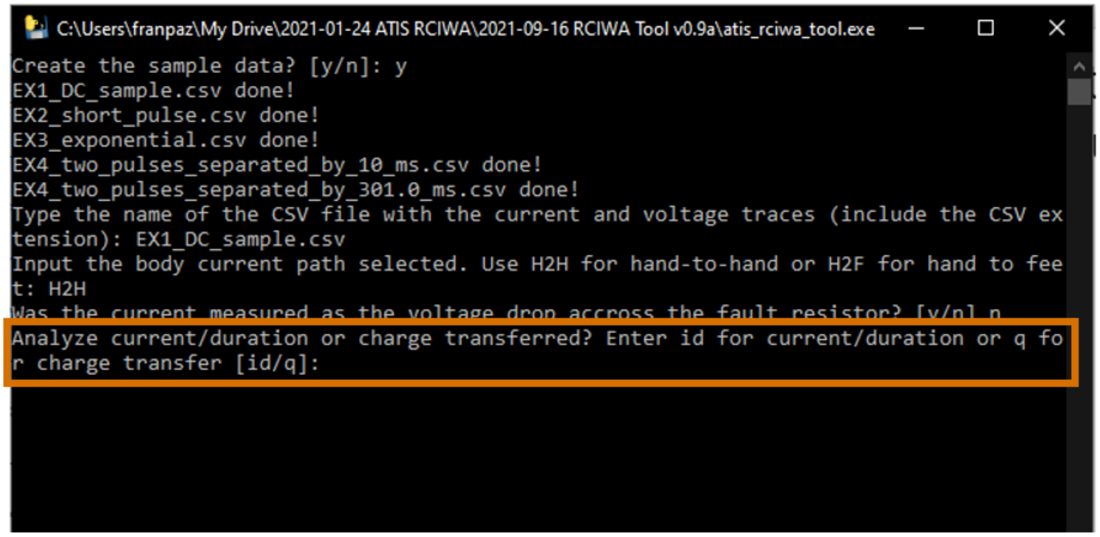
#12 - If the current is to be calculated based on voltage drop across the fault resistor, the program will prompt for the measured value of the resistor.



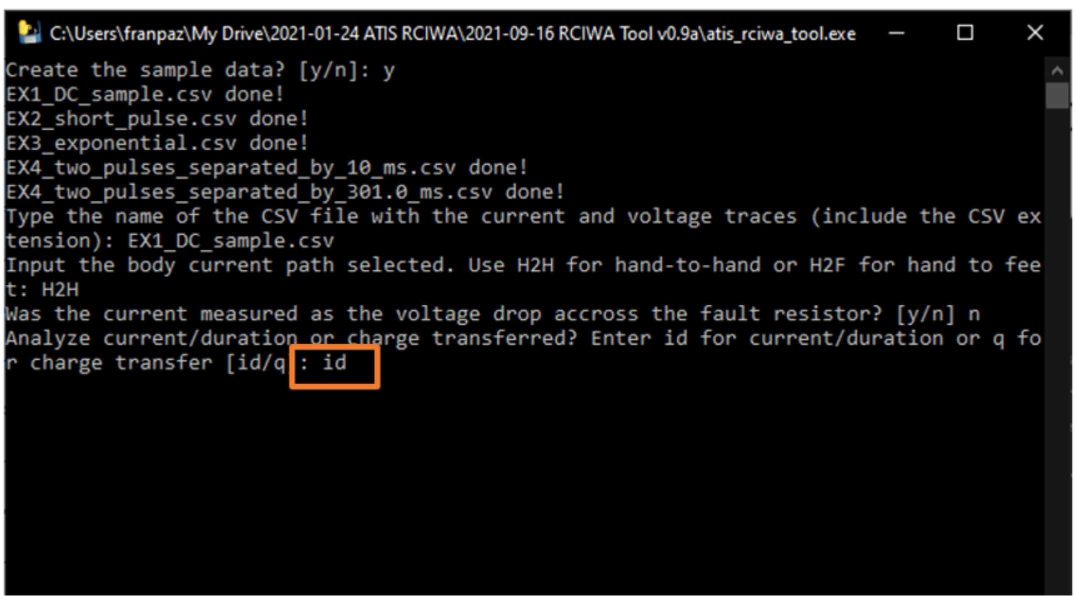
#13 - Enter the value of the resistance in Ohms



#14 - The program will prompt the user to choose between computing charge [q] or current-duration [id].

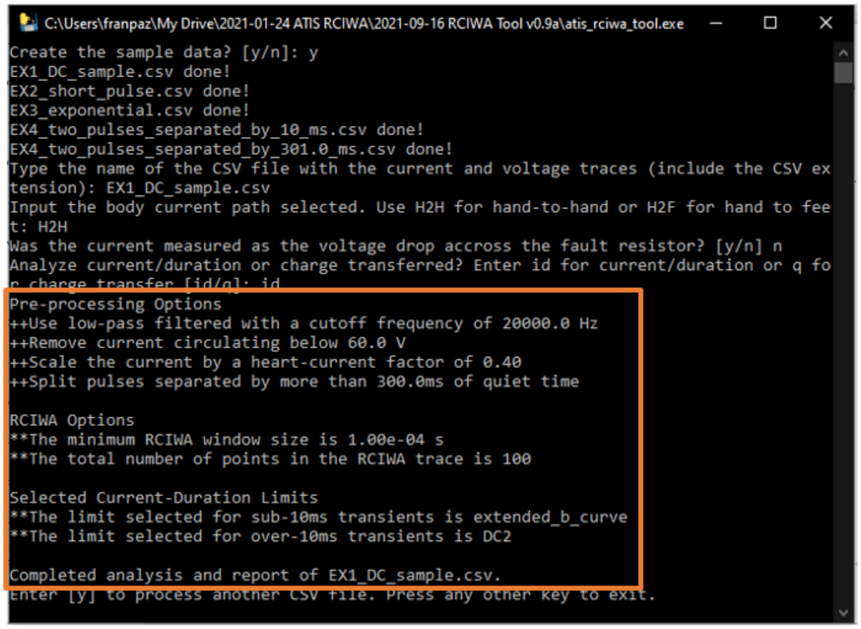


#15 - Enter "id" to calculate the current-duration.

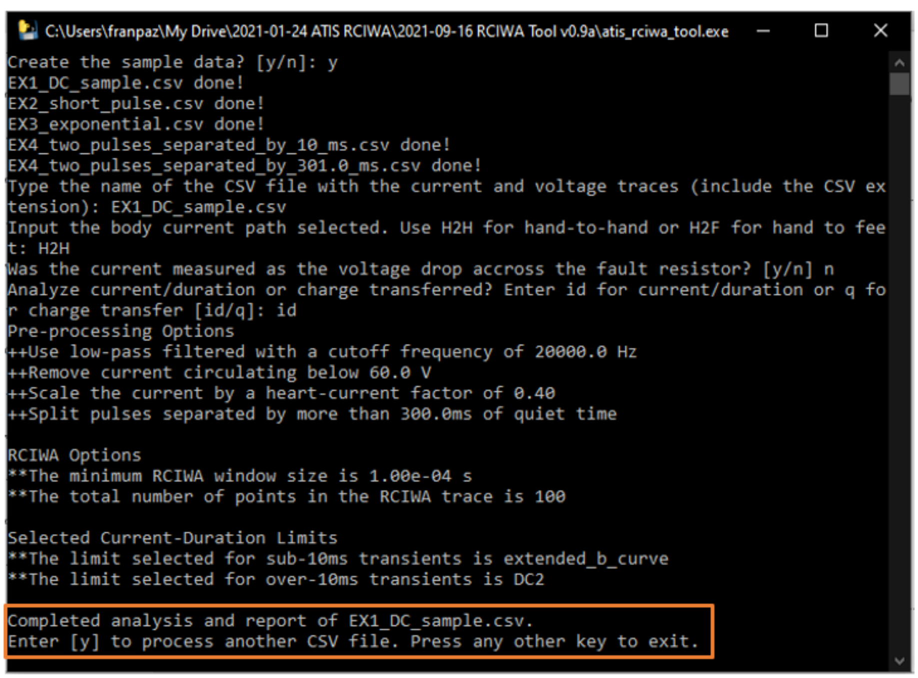


Note:
Choosing "q" will result in an error message since this function is not yet implemented in version v9.0a.

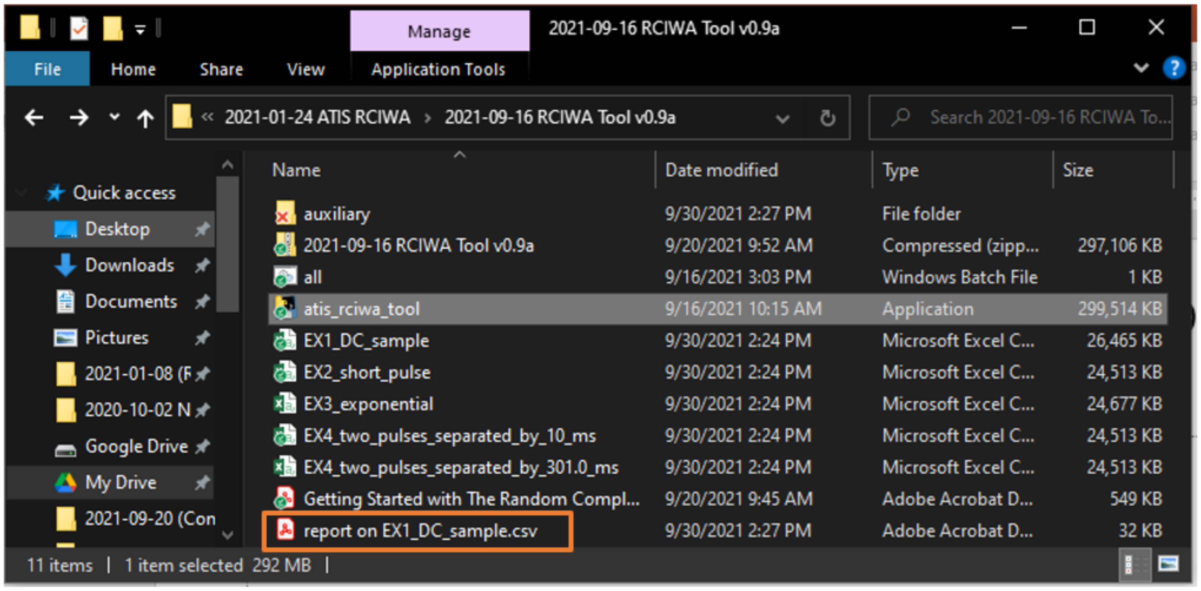
#16 - The program will process the file, display the RCIWA software tool presets and provide notification upon completion of analysis.



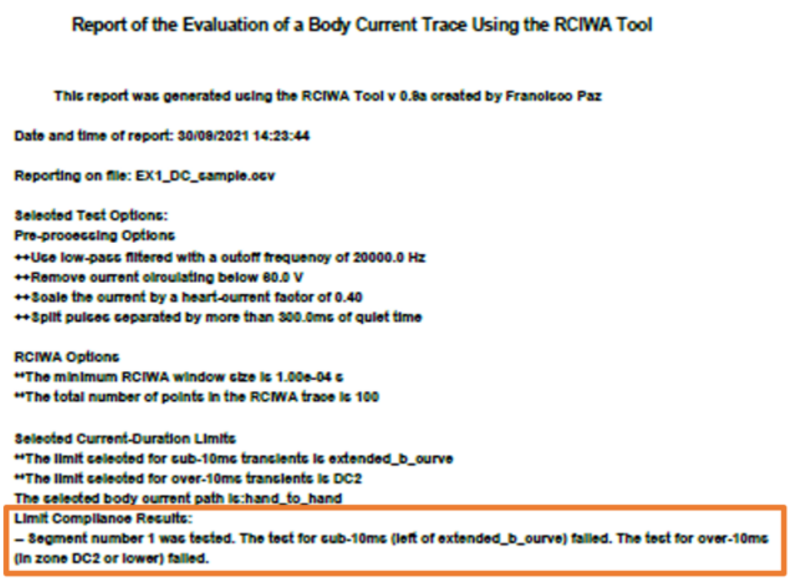
#17 - Once CSV file analysis has been completed, the user can choose to process another file (returns to step #7) or exit.



#18 - The program will have created a PDF report providing the analysis results for the transient waveform.



#19 - The report includes the plot and the pass/fail results


Report of the Evaluation of a Body Current Trace Using the RCIWA Tool

This report was generated using the RCIWA Tool v 0.8a created by Francisco Paz

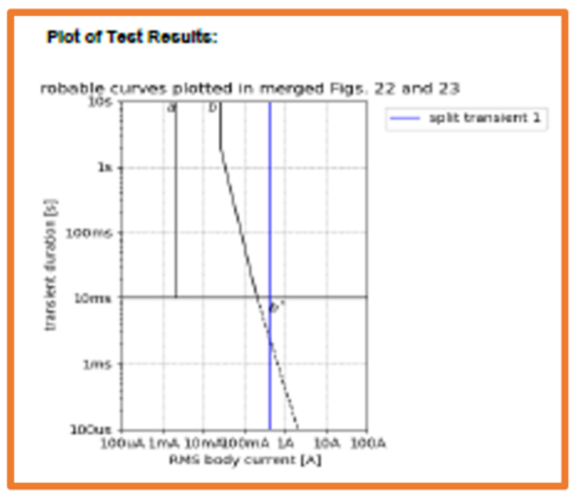
Date and time of report: 30/09/2021 14:23:44

Reporting on file: EX1_DC_sample.csv

Selected Test Options:
Pre-processing Options
++Use low-pass filtered with a cutoff frequency of 20000.0 Hz
++Remove current circulating below 60.0 V
++Scale the current by a heart-current factor of 0.40
++Split pulses separated by more than 300.0ms of quiet time

RCIWA Options
**The minimum RCIWA window size is 1.00e-04 s
**The total number of points in the RCIWA trace is 100

Selected Current-Duration Limits
**The limit selected for sub-10ms transients is extended_b_curve
**The limit selected for over-10ms transients is DC2
The selected body current path is:hand_to_hand
Limit Compliance Results:
-- Segment number 1 was tested. The test for sub-10ms (left of extended_b_curve) failed. The test for over-10ms (in zone DC2 or lower) failed.



B.2.3 RCIWA Software-Based Tool Example Plots

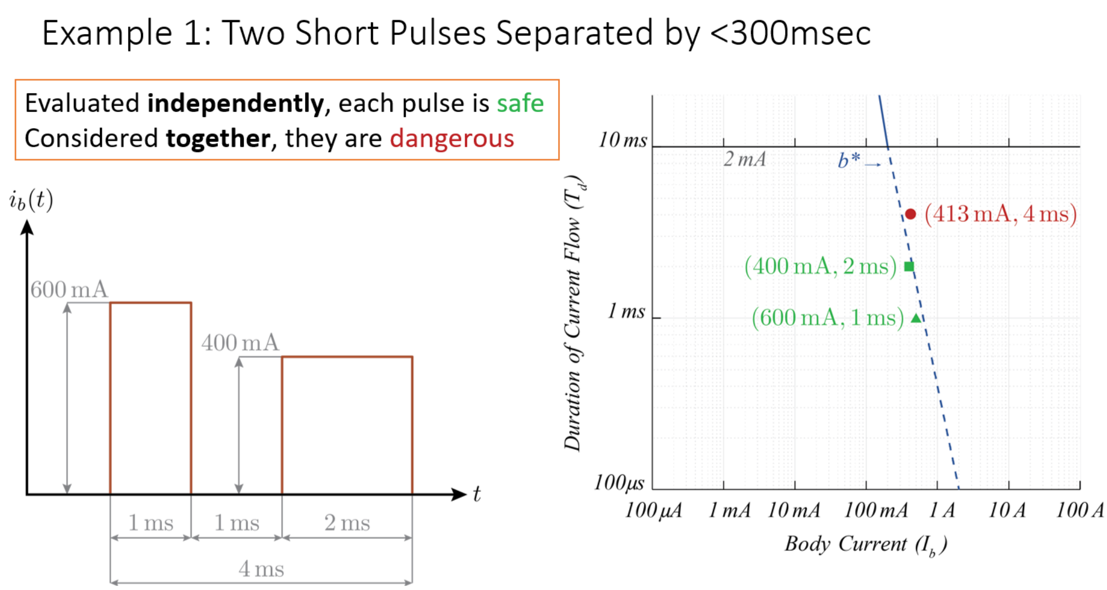


Figure B.2 – RCIWA Example: Two Short Pulses Separated by <300msec

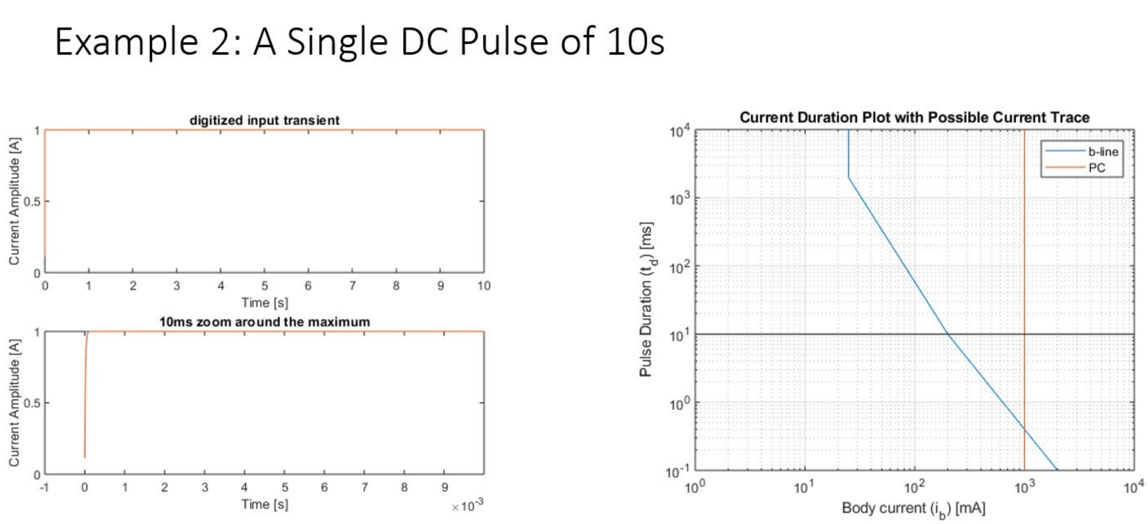


Figure B.3 – RCIWA Example: Single DC Pulse of 10s Duration

Example 3: A Short DC Pulse

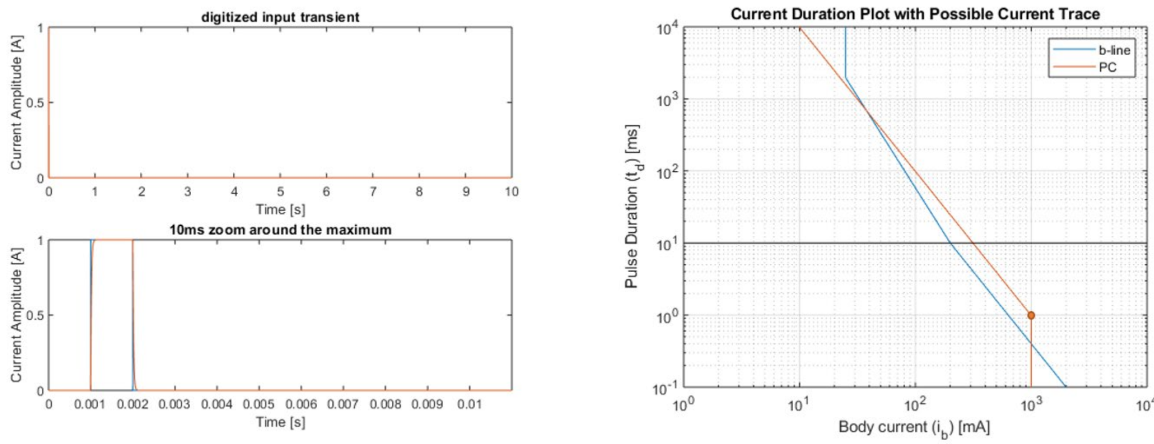


Figure B.4 – RCIWA Example: One Short DC Pulse

Example 4: Two Short DC Pulses

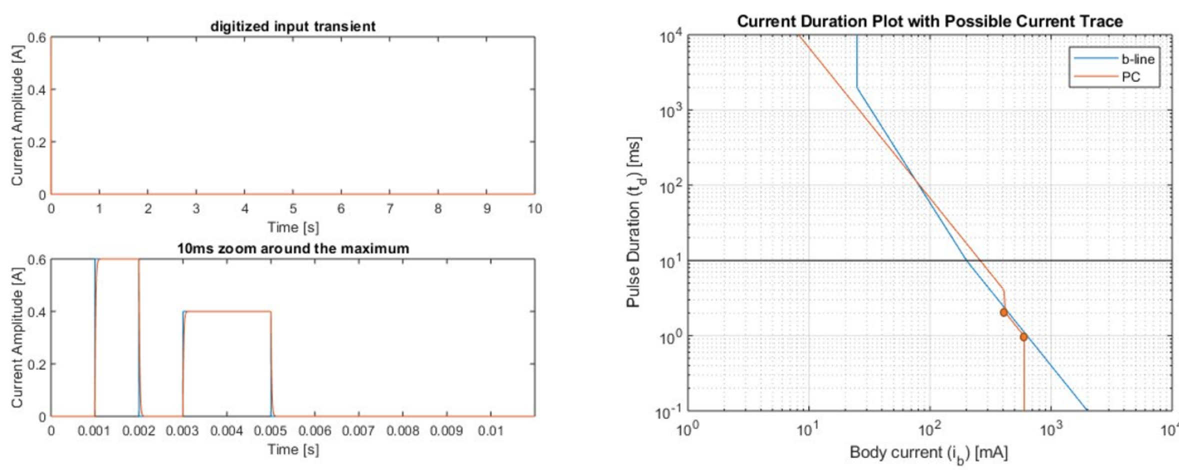


Figure B.5 – RCIWA Example: Two Short DC Pulses

Example 5: Several Random Pulses

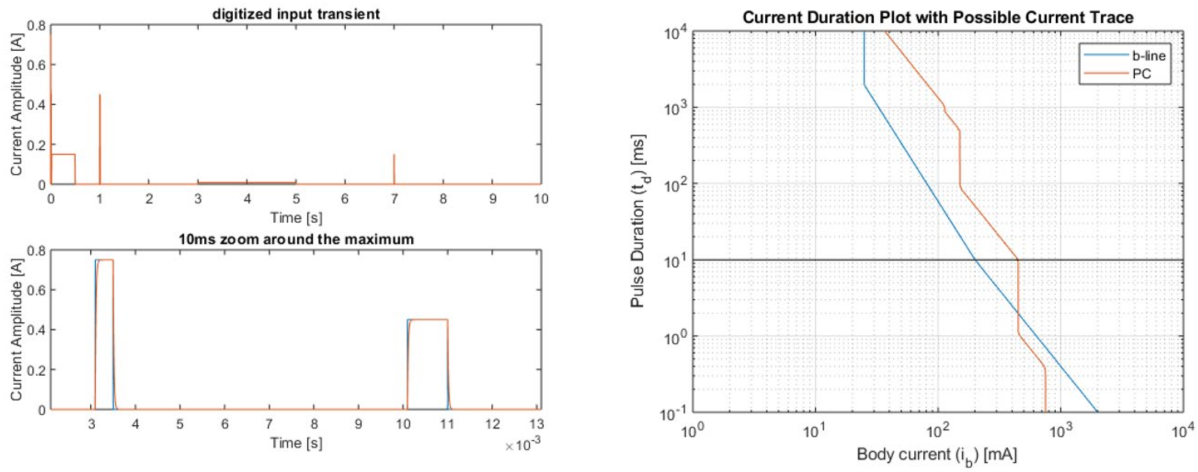


Figure B.6 – RCIWA Example: Several Random Pulses

Example 6: A pulse from an Oscilloscope Capture

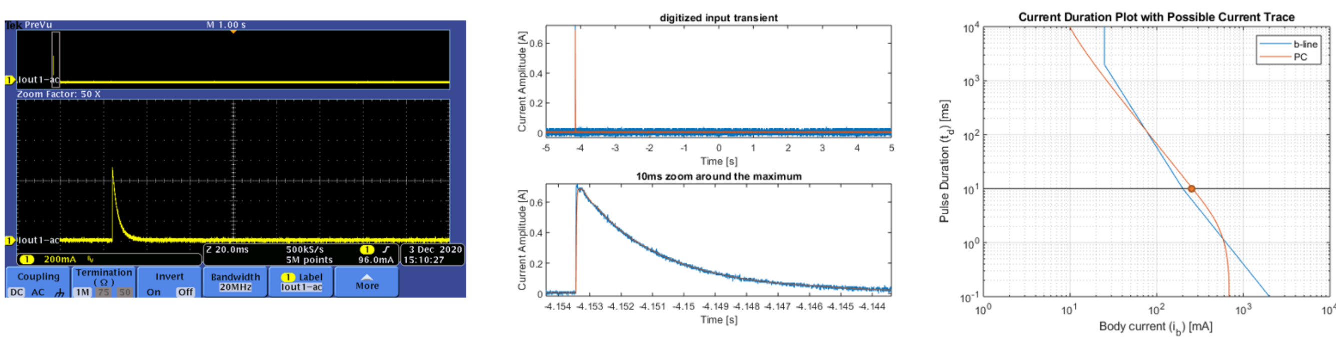


Figure B.7 – RCIWA Example: Single Pulse Oscilloscope Capture

Annex C

(normative)

C Evaluation Procedure for Equivalent Load Circuit Model

The purpose of this Annex is to provide a manufacturer of an FMPS, regardless of the number output ports in a bus configuration, with a process to create a simplified model, consisting of a single PSE, AEN and Equivalent Load Circuit (ELC), for the purpose of evaluating a manufacturer's worst-case FMPS for deployment while reducing the number of tests needed to be performed to qualify the FMPS. It is expected that the manufacturer works with the testing lab to develop the specific worst-case architecture(s) and ELC(s) for each system type evaluated as well as the associated Characteristic Record Tables C2 through C4, which are to be published as part of the testing results report. The following is an outline of the sections presented in this Annex:

C1) Show a general power distribution system for the purpose of defining the system elements, the test points, and the factors that affect the amount of energy transferred into a fault.

C2) Show a list of factors and assumptions for the manufacturers consideration to aid in building the simplified model.

C3) Show a simplified model based on a single PSE, an AEN with N number of output ports and an ELC based on an effective capacitance value.

C4) Show an example of a circuit analysis for both L-L and L-G for the simplified FMPS model to demonstrate that the effective capacitance values used in the ELC can be acceptable given a manufacturers FMPS response time.

C5) Show a procedure to determine the number of tests required based on the FMPS simplified model.

C6) Show considerations for further reductions in the number of tests to be performed.

C7) Show an example system and the associated results when following the steps outlined in this Annex.

C.1 Defining a test configuration for FMPS:

If a system is comprised of a power sourcing equipment (PSE) and n output locations designated Fault Location 1 though n (FL1 – FLn), each with one input (FLn,1) and two outputs (FLn,2 and FLn,3), as shown in Figure C.1, then a system can be developed using an equivalent circuit model to result in a single PSE (transmitter) (FL0) and single AEN (receiver) (FL1) with multiple outputs, in this case 2, (FL2 and FL3) as shown in Figure C.2.

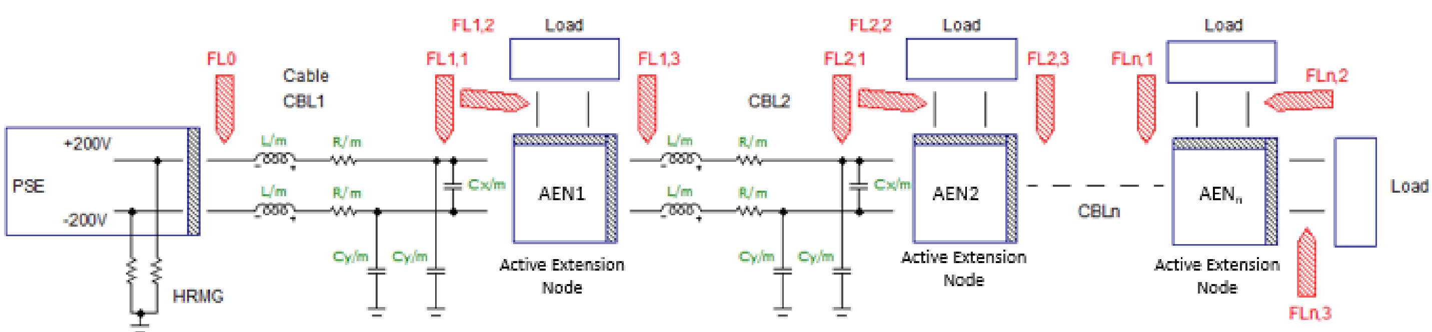


Figure C.1 – General fault managed power distribution system with potential fault locations

(In Figure C.1, the fault management circuitry is designated with a hatched box:)

C.2 Factors and assumptions to aid in building a simplified model:

To simplify the configuration for testing purposes, the following factors and assumptions are considered:

- Fault energy management circuity exists at every AEN.
- The fault management circuitry at each output location is identical (only unique combinatorial configurations are to be tested, as there is no need to test symmetrically equivalent cases).
- The transient current which flows into a fault is dominated by system capacitance (inductance can be neglected).
- The fault management circuitry upstream of the fault and closest to it responds most quickly.
- Downstream capacitive energy may remain connected and discharge into the fault.
- The highest fault current condition is when a fault occurs at AEN power output ports, with a fully populated system downstream. This case results in the largest potentially unmanaged current into the fault.
- Under load, system voltages line-to-line (V_{LL}) and line-to-ground (V_{LG}) are lower for locations further from the PSE. Thus, worst case available fault energy occurs at the output power ports of AEN1.

C.3 Simplified Model:

Therefore, for worst-case fault testing the system downstream of the fault location can be replaced with a lumped-element Equivalent Load Circuit (ELC) at the output ports of AEN1. This is represented with the equivalent network shown in Figure C.2 below:

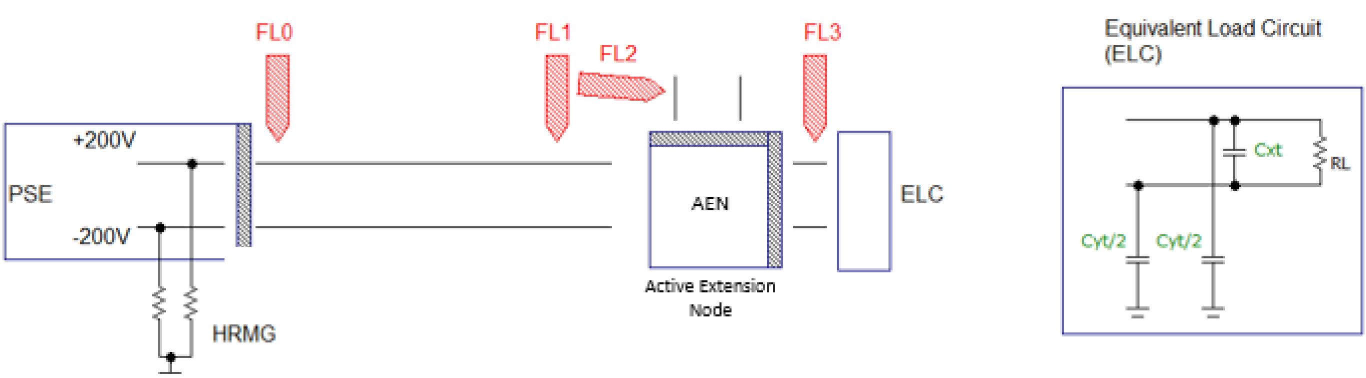


Figure C.2 – Equivalent Worst-case Network Test Circuit

In Figure C.2, maximum system capacitances C_{yt} and C_{xt} are used as defined in Section 4.3 of this TR. However, it is understood that the conditions for system acceptance include current and time fault response per IEC 60479 as highlighted in this document; therefore C_{yt} and C_{xt} values must be chosen to represent available fault energy in the worst-case of a fully populated system. To simulate the worst-case unmanaged fault energy, an equivalent load circuit shall be utilized in the configuration under test provided the ELC is proven to match the actual equipment's response characteristics, as shown in the Section C7 of this Annex. C_{xt} and C_{yt} capacitors will be sized to maximize system capacitances which must include, at a minimum, the capacitance of the interconnecting cables, sum of capacitance in the AENs, the input capacitance of the PDs, and the output capacitance of the PSE.

For testing purposes, the cable length between the PSE and the AEN may be minimized, and the effective capacitance of maximum cable length included in C_{xt} and C_{yt} of the ELC. Further, if FL_0 and FL_1 in Figure C.2 contain the same fault energy management circuitry on their output, then FL_0 can be eliminated from the testing procedure.

C.4 Circuit Analysis Evaluations:

The following analysis considers the equivalent fault circuit within the network from time t_0 (time of fault connection) to t_1 (response time of first upstream fault management segment).

Line to Line equivalent circuit analysis:

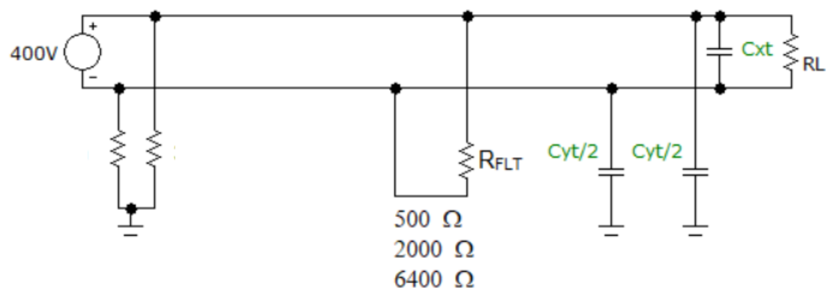


Figure C.3 – Equivalent circuit for L-L fault prior to actuation of fault management circuit

Fault current for Figure C.3 is defined by:

$$\mathbf{I_{FLT}} = \frac{\mathbf{V_{LL}}}{\mathbf{R_{FLT}}} \qquad \textbf{(1)}$$

Equation 1 represents a steady state DC current into the fault. The maximum fault current at 400 V, 500 Ohms:

$$\mathbf{I_{FLT}} = \frac{\mathbf{400}}{\mathbf{500}} = \mathbf{800}\ \boldsymbol{mA} \qquad \textbf{(2)}$$

For the maximum L-L fault current, applying the heart factor of 0.4 for Hand to Hand faults, fault management response must act within ~4 ms according to the recommendations for extending the DC-2 region of IEC60497-1 below 10 ms, see Annex B. The fault management system must not only disconnect from the source of power, but also prevent stored energy from C_{xt} and C_{yt} from discharging into the fault.

Line to Ground equivalent fault analysis:

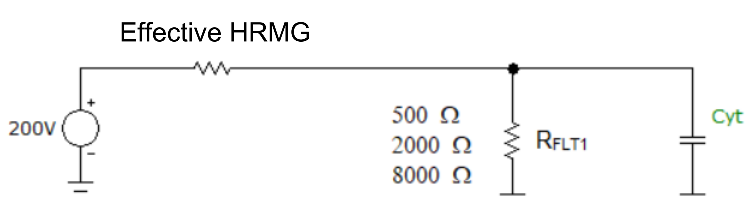


Figure C.4 – Equivalent circuit for L-G fault prior to actuation of fault management circuit

Fault current for Figure C.4 takes the form of an exponential decay:

$$\mathbf{I_{FLT}} \approx \frac{\mathbf{V_{LG}}}{\mathbf{R_{FLT}}} e^{\frac{-t}{(R_{FLT}C_{yt})}} \qquad \textbf{(3)}$$

Where the peak current is equal to:

$$\mathbf{I_{FLTpk}} = \frac{\mathbf{V_{LG}}}{\mathbf{R_{FLT}}} \qquad \textbf{(4)}$$

The highest magnitude peak fault current is therefore (given 500 ohm fault resistance):

$$\mathbf{I_{FLTpk}} = \frac{\mathbf{200}}{\mathbf{500}} = \mathbf{400}\ \boldsymbol{mA} \qquad \textbf{(5)}$$

The RC time constant (given 3.2 uF of system capacitance):

$$\boldsymbol{\tau} = \mathbf{500\ \Omega * 3.2}\ \boldsymbol{uF} = \mathbf{1.6}\ \boldsymbol{ms} \qquad \textbf{(6)}$$

Per IEC 60479-2 [Ref 2], the RMS current of equation 5 over the time period of three RC time constants is:

$$\boldsymbol{I_{rms}} = \frac{\mathbf{400}\ \boldsymbol{mA}}{\sqrt{\mathbf{6}}} = \mathbf{163}\ \boldsymbol{mA} \qquad \textbf{(7)}$$

From Equation 7, the maximum fault current over a time period equal to 4.8 ms is 163 mA. The RMS current into the fault continues to decrease as time increases. Per IEC 60479-1 [Ref 1], Figure 23, the DC-2 boundary current for 4.8 ms ≈ 1000 mA, therefore, the discharge of the maximum value of y capacitance of 3.2 uF for a 200 V L-G system into a worst-case fault resistance of 500 ohms can be considered an acceptable condition.

C.5 Test Count Determination

To test and evaluate all possible combinations of network construction and loading for worst-case conditions, a minimum number of tests need to be determined for system acceptance.

If a distributed power system utilizes functionally equivalent AEN(s) containing fault energy management with one or more outputs, then a system can be reduced to a single PSE and AEN and equivalent load circuit(s) as shown above in Figure C.2. The following Test Cases 1 through 5 provide the framework for each manufacturer to evaluate the minimum number of tests to be performed for their FMPS based on the conditions of a fault, H-H and H-F, and the associated resistances, defined in Annex A. This section does not include tests to be performed for the evaluation of systems at startup or during steady state operation or every combination without a terminated loop or PD. Instead, Section 5.4 further develops a detailed test plan including these items to be followed based on this Annex.

Test Case 1: PSE Testing

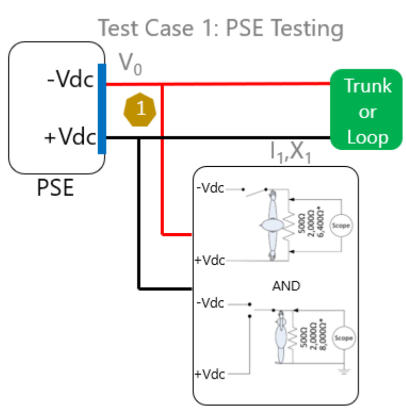


Figure C.5 – Test Case 1 – PSE

Since there is 1 unique output at the PSE with 4 load combinations, 3 resistance values for the simulated human body resistance and 3 test types (H-H, +L-G, and -L-G) a minimum of 36 tests at the PSE output are required.

Test Case 2, 3 and 4: AEN Testing with 1 Input and N = 2 Output Branches

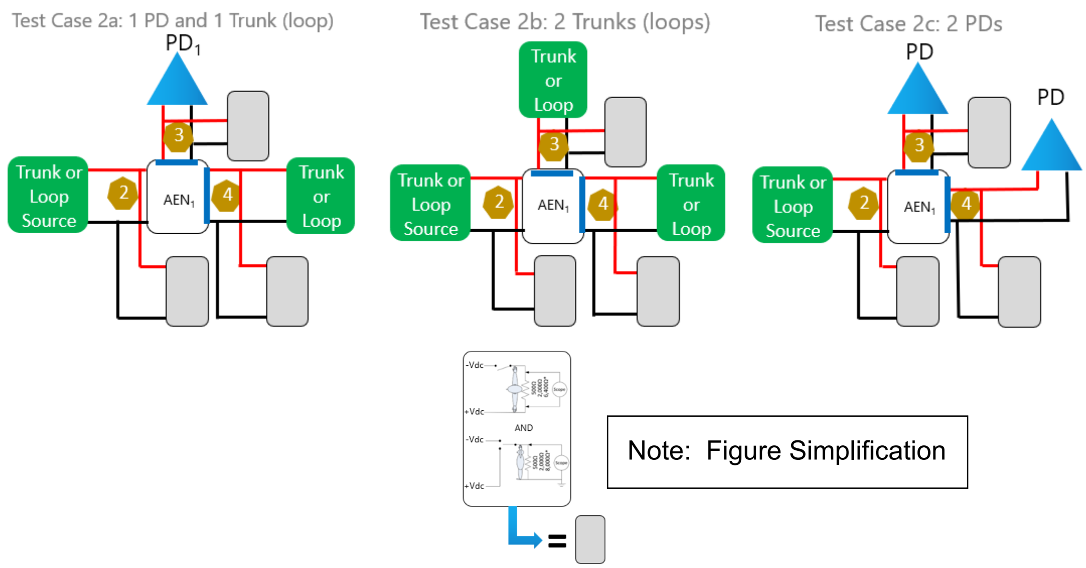


Figure C.6 – Test Cases 2, 3 and 4: AEN with 1 Input and N = 2 Output Branches

<u>AEN Output:</u>

There are 3 load cases for each output, therefore the number of combinations of load tests are 3^{NB}, where NB is the number of output branches. With 2 output branches in this example, then 9 load combinations are possible. Similarly, with 2 output groups, PD and ELC, and 2 output branches (see Figure C.6), then 2^{NB} group combinations are possible or 4 groups yielding 9 X 4 or 36 tests. Adding a No Load (NL) test case on each output and for each group's opposing load condition yields 13 tests. Making the total number of possible test combinations for 2 output branches equal to 49, as shown in Table C1.

Table C.1 - Test Matrix - Combinations for 2 Output AEN

Possible Load Combinations for Equivalent Load Circuit (ELC) for NB = 2								
Outputs		No Load (No PD)	Based on Maximum PD Power*			Based on Maximum AEN Power*		
2 \ 1			PD @ 0%	PD @ 50%	PD @ 100%	ELC @ 0% or ELC_2 @ 0%	ELC @ 50% or ELC_2 @ 50%	ELC @ 100% or ELC_2 @ 100%
No Load (No PD)		X	X	X	X	X	X	X
Based on Maximum PD Power*	PD @ 0%	X	X	X	X	X	X	X
	PD @ 50%	X	X	X	X	X	X	X
	PD @ 100%	X	X	X	X	X	X	X
Based on Maximum AEN Power*	ELC @ 0% or ELC_2 @ 0%	X	X	X	X	X	X	X
	ELC @ 50% or ELC_2 @ 50%	X	X	X	X	X	X	X
	ELC @ 100% or ELC_2 @ 100%	X	X	X	X	X	X	X

*Notes:
PD - Based on a maximum power in Table C2
ELC - When paired with a PD, based on AEN maximum output current, residual line current, in Table C2
ELC_2 - Used when paired with another ELC, ELC_2 current = PSE maximum current/2

With 3 resistance values for the simulated human body, 3 test types (H-H, +L-G, and -L-G), an AEN with NB = 2 yields 49 x 3 x 3 or 441 fault test combinations for the AEN output, minimum.

AEN Input:

Since there is 1 unique input to the AEN with 4 load combinations, 3 resistance values for the simulated human body and 3 test types (H-H, +L-G, and -L-G) a minimum of 36 tests at the AEN input are required.

Test Case 5: Midspan Cable Testing:

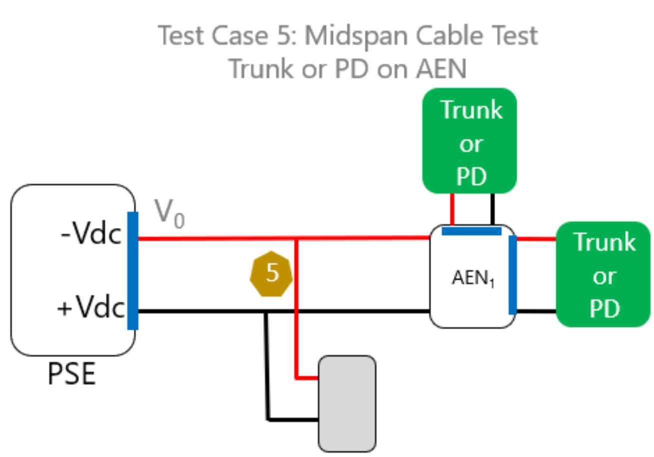


Figure C.7 – Test Case 5 – Midspan Cable Testing with AEN with N = 2 output Branches

Since there is 1 unique line in the cable with 4 load combinations, 3 resistance values for the simulated human body and 3 test types (H-H, +L-G, and -L-G) a minimum of 36 tests are required at the midspan of the cable.

Test Case Summary: PSE, AEN, and Midspan Cable Testing

The number of test combinations for the PSE, AEN, and cable is 36 + 441 + 36 + 36 or 549 tests.

C.6 Fault Test Number Reduction Possibilities:

1) If each AEN in a distribution network is shown to be identical in function – resulting in 1 PSE and 1 AEN with equivalent load circuit (max capacitance) – then fault testing can be reduced to the test conditions shown in C5 of this Annex.
2) If each component in the system, PSE and AEN for example, contains an FMPS at every input or output and they are identical in function, then measuring fault current at the one location with the worst-case condition is sufficient.
    - This could potentially focus all testing to the AEN resulting in a reduction of PSE tests or 36 tests. For example, elimination of FL_0 in Figure C.2.
3) If the No Load (NL) case assumes a non-connected or Loop Only condition, and the system is shown to not power a non-connected loop, then this is considered an interlock protection and fault testing is not applicable (NA).
    - This could potentially reduce the number of tests by 14 NL conditions x 3 test types x 3 resistance values or 126 tests.
4) Since the maximum voltage yields highest stored energy levels stored in a capacitor, then testing at lowest possible load will result in a worst-case fault condition and therefore shall reduce the number of tests to that of highest voltage or lowest load.
    - This would reduce the number of tests for each output to the 0% load condition or a reduction of 90 tests.
5) If the remote device has only 1 output, then it is tested with NB = 1 or similar to the “point to point” systems.

If a manufacturer’s system meets the above criteria and the test count reductions are allowed, then the number of tests can be significantly reduced. This does not account for the tests to show acceptability of the ELC or to prove that certain tests are not applicable (NA).

C.7 Example – System Evaluation and Testing:

The following example system will be used to show how to test the performance of an FMPS and its similarity to an Equivalent Load Circuit (ELC) to support the certification of deployed systems based on maximum values of Current, Power and individual component capacitances, L-L and L-G.

Step 1: Determine the parameters of the FMPS system. These parameters include the maximum allowable voltage drop in the distributed loop, the maximum allowable current in the loop, and the PSE, PD, AEN and Cable capacitance and resistance values. An example list is shown in Table C2.

* It is important to note that the values provided in this table are an example for evaluation purposes and do not necessarily constitute a working or safe system.

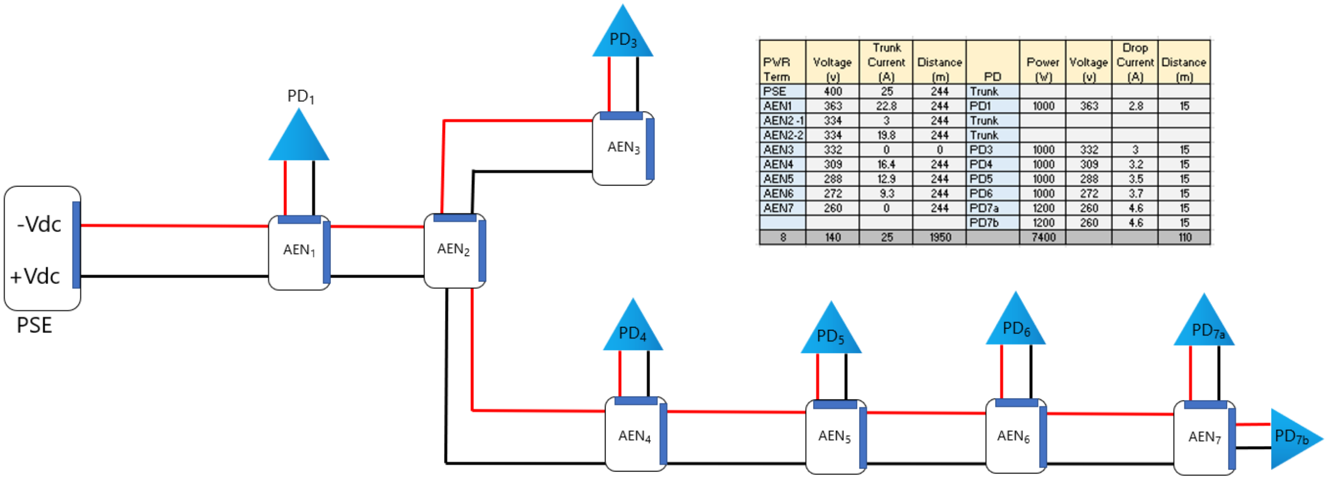
Table C.2 - System and Component Characteristic Record

Element	Description	Value	Units	Notes
Power Sourcing Equipment	Voltage	400	vdc	maximum voltage
	HRMG (Resistance)	16000	ohms	
	Max Current	25	amps	exiting PSE
Cable	Cap (L-L)	50	pF/ft	
	Cap (L-G)	40	pF/ft	
	Resistance	0.81	ohms/kft	
	Inductance (L-L)	0.2	mH/ft	
	Inductance (L-G)	0.1	mH/ft	
Powered Device	Cap (L-L)	1	uF	
	Cap (L-G)	10	nF	
	Load	1000	watts	max load
	Max current	5	amps	at lowest line voltage of 250 vdc
	Voltage, max	400	vdc	
	Voltage, min	250	vdc	
Power Termination - Active Extension Node	Cap (L-L)	0.5	uF	per output
	Cap (L-G)	5	nF	per output
	*Input Current	25	amps	maximum
	Output 1 Current, min	0	amps	
	Output 1 Current, max	25	amps	
	*Output 2 Current, min	0	amps	
	*Output 2 Current, max	$= I_{input\ (max)} - I_{output\ 1}$	amps	residual line current

* Notes: Input Current: The maximum current as Input to the AEN

Output Current: Range of current at Output 2 of AEN = Input Current $_{(max)}$ - Output 1 Current

Step 2: Build a model that contains all the unique components in the system that require evaluation for certification. In a bus-based architecture it has been shown that for a 2-output AEN, there are three termination configurations and they are shown above under the heading "Test Case 2: AEN Testing with N Output Branches" and Figure C.6. This model will include several of these AENs and PDs to maximize voltage drop and system current. An example of one such system is shown in Figure C.8.



PWR Term	Voltage (v)	Trunk Current (A)	Distance (m)	PD	Power (W)	Voltage (v)	Drop Current (A)	Distance (m)
PSE	400	25	244	Trunk				
AEN1	363	22.8	244	PD1	1000	363	2.8	15
AEN2 -1	334	3	244	Trunk				
AEN2-2	334	19.8	244	Trunk				
AEN3	332	0	0	PD3	1000	332	3	15
AEN4	309	16.4	244	PD4	1000	309	3.2	15
AEN5	288	12.9	244	PD5	1000	288	3.5	15
AEN6	272	9.3	244	PD6	1000	272	3.7	15
AEN7	260	0	244	PD7a	1200	260	4.6	15
				PD7b	1200	260	4.6	15
8	140	25	1950		7400			110

Figure C.8 – Basic Test Model Example – Simulating Worst-Case System with Production Equipment

From the calculation, the current and voltage drop is maximized.

Step 3: Calculate from the example above the system characteristics based on the component characteristics record, Table C2, to build the ELC. Items to note are:

i. The maximum cable length is 1950 + 110 = 2060 meters
ii. The number of PDs is 7
iii. The number of AENs is 6 (minus AEN1 as this component will be used in the system test model)

From these results the system energy storage and line resistance characteristics are:

Table C.3 - System and ELC Characteristic Record

Element	Description	Value	Units	Multiplier	Total Value	Units
Power Sourcing Equipment	Voltage	400	vdc	1	400	vdc
	HRMG (Resistance)	16000	ohms	1	16000	ohms
	Max Current	25	amps	1	25	amps
Cable	Cap (L-L)	50	pF/ft	6760	0.34	uF
	Cap (L-G)	40	pF/ft	6760	0.27	uF
	Resistance	0.81	ohms/kft	6760	5.48	ohms
	Inductance (L-L)	0.2	mH/ft	6760	1.35	mH
	Inductance (L-G)	0.1	mH/ft	6760	0.68	mH
Powered Device	Cap (L-L)	1	uF	7	7	uF
	Cap (L-G)	10	nF	7	70	nF
	Load	1000	watts	7	7,000	watts
	Max current	5	amps	4.6	4.6	amps
	Voltage, max	400	vdc	NA		vdc
	Voltage, min	250	vdc	NA		vdc
Power Termination - Active Extension Node	Cap (L-L)	0.5	uF	6	3	uF
	Cap (L-G)	5	nF	6	30	nF
	*Input Current	25	amps	NA		amps
	Output 1 Current, min	0	amps	NA		amps
	Output 1 Current, max	25	amps	NA		amps
	*Output 2 Current, min	0	amps	NA		amps
	*Output 2 Current, max	$= I_{input\ (max)} - I_{output\ 1}$	amps	NA		amps

* Notes: Input Current: The maximum current as Input to the AEN

Output Current: Range of current at Output 2 of AEN = Input Current $_{(max)}$ - Output 1 Current

Step 4: Assemble and test the basic test model per this TR as it represents a manufacturer's fully populated system (example shown in Figure C.8 above) at the output of the PSE and the input/output of AEN 1 and show that the FMPS results as plotted per Annex B, fall to the left of the "b line".

Step 5: Now that a worst-case model has been built and tested based on production equipment for a single deployment type, an ELC consisting of a resistive/capacitive circuit defined by Table C3 needs to be constructed to compare the results from Step 4 to the test results with an ELC.

Upon acceptance of a proven ELC that matches the results from production equipment, maximum allowable values for resistance and capacitance can be used in the ELC to test a worst-case system, by emulating the maximum energy storage using the X and Y capacitors (simplified ELC modeling) yet still meeting the safety criteria defined in this TR.

Since acceptance is based on all of the load and network combinations shown in Table C1, Test Matrix – Combinations for 2 Output AEN, circuits A - D of Figure C.9 are to be created, tested and analyzed based on the conditions of acceptability, resulting in a system response of current and time plotting to the left of the "b line", when plotted per Annex B.

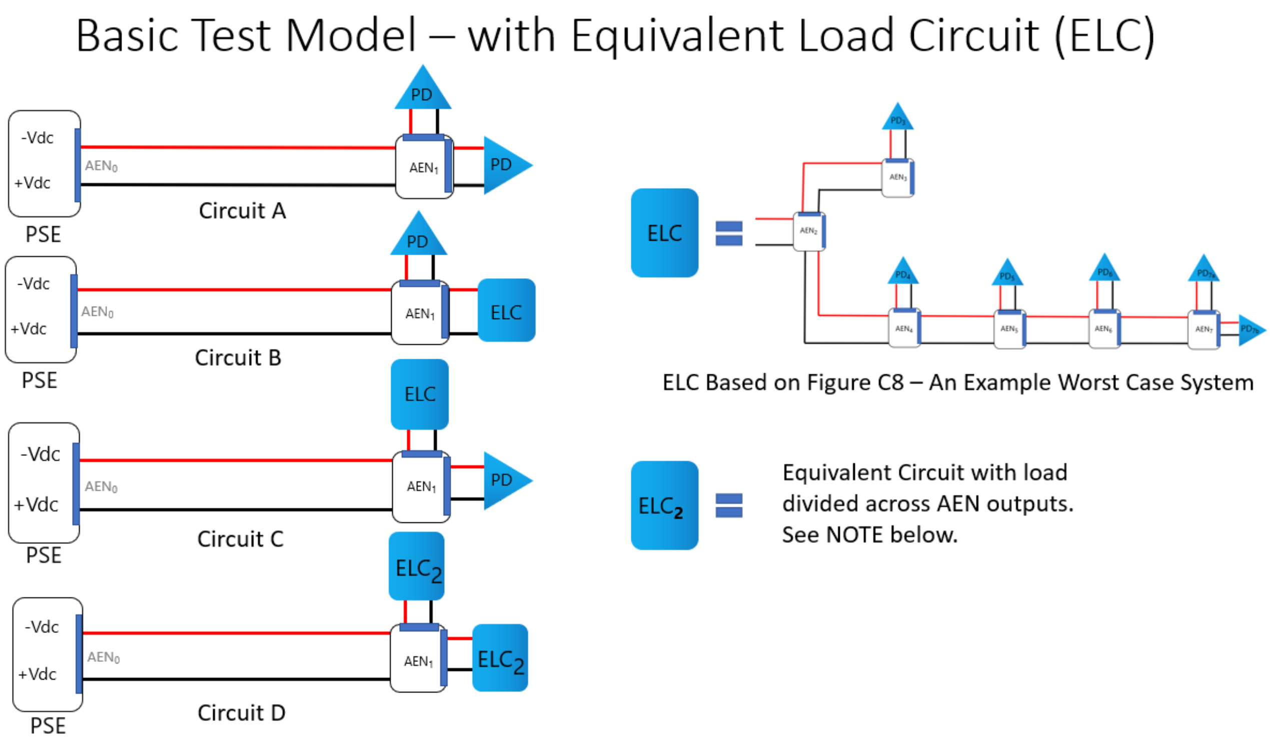


Figure C.9 – ELC Test Model Example – Simulating Worst Case System with ELC

NOTE: While Circuits A through C utilize a single ELC, the configuration shown in Circuit D utilizes two circuits (designated ELC_2) that collectively serve to emulate the stored energy of the worst-case system. Thus, each ELC_2 can be constructed with half of the maximum L-L and L-G capacitance, loop resistance and system power consumption, or any other workable combination of values that effect the same equivalent total (similar to the previously defined ELC) stored energy and power consumption.

Step 6: To certify a worst-case system, the testing entity shall record the maximum capacitance values used for L-L (X capacitance), and L-G (Y capacitance) for each ELC required, plus the maximum power for the system. Table C4 below presents an example of how this information can be stated. The manufacturer shall document that each system deployed has equal to or less total power and capacitance of the system, which relates to worst case energy transferred into a fault.

Table C.4 - Example System Worst Case Test Characteristic Record

Element	Description	Value	Units
ELC	Cap (L-L)	10.3	uF
	Cap (L-G)	0.37	uF
	Resistance	4.82	ohms
System	Power	8200	watts

Annex D
(normative)

D Test Resistance Insertion Apparatus (TRIA)

D.1 Overview

For the test cases defined in sections 4.4, 5.4 and 5.5 which involve the application of the test resistor after the PSE has been energized and stabilized, the test resistor shall be inserted using an apparatus that guarantees the steady state value of the simulated body current is established in less than5 microseconds.

The insertion of the test resistor shall be done using a solid-state switch such as a MOSFET or IGBT switch to avoid the creation of transient events caused by the mechanical nature of other mechanical or electro-mechanical switching devices.

The proper operation of the Test Resistance Insertion Apparatus (TRIA) shall be verified prior to performing tests listed in this document by discharging a 1uF capacitor charged at 48Vdc through a 500Ω resistor as depicted in Figure D.1 shown below. The transient voltage across the capacitor and current through the test resistor shall be recorded (5ms before and after the switch is closed) and attached to the test plan report. The parameters outlined in Figure D.2 shown below shall be measured and reported. All parameters shall comply with the listed values +/-5%. The parameters to be measured are initial capacitor voltage (48Vdc), peak resistor current (96mA), current rise time (less than 5μs) and current fall time (between 95% and 5% of the peak value should be 1.474ms). There shall be no spurious currents through the resistor before the turn on ramp.

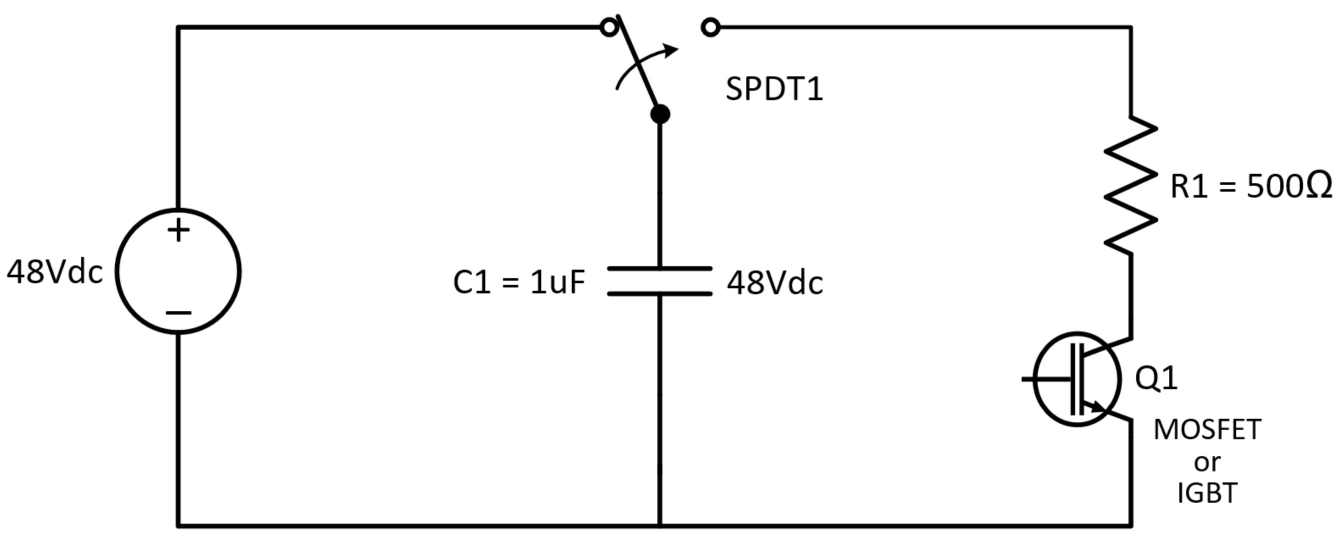


Figure D.1 – TRIA Proper Operation Verification Test Circuit

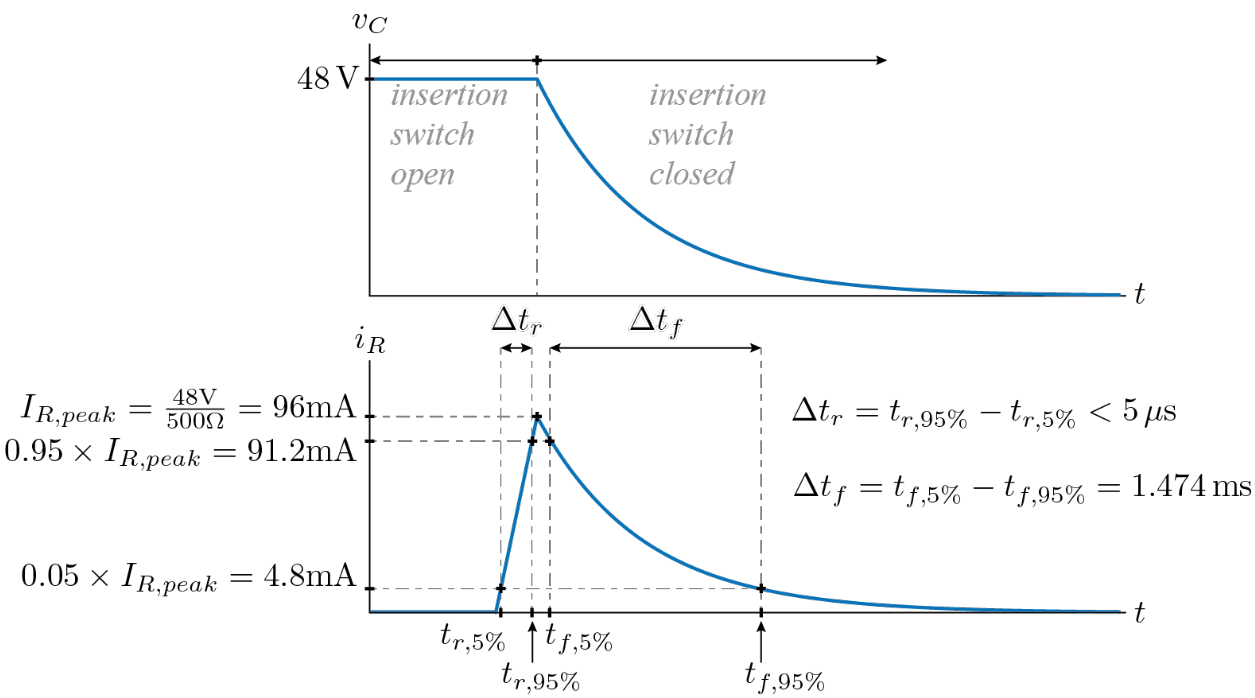


Figure D.2 – TRIA Proper Operation Test Parameters

D.2 Rationale

This Technical Report aims to measure the transient current through a test resistor and plot its magnitude and duration on a merged version of Figures 22 and 23 from IEC 60479-1 [Ref 1] and 60479-2 [Ref 2] respectively. Current flow durations as short as 100us are represented on the merged time-current graph. Therefore, the mechanism used to insert the test resistor in the circuit when the PSE is energized and stabilized should not introduce spurious transients at similar time scales. When a mechanical or electro-mechanical switch (such as a pushbutton or a relay) closes, the contact can bounce producing current oscillation. This can lead to misleading readings in the software-based fault evaluation tool that do not accurately represent the simulated body current transient according to the human body resistance model outlined in Annex A. Using a solid-state switch allows for application of the test resistor with a slew rate lower than5μs, which makes the tests prescribed in this TR reliable and repeatable.

To ensure that the TRIA is functioning properly, the device should be tested before it is used to capture the current and voltage transients produced by charge transfer and fault current test cases defined in this TR. A way to validate the proper operation of the Test Resistance Insertion Apparatus is to measure a known transient that is not related to the PSE, AEN, line, or PD. For this TRIA validation test, a 1uF capacitor charged at 48Vdc is connected to the terminals of the TRIA. The TRIA is configured to insert a 500Ω resistor. When inserted, the rise and fall times are measured.

The peak value of the current should be 96mA.

There shall be no current circulation through the resistor prior to the beginning of the current rise.

The rise time is measured between the moment when the current reaches 5% of the peak value and when it reaches 95% of its peak value. This interval should be less than 5μs.

The fall time is measured between the instant when the current reaches 95% of its peak value (discharging) and when it reaches 5% of its peak value (discharging). This interval should be 1.474ms (2.948 x 500us, where 500μs is the time constant of the discharge of a 1μF capacitor through a 500Ω resistor).

All the parameters shall be measured using an oscilloscope showing 5ms before the beginning of the current rise and 5ms after to show evidence of no spurious current circulating in the test resistor prior to the insertion of the fault.

All the parameters shall match the values specified within 5% tolerance.

D.3 Sample TRIA circuit implementation and component selection

The following proposed components and circuit diagram are presented as a sample and should not be considered prescriptive. Any selected switch and gate driving circuit that delivers the performance requirements outlined above in this Annex will constitute an acceptable implementation of the TRIA.

Switch Selection

The requirements of the switch are given in Table D.1.

1. $V_{ds,max} > 400\ V_{dc}$ to operate with the maximum allowable line to line voltage of the FMPS
2. $I_{d,max} > 0.8\ A$ (continuous) which corresponds to the current circulating through the lowest fault resistance (500Ω) at the highest voltage ($400V_{dc}$)
3. $R_{ds,on} \ll 25\Omega$ so that the on-state resistance is much lower than the tolerance of the fault resistance (5% of 500Ω)
4. MOSFET $\frac{dv}{dt}$ ruggedness $\gg 0.08\frac{V}{ns}$ so the device can withstand the transition from $400V$ to $0V$ in $5\mu s$
5. Rise time ($t_r \ll 5\mu s$) for the switch to meet the 5μs rise time requirements of the TRIA.
6. Power dissipation must be enough to operate continuously with the maximum current (depends on R_{ds}, on)

The selected switch is the **STP9N65M2** from STMicroelectronics (https://www.st.com/en/power-transistors/stp9n65m2.html#overview)

The values for each of the requirements is outlined in the third column of Table D.1. The values in the lower rows (highlighted) are not specific requirements of the device but are needed to select and design the gate driving circuit. This switch exceeds the requirements of the application and it costs $1.67 from Digikey.

Table D.1 – MOSFET Switch Requirements

	Requirement	STP9N65M2
Maximum Drain-Source Voltage ($V_{ds,max}$)	$> 400\ \mathrm{V}$	$650\ \mathrm{V}$
Drain current (continuous) ($I_{d,max}$)	$> \frac{400\ \mathrm{V}}{500\ \Omega} = 0.8\ \mathrm{A}$	$5\ \mathrm{A}$
On-state resistance	$\ll 0.05 \times 500\ \Omega = 25\ \Omega$	$0.9\ \Omega$
$\frac{dv}{dt}$ ruggedness	$\gg \frac{400\ \mathrm{V}}{5\ \mu\mathrm{s}} = 0.08\ \frac{\mathrm{V}}{\mathrm{ns}}$	$50\ \frac{\mathrm{V}}{\mathrm{ns}}$
Rise time (t_r)	$\ll 5\ \mu\mathrm{s}$	$6.6\ \mathrm{ns}$
Power dissipation	$> R_{ds,on} I_{d,max}^2 = 0.9\ \Omega \times (0.8\ \mathrm{A})^2$	$60\ \mathrm{W}$
V_{gs} for full turn on	-	$10\ \mathrm{V}$
Gate charge (Q_g)	-	$10.3\ \mathrm{nC}$
Input Capacitance (C_{iss})		$310\ \mathrm{pF}$

Gate Driver Selection

The requirements for the gate driver come from the selected switch:

1. Be capable of driving a MOSFET switch
2. Be able to drive on the low-side
3. Output voltage $> 10V$ (to guarantee the switch fully turns on)
4. Able to charge $10.3\ nC$ gate capacitance in less than $5\mu s$

For this example, the gate driver selector tool from Texas Instruments was used, in the low-side driver sub-menu (https://www.ti.com/power-management/gate-drivers/low-side-drivers/overview.html). Configured for:

- Switch Type: MOSFET
- Number of Channels: 1
- Input Voltage: 12V
- Gate Charge: 10.3nC
- Target Rise/Fall Time: 100ns

The selected component is UC3705 (https://www.ti.com/product/UC3705). The device accepts an input voltage between 5V and 40V (the proposed circuit uses 12V) and can drive an output capacitance of $1000pF$ in $40ns$ (the proposed switch has $310pF$). These all meet the requirements to drive the selected circuit. Figure D.3 shows a connection diagram adding the additional components to the circuit as recommended by the datasheet. R_g was reduced to 4.7Ω from the recommended 10Ω in the datasheet of UC3705 to match the design timing test consideration for the MOSFET (see Table 6 in the MOSFET Datasheet shown later in this Annex).

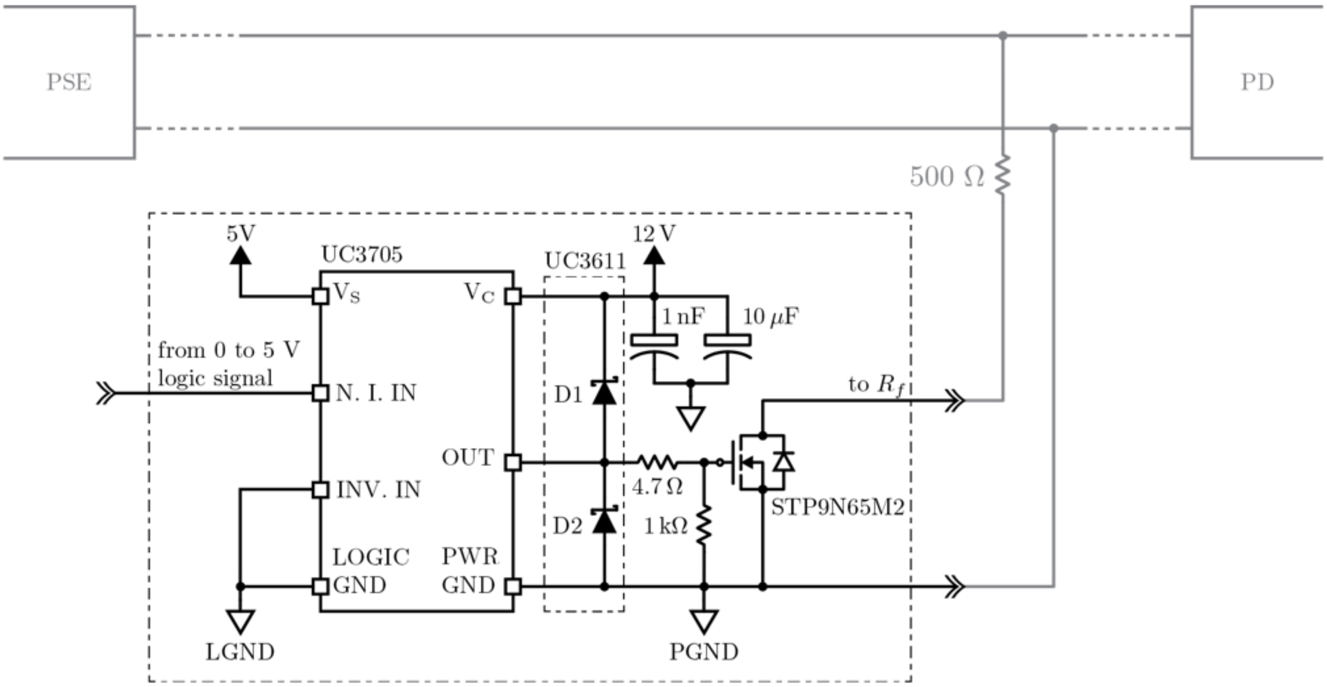


Figure D.3 – Sample Switch and Gate Driver Circuit for Fault Insertion

The diodes D1 and D2 are implemented using UC3611 (as recommended in the datasheet of UC3705). All components are available in Surface Mount Device (SMD) format and through-hole packages.

Example Component Datasheets

Shown below are the datasheets of the example components selected, with relevant parameters highlighted.

stp9n65m2.pdf   uc3705.pdf   uc3611.pdf

Annex E
(informative)

E Random Complex Irregular Waveform Analysis - Theory of Operation for Fault Managed Power System Evaluation

E.1 Introduction

Human contact with live parts of Fault Managed Power Systems (FMPS) under evaluation by this ATIS TR can result in complex body current transients that are not easily described by traditional waveforms. The traditional method of analyzing these transients has been to identify individual pulses and plot their current magnitude and duration coordinates on the merged current-duration graph depicted in Figure 5.1 using an Excel based manual plotting tool. However, this method has limitations when it comes to identifying combined effects of a series of pulses and can lead to an underestimation of the RMS body current. This Annex presents the use of the Random Complex Irregular Waveform Analysis (RCIWA) method, outlined in Annex A of IEC 60479-2 [Ref 2], to provide a more comprehensive analysis of the body current transient. The RCIWA method can perform a thorough analysis of the body current transient, through a moving and expanding window, which ensures that the resulting trace reflects the worst possible current-duration pair for each possible duration. While the traditional method results in a number of discrete points plotted on the merged IEC current-duration graph and evaluated independently, the RCIWA method results in a continuous trace that contains all possible combinations of current magnitude and duration. By using the RCIWA method to evaluate physiological effects of the body current, the results are representative of the worst possible combinations and can give confidence that the transient is evaluated in the most comprehensive manner possible.

The left side of Figure E.1 shown below illustrates a transient consisting of two pulses of different duration and amplitude. The traditional method to evaluate the risk of this body current transient is to measure the RMS value of each pulse and plot them on the time - current graph shown on the right side of Figure E.1. This leads to two marks in the right curve: one at 1ms/600mA, and another at 2ms/400mA. Both marks are located to the left of the extended b curve and would be considered acceptable by the requirements outlined in this TR. However, when the RCIWA method is applied (resulting in the orange trace) it becomes clear that the combined effect puts the transient to the right of the extended curve b. This is the correct result, as the RMS value should reflect the accumulated energy transferred in a window of time, and this transient should be classified as dangerous. The following section explains the RCIWA methodology in detail and demonstrates how the trace is computed.

The method explained below forms the “engine” that powers the RCIWA tool described in this Annex. An outline of the tool is presented after the explanation of the core tool.

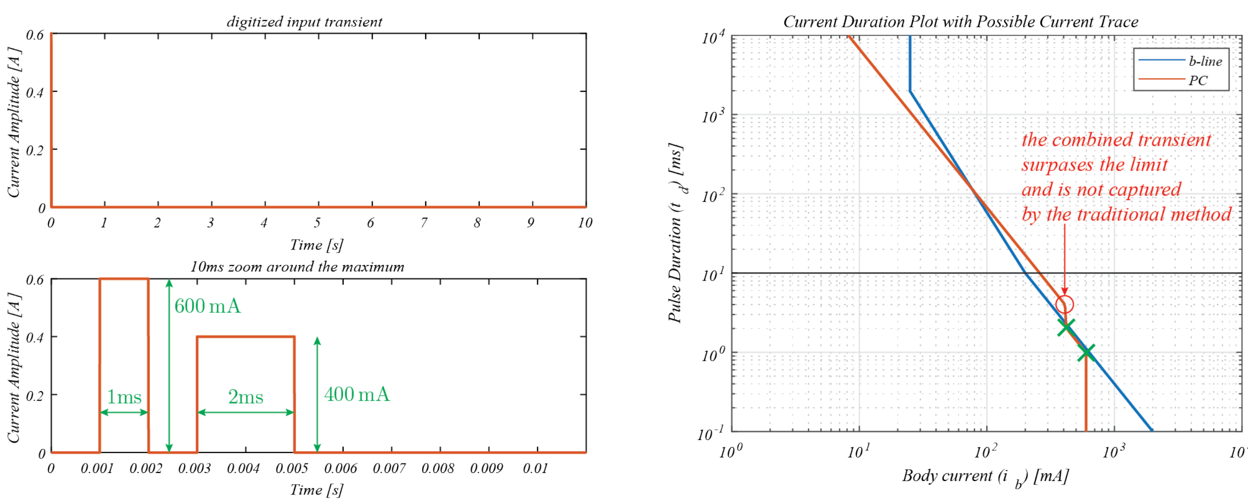


Figure E.1 – Fault Current Waveform Plotting Example

Shown on the left of Figure E.1 is a body current transient and a zoom on the first 10ms, the transient has two pulses of different amplitude and duration. On the right, the current duration points (green crosses) and the probable current (the output of the RCIWA method) are plotted on the merged time – current graph. From the two crosses the conclusion would be that the transient is safe, while in fact the RCIWA reveals the combined effect is beyond curve b and would indicate that the FMPS response is not in compliance with requirements defined in this TR.

E.2 Random Complex Irregular Waveform Analysis Method

The Random Complex Irregular Waveform Analysis (RCIWA) method is introduced in Annex A of IEC60479-2 [Ref 2]. It allows mapping a body current vs. time transient trace to a current vs. duration trace that can be compared with the boundary curves presented in Figures 20 or 22 or IEC60479-1 [Ref 1] or Figure 23 of IEC60479-2 [Ref 2]. The RCIWA method is based on selecting a time duration window and computing the RMS value for different locations in the transient. Then, expanding the window size to grab a longer segment of the transient and repeating windowed RMS value calculation. The output of the method, called "probable current" (pc), is given by the combination of the maximum RMS value for each duration. This section will cover the step-by-step description of this method.

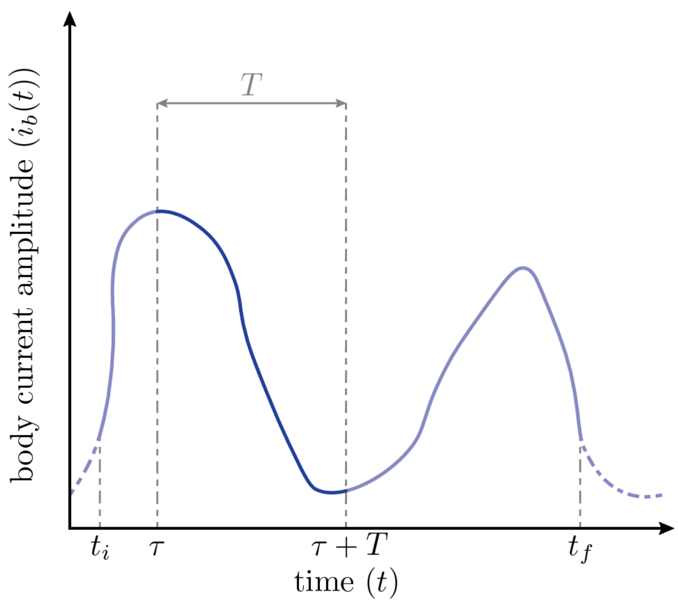


Figure E.2 - Body Current Transient Example

The values of interest are between t_i and t_f, and the windowed RMS value is calculated between τ and $\tau + T$.

Consider a body current transient ($i_b(t)$) such as the one illustrated in Figure E.2 above. The RMS value of the current over a window of duration T starting at given instant τ ($I_b(T,\tau)$) is given by:

$$I_b(T,\tau) = \sqrt{\frac{1}{T}\int_{\tau}^{\tau+T} i_b^2(t)dt}$$

To evaluate the risk related to a given $i_b(t)$, $i_b(t)$ is considered of interest between a given initial time (t_i) and a final time (t_f) given by other requirements or agreement. This leads to limiting the values of T and τ to

$$0 < T \le t_f - t_i$$

$$t_i \le \tau \le t_f - T$$

As Figure E.2 shows, changing the parameter τ "slides" the window of fixed width T through the trace of $i_b(t)$. Meanwhile, changing T increases or decreases the amount of the $i_b(t)$ analyzed. For a given fixed T, the sliding window method computes a series of RMS values $I_b(T,\tau)$ of which some are higher and some are lower. To evaluate the risk the RCIWA method selects the highest valued RMS value for a fixed window size and stores it as the corresponding RCIWA point for that duration. For a given T, the most dangerous RMS value is given by:

$$I_{b,worst}(T) = \max_{t_i \le \tau \le t_f - T}(I_b(T,\tau))$$

Then, the probable current ($pc(T)$) is given by the collection of $I_{b,worst}(T)$ for all possible T:

$$pc(T) = I_{b,worst}(T)$$

For

$$0 < T \le t_f - t_i$$

In practice, the $pc(T)$ is calculated over a recorded transient sampled at intervals T_s using an instrument such as an oscilloscope or data acquisition tool. This results in time-quantization such that:

$$t_f - t_i = N \times T_s$$

Where N is the record length, the sampled current record is then given by the sequence:

$$i_b[k] = i_b(t_i + kT_s)\ for\ 0 \le k < N$$

The discrete RMS for a window length of m samples starting from the $j - th$ sample is given by:

$$I_b(m,j) = \sqrt{\frac{1}{m}\sum_{k=j}^{j+m-1} i_b^2[k]}$$

Therefore, the discretized pc curve is given by:

$$pc(mT_s) = \max_{0 \le j < N-m} I_b(m,j)\ \ for\ m = 1,2,\ldots,N-1$$

The previous equation summarizes all the possible combinations of RMS values that can be evaluated from a given $i_b(t)$ trace. In the case of transients with many pulses separated by various intervals, the method will naturally evaluate each pulse independently as well as in combination with adjacent pulses to evaluate if the overall RMS value is dangerous. (i.e., plots to the right of the b line) It will combine all the information in the transient from the minimum sampling time to the overall duration of the record which is required by this TR to be 10 seconds. Using the pc trace to compare against the thresholds in IEC 60479-1 [Ref 1] Figures 20 and 22 or IEC 60479-2 [Ref 2] Figure 23 gives a very conservative evaluation of the given body current transient.

Returning to the example illustrated in Figure E.1, the RCIWA method would scan the transient with $T = 1ms$ and determine that the worst location for the $1ms$ window is the one that starts at $\tau = 1ms$ and captures the complete $600mA$ pulse. Then, the method would increase $T = 2ms$ and find that the worst location is the one that starts at $\tau = 3ms$. For $T > 2ms$ the worst window can grab parts of the first and the second pulses, and for $T = 4ms$ the worst location is the one that starts at $t = 1ms$ and captures both pulses. For durations longer than $4ms$, the worst window always captures both pulses and adds zeros at the end, causing a fixed amount of energy to be spread over a longer period of time. Therefore, the trace decreases at a rate of $1/\sqrt{T}$.

Incidentally, this is the same slope selected for the extension of curve b below 10ms, which gives further rationale to this selection: to ensure the pc curve enters Figure 22 of IEC60479-1 [Ref 1] to the left of curve b (DC2), the fibrillation energy transferred before must be low enough to allow the RMS to average below 200mA at 10ms. Therefore, the requirement for the sub-10ms transient is:

$$I_b < 200mA \times \sqrt{\frac{10ms}{T}}$$

E.3 Outline of the RCIWA Software-Based Program

Figure E.3 is a flowchart delineating the steps performed by the RCIWA software-based program. The RCIWA method is the core of the program that is applied to each sub-segment as outlined in the diagram. In the development of the RCIWA analysis program, the application of the RCIWA method itself is straightforward, except for necessary algorithmic optimizations to compute the trace in a reduce time. As this is an automated tool, the challenge comes from building the guards and checks that ensure the loaded traces and selected options are correct, compatible and will lead to the correct interpretation.

The first part of the method consists of loading from a file or terminal the options file and the current and voltage trace. The program needs to implement guards and checks to ensure the loading is done properly and the files are properly formatted. Moreover, the selected options must be compatible and consistent with the requirements of this ATIS TR.

The second part of the program consists of applying the different pre-processing methods to the loaded current/voltage trace. These methods include a low pass filter (to remove noise), removing the current that circulates below a certain threshold voltage, applying the heart-current factor to the trace if it represents a hand to hand current path, and splitting the transient after 300ms of quiet time.

The next block applies the RCIWA method to each of the sub-segments of the transient and compares the resulting probable current against the selected limits (DC2, left of the extended curve b).

Finally, the program outputs a PDF report for the complete transient that details the results for each sub-segment.

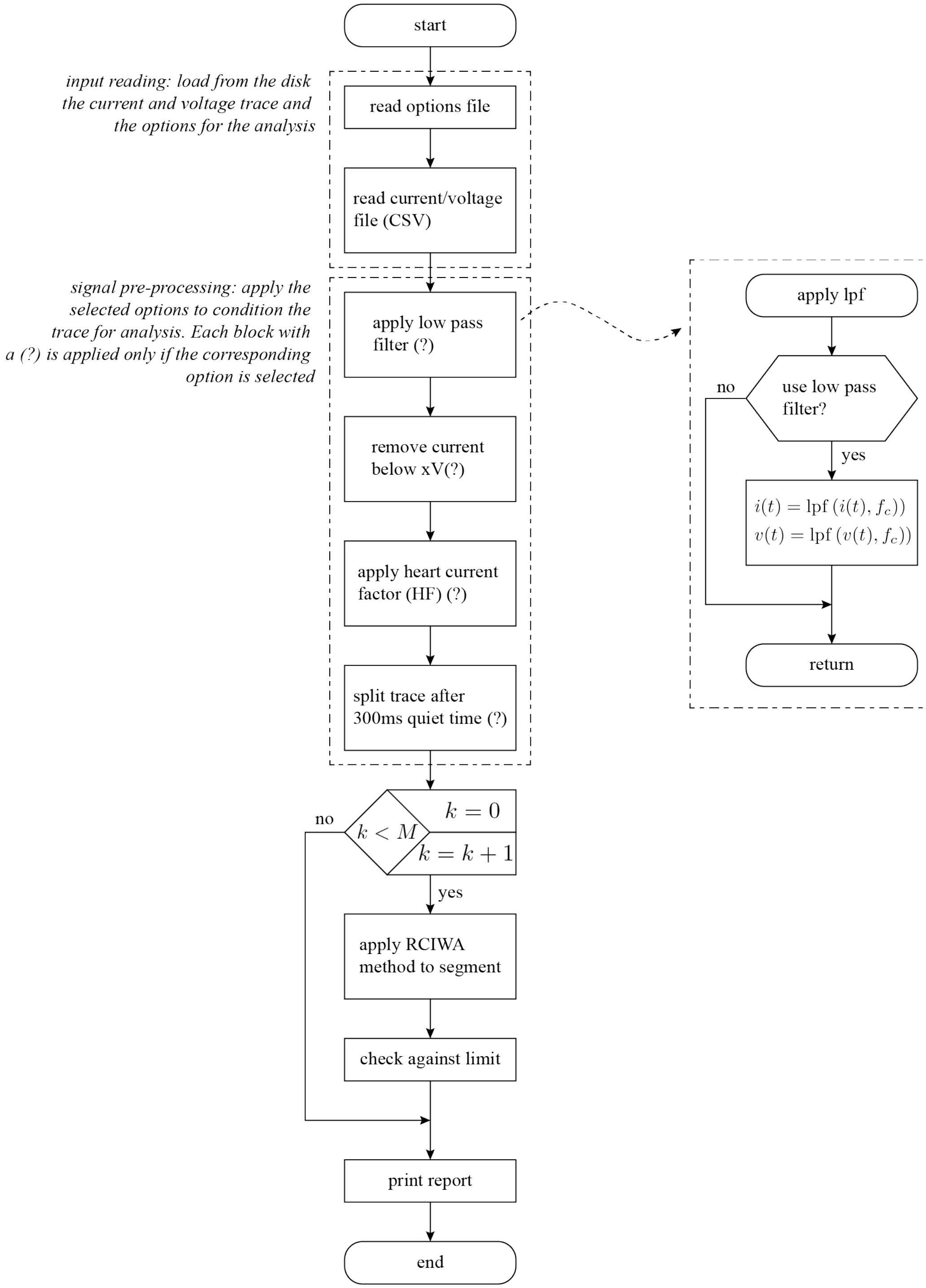


Figure E.3 – RCIWA Software-Based Program Flowchart

Annex F
(informative)

F Fault Managed Power Systems, Termination Panel and Cable Conductor Access Evaluation

To evaluate technology approaches that employ mechanical protections and disconnecting interlocks, that address electrical safety by detecting a terminal, cable insulation or shield breach, a test engineer should activate the interlock and breach the cable insulation using one or more methods that might reasonably occur in the field in accordance with the training and skill level of the qualified telecom worker. For example, as opposed to making a circumferential cut in the insulation and/or shield, the test technician should investigate exposing internal conductors by making a slit in the cable insulation or breaching the insulation in any location deemed appropriate to access live conductors of the cable or terminal blocks per manufacturer's instructions for the purpose of testing its safety. If the system does support field installation of exposed metallic cable conductors, connectors or terminal blocks, the technician should consider these exposed wires or terminals that may be present during field assembly or termination, including the order in which wires are connected per the manufacturer's instructions into a terminal block or connector.

To properly evaluate a system's reaction upon an interlock and/or cable breach, the ITL technician shall consider the methods used to enter the terminal compartment(s) and a cable(s). Then to test the effects of access using the device to cause the breach. For example, using a 216 tool to access a terminal compartment or the use of cable cutters to enter a cable and to record if a shutdown occurs upon access and if the access exposes live terminals or conductors. If a shutdown does occur, then FMPS testing defined in sections 5.4.4 and 5.4.5 is not necessary. However, If the access panel or cable breach exposes live conductors to a telecommunication worker, then testing in accordance with sections 5.4.4 and/or 5.4.5 is necessary.

or

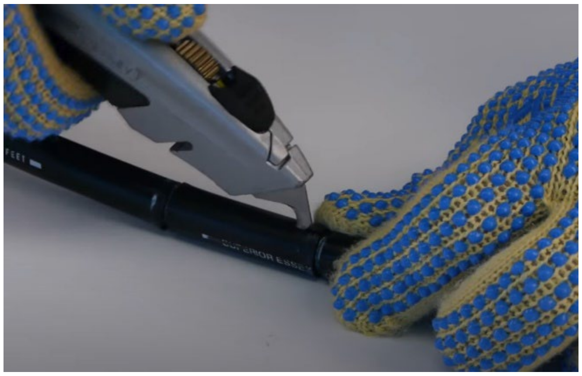


Figure F.1: Midspan Cable Breach Testing

To test this first step, the technician shall perform the steps necessary to access the power terminals and conductors within the cable by following the methods and procedures defined for the skilled telecommunications worker to access the cable to install, repair, and maintain the FMPS (PSE - AEN - PD). The technician shall record the reaction of the system upon access. If a power shutdown occurs prior to exposing the live power terminals or conductors, then the testing can stop and the results recorded in the appropriate table from Section 5.5.

Annex G

(Normative)

G Arc Flash Current Magnitude – Duration Limit

Assumptions, rationale and calculations pertaining to the development of the Arc Flash Current – Duration Limit presented in this Technical Report are provided in this annex. This current – duration limit is based on the minimum arc flash incident energy level of 1.2 calories / cm^2 (5.021 Joules / cm^2) which is considered to be the lowest threshold of incident energy constituting an arc flash hazard. The area to the left of the current – duration limit line corresponds to an incident energy level of less than 1.2 calories / cm2 (5.021 Joules / cm2).

G.1 Assumptions:

- Surface Incident Energy Limit is less than 1.2 calories / cm^2 *or* 5.021 Joules / cm^2.
- Arc flash incident energy level is calculated assuming a distance of 18 inches (45.72cm) from the point of the origin of an arc flash.
- Arc flash energy spreads as a sphere where the surface area is defined by the following equation:

  $S = 4\pi d^2$

  Where: $S = \text{Surface Area}$ (cm^2)

  And for a distance of 18 inches (45.72cm) from the point of origin of an arc flash, the surface area is:

  $S = 26{,}267$ cm^2
- It is assumed that the maximum duration of an arc event will be 2 seconds based on standard industry practice.
- To ensure the worst-case scenario, it is assumed that the PSE operates as an ideal voltage source with no voltage drop due to cables or load.
- PSE output voltage level is 400 Volts line to line which is the maximum allowed for FMPS.
- Any fault current flow at less than 60 Volts will not be included in the test result. It is assumed that 60 Volts is an insufficient voltage level to sustain an arc.

G.2 Current - Duration Calculations

- Maximum allowed energy: $E = 5.02\,\frac{\text{J}}{\text{cm}^2} \times 26{,}267\text{cm}^2 = 131{,}860 \text{ Joules}$
- Energy is defined by the equation: $E = V \times I_f \times T_d$

  Where:

  E = Fault Energy (Joules)

  V = Maximum allowed FMPS Voltage (Volts)

  I_f = Fault Current (Amps)

  T_d = Fault Duration (Seconds)
- Therefore, the current limit (for a given duration) is defined by the following equation:

$$I_f = \frac{E}{V \times T_d} = \frac{131{,}860 \text{ Joules}}{400 \text{ Volts} \times T_d \; Seconds} = \frac{329.65 \text{ Coulombs}}{T_d \; Seconds}$$

$$I_f = \frac{329.65 \text{ Coulombs}}{T_d \; Seconds}$$

Table G.1 shown below illustrates sample current data points calculated for various arc flash durations using the current limit for given durations equation shown above.

Duration	Rms Current
1 ms	329.65 kA
5 ms	65.9 kA
10 ms	32.97 kA
50 ms	6.59 kA
100 ms	3.3 kA
500 ms	659.3 A
1 s	329.65 A
2 s	164.8 A

Table G.1 – Sample Arc Flash Limit Data Points

A continuous plot of all data points for durations from 1ms to 2 seconds defining the Current Magnitude – Duration Limit for Arc Flash is shown in Figure 5.44 below.

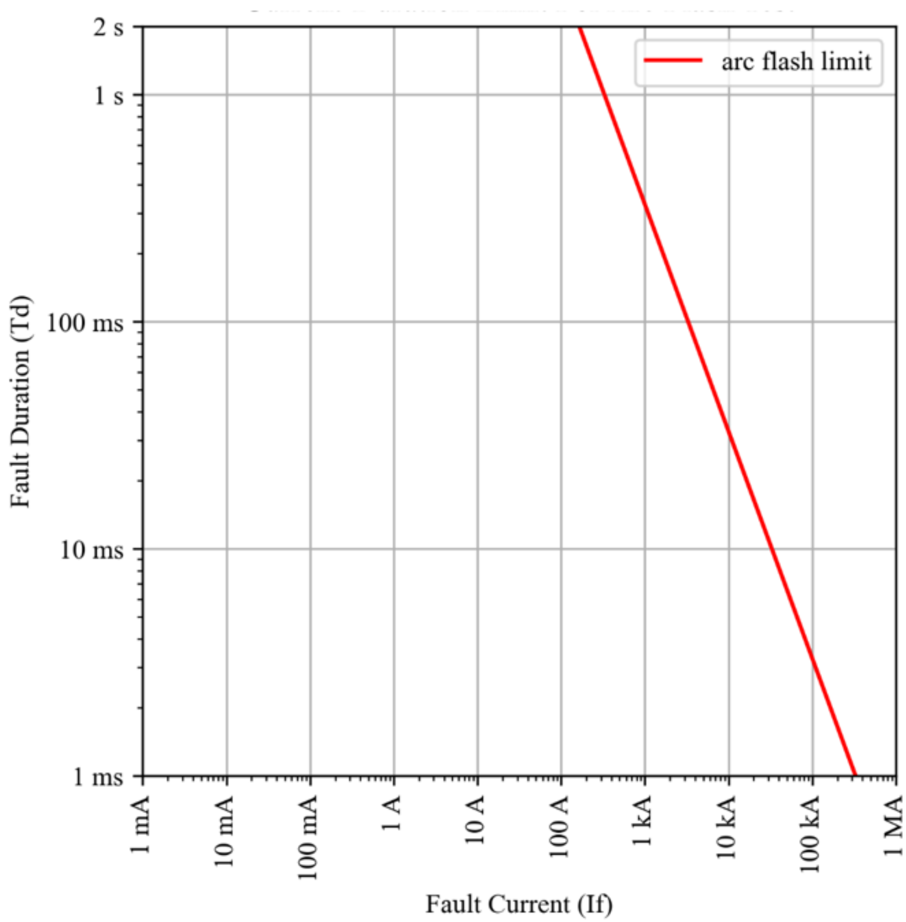


Figure 5.44 – Current Magnitude – Duration Limit for Arc Flash