



AEROSPACE STANDARD

AS5698™**REV. A**Issued 2012-04
Revised 2018-09

Superseding AS5698

(R) Space Power Standard

RATIONALE

This A Revision of the standard addresses 4 years of compiled questions, clarifications, and updates to requirements that have been brought forward by standard users. Comments have been assembled from government agencies and industry. The areas addressed and modified include modifications to the inrush requirement to include very high power loads, the deletion of the EPCE load impedance curve, replacement of the Local Stability curve with a Large Signal Stability test that was found to be a stronger test, updated the abnormal drop out waveform, modified the ripple spectrum and slightly increased the peak ripple requirement to provide additional margin. These changes were all the result of standard users making revision suggestions.

INTRODUCTION

This standard defines the requirements and characteristics of electrical power for spacecraft. This standard also defines analysis, verification, and testing methodologies to be used to ensure that the loads operate when connected to the specified power quality and performance as defined by this standard.

PREFACE

Historically, space power system requirements have been unique for every platform, vehicle, and contractor. This is a roadblock for re-use of equipment on new designs or development of standard products for space applications. The majority of existing power quality specifications were developed for aircraft systems and generally are based on engine driven alternator power sources for ac and transformer rectifier units for dc. Space power sources include fuel cells, thermal electric generators, rotating and reciprocating electromagnetic machines, photovoltaic, and electrochemical systems. All of these sources have unique properties that must be considered in the development of a power system. In a similar manner, spacecraft loads are often designed for specific platforms, and must be adapted and modified to meet unique voltage ranges and power quality characteristics for new applications. Designing equipment to a common power standard allows transportability to new platforms with high confidence of compatibility without extensive requalification.

SAE Technical Standards Board Rules provide that: "This report is published by SAE to advance the state of technical and engineering sciences. The use of this report is entirely voluntary, and its applicability and suitability for any particular use, including any patent infringement arising therefrom, is the sole responsibility of the user."

SAE reviews each technical report at least every five years at which time it may be revised, reaffirmed, stabilized, or cancelled. SAE invites your written comments and suggestions.

Copyright © 2018 SAE International

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of SAE.

TO PLACE A DOCUMENT ORDER:
Tel: 877-606-7323 (inside USA and Canada)
Tel: +1 724-776-4970 (outside USA)
Fax: 724-776-0790
Email: CustomerService@sae.org
<http://www.sae.org>

SAE WEB ADDRESS:

Full document details: **SAE AS5698A**

**SAE values your input. To provide feedback
on this Technical Report, please visit
<http://standards.sae.org/AS5698A>**

Documents
Document Sharing Hub

TABLE OF CONTENTS

1.	SCOPE.....	3
1.1	Purpose	3
2.	REFERENCES.....	3
2.1	Applicable Documents	3
2.1.1	U.S. Government Publications.....	3
2.2	Abbreviations and Definitions	3
2.2.1	Abbreviations	3
2.2.2	Definitions	4
3.	GENERAL REQUIREMENTS.....	7
3.1	Electrical Power Characteristics	7
3.1.1	System Characteristics	7
3.2	EPS Electrical Requirements.....	9
3.2.1	Normal Operation.....	9
3.2.2	Source Impedance	10
3.2.3	External Power Source	10
3.2.4	Abnormal Operation	11
3.2.5	Faults.....	12
3.2.6	Emergency Operation	13
3.3	EPCE Requirements.....	13
3.3.1	EPCE Normal Operation.....	13
3.3.2	EPCE Abnormal Operation	15
4.	VERIFICATION	19
4.1	Electrical Power Characteristics	20
4.1.1	System Characteristics	20
4.2	EPS Electrical Requirements.....	21
4.2.1	Normal Operation.....	21
4.2.2	Source Impedance	22
4.2.3	External Power Source	22
4.2.4	Abnormal Operation	22
4.2.5	Faults.....	23
4.2.6	Emergency Operation	23
4.3	EPCE Requirements.....	23
4.3.1	EPCE Normal Operation.....	23
4.3.2	EPCE Abnormal Operation	25
5.	NOTES.....	26
5.1	Revision Indicator.....	26
APPENDIX A	TEST METHODS	27
APPENDIX B	GENERAL DISCUSSION.....	33
Figure 1	EPS Nyquist stability criteria	8
Figure 2	28 V normal transient response	16
Figure 3	28 V ripple voltage spectral components	16
Figure 4	Large signal stability.....	17
Figure 5	28 V abnormal voltage limits for overvoltage and undervoltage	17
Figure 6	120 V EPS normal transient response.....	18
Figure 7	120 V ripple voltage spectral components	18
Figure 8	120 V EPS abnormal voltage limits for overvoltage and undervoltage.....	19
Figure 9	Large signal stability test transient.....	24
Table 1	Power characteristics	11

1. SCOPE

This standard defines the requirements and characteristics of electrical power for spacecraft. This standard also defines analysis, verification, and testing methodologies to be used to ensure that the loads operate when connected to the specified power quality and performance as defined by this standard.

1.1 Purpose

The purpose of this electrical power quality standard is to ensure commonality, reliability, interchangeability, and interoperability for load applications between space application power systems that meet these requirements.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 U.S. Government Publications

Copies of these documents are available online at <http://quicksearch.dla.mil>.

MIL-STD-461F Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment

2.2 Abbreviations and Definitions

2.2.1 Abbreviations

AC	alternating current
A	Ampere
dB	decibels
DC	direct current
DUT	device under test
E3	Electromagnetic Environmental Effects
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EPCE	Electrical Power Consuming Equipment
EPS	Electrical Power System
EUT	Equipment Under Test
FET	Field Effect Transistor
GSE	Ground Support Equipment
Hz	Hertz

kHz	kilohertz
MHz	Megahertz
ms	millisecond
NVR	No Verification Required
POR	Point of Regulation or Point of Reference for unregulated systems
pps	pulses per second
PU	Per Unit
RC	Resistor/Capacitor
rms	root mean square
TBD	To Be Determined
TBR	To Be Resolved
μF	microfarad
μs	microsecond
V DC	Volt direct current
V p-p	Volts peak-to-peak
W	Watt
Zn	normalized input load impedance

2.2.2 Definitions

ABNORMAL OPERATION: Abnormal operation is that condition of the EPS wherein a fault or failure in the EPS distribution wiring, or connected loads, has occurred and the protective devices of the EPS are operating to isolate or remove the fault from the appropriate EPS interface.

BRANCH CIRCUIT: A power distribution line that delivers power from an overcurrent protection device to an electrical load device.

BUS CONTROL: A means of controlling the direction and flow of current across an interface.

CLEARING TIME: The time for an overcurrent protection device to interrupt a circuit fault.

CURRENT LIMITING: The process of actively controlling the flow of electrical current to a level at, or below, a defined threshold when it might otherwise be exceeded. Also, the role of electrical protection controls that perform this function.

DISTRIBUTION SYSTEM: The means to distribute power through the power system.

DROP-OUT TIME: Drop-out time is the time interval during which the electric power is interrupted. Voltages will be below defined values for the duration of the drop-out and are assumed to fall to 0 V.

ELECTRIC POWER CONSUMING EQUIPMENT: EPCE is used in this document as a generic term to refer to any piece of electrical equipment acting as a load on the Spacecraft.

ELECTRIC POWER SYSTEM: The EPS consists of the electric power generation and distribution subsystems, including all devices up to the EPCE power interface such as generators, energy storage devices, cables, switches, protective devices, converters, and regulators.

ELECTROMAGNETIC COMPATIBILITY: The ability of systems, and EPCEs that are exposed to or use the electromagnetic spectrum to operate in the operational environments without suffering unacceptable degradation or causing unintentional degradation because of electromagnetic radiation.

EMERGENCY OPERATION: Emergency operation occurs upon failure of a primary power generation/energy storage system and/or contingency cases requiring deep discharge users of electrical power.

EPS POWER INTERFACE: The EPS Power Interface is the point of connection for a fixed EPCE. For portable equipment, the EPS power interface is at the EPS receptacle.

FAULT: A condition causing an overcurrent condition on the EPS.

FAULT CLEARING: The action in power system protection devices that disconnects a faulted line from the rest of the system.

FAULT CONTAINMENT: A mechanism to localize a circuit fault to the closest protective device.

FAULT COORDINATION: Coordinating a series of protective devices in such a way as to make sure the protective device nearest to the fault clears the fault before affecting upstream switchgear.

FEEDER LINE: Cables that distribute electrical power from a primary bus to lower level protective switchgear.

GROUND: Common circuit reference point considered to have 0 V.

HIGH CURRENT FAULT: A fault condition that produced very high currents generally conducting fault current through a hard physical connection. This condition is often referred to as a "bolted fault."

HIGH IMPEDANCE FAULT: A fault condition that produces unacceptable currents but is not considered high currents. This fault is often considered the most dangerous and difficult to clear. This fault is often referred to as a "soft fault."

IMPEDANCE: Electrical impedance describes the amplitudes of the voltage, current, and phase. Impedance is the complex quantity $\tilde{Z}$.

INRUSH CURRENT: Inrush current is defined as EPCE initialization current to energize loads or portions thereof. The current envelope is the total charging current in amp-seconds that starts at the instant current exceeds the rated load current of the EPCE and ends once the input current returns to the rated load current value.

INSTABILITY: Characterized by an output or internal state of a system growing without bounds.

INTERFACE POWER: The electrical power supplied/consumed to/from an electrical load.

LEAKAGE CURRENT: Current flow as a result of imperfect insulation or semiconductor materials.

LOCAL STABILITY: A limited measure of EPCE stability under representative (or typical) source impedance conditions.

NOMINAL RATING: An approximate value used to indicate its intended application or to differentiate it from similar devices with different ratings.

NUISANCE TRIPPING: An inadvertent or improper interruption of an EPCE by the protection switchgear during normal operation of the load.

NORMALIZED INPUT IMPEDANCE: EPCE Input impedance curve scaled to 0 dB (1 Ω) at zero frequency.

OVERCURRENT: A situation where larger than intended electric currents exist in a circuit.

OVERCURRENT PROTECTION: The limiting of excessive circuit current by some means.

OVERVOLTAGE: A potentially hazardous condition when the voltage in a circuit or part of it is raised above the system upper design limit.

PEAK RIPPLE VOLTAGE: The absolute value of the maximum difference between the steady state and instantaneous voltage. The peak ripple voltage is the sum total peak voltage amplitude of a ripple composite, including nonperiodic events that can be present on the EPS for a fixed bandwidth.

PEAK-TO-PEAK VOLTAGE: A voltage measurement of a periodic voltage waveform from the lowest well to the highest point (peak).

POWER QUALITY: Electrical characteristics that allow the system to function properly without significant loss of performance or life.

PULSED LOADS: EPCE that operates in a periodic manner with a frequency below 30 Hz.

RATED LOAD CURRENT: The maximum current draw from a load after all start-up or mode change transients have settled out.

RATED POWER: The nominal output power for EPS branch circuits or power consumption of an EPCE.

REVERSE CURRENT: Direct current flowing in the opposite direction from the intended circuit design. For loads, this can be created from the energy discharge of a circuit due to counter electromagnetic force due to regenerative loads (such as motor controllers or actuators) or under a fault condition upstream of the load power interface.

RIPPLE VOLTAGE AMPLITUDE: Ripple voltage is the RMS value of all AC voltage components that are superimposed on the steady-state DC voltage.

RIPPLE VOLTAGE SPECTRUM: The frequency distribution of ripple voltage components.

SHORT CIRCUIT: Abnormal low impedance/resistance connection between nodes of an electrical circuit at different voltages.

SINGLE-POINT GROUND: Single-Point Ground is a single ground reference to structure.

STABILITY: The quality of electrical device operation wherein key characteristics resist deviation from intended values under both static and dynamic conditions.

SURGE CURRENT: Surge current is defined as a transient, or pulsed, current due to operation of an EPCE that is greater than the average over any interval of time.

SWITCHGEAR: The combination of electrical/electronic disconnects or fuses used to operate/isolate electrical equipment. Switchgear can be designed to both operate and protect (clear circuit faults) equipment.

TRANSIENT RESPONSE: A system or device response to a disturbance in an electrical system brought about by a sudden change of load or system voltage.

TWO-WIRE: An electrical distribution system using separate supply and return conductors to supply electrical power to an EPCE.

VOLTAGE DROOP: The reduction in system voltage due to a sudden change in the system or a fault or failure.

VOLTAGE SPECTRUM: A graph of individual voltage intensity components plotted against frequency.

3. GENERAL REQUIREMENTS

3.1 Electrical Power Characteristics

The following sections specify the characteristics for electric power supplied to electrical loads at the point of connection with an electric power user.

The EPS consists of the electric power-generating source (e.g., generators, batteries, fuel cells, solar arrays, and distribution subsystems) including the associated cables, switches, protective devices, converters, and regulators. The EPS performance is specified at the electrical connection of individual electrical EPCEs (electrical loads).

Power quality is directly related to the effects produced by electromagnetic interference (EMI), regenerative energy, and voltage spikes. To properly maintain power quality, specification requirements controlling EMI, lightning induced voltage spikes, and switching transients should be followed but may not be specifically covered by this standard.

3.1.1 System Characteristics

The power system distribution shall maintain the concept of grounded sources and isolated loads proven in existing spacecraft.

3.1.1.1 Single-Point Ground

A single-point ground shall be established for each EPS system.

Rationale: Establish a consistent internal grounding philosophy. This is a proven practice and consistent with heritage designs. The single-point grounding should be employed with the return lines grounded to the vehicle structure at a single point. The main characteristics of this concept are:

- The spacecraft structure is used as a low-impedance equipotential ground plane.
- No current intentionally flows through the spacecraft structure.
- All primary power sources are referenced to a single point on the spacecraft structure.
- Primary power sources are galvanically isolated from secondary power supplies.
- Secondary power supply outputs are referenced to the housing of the unit that they supply.
- The housing of each unit is referenced to the spacecraft structure at a single point.

3.1.1.2 Distribution Wiring

The power distribution system shall provide a two-wire power distribution system in which one wire serves as a return path for load currents.

Rationale: The wiring system is required to maintain the distributed single-point ground per requirement. The two-wire distribution system does not preclude using parallel wiring for current sharing. It is recommended to minimize spacing between power and return conductors to reduce wiring inductance. No current should intentionally flow through the spacecraft structure.

3.1.1.3 Isolation

The power distribution system feeders and returns from multiple internal sources shall be isolated.

Rationale: Isolation of power sources will be implemented such that a fault in one source will leave the other source operational. The isolation requirement is based on the distributed single-point ground and 1 M Ω hardware configuration end item (box level) isolation requirements. No single failure within the EPS or EPCE will cause the independent power buses to lose electrical isolation. Isolation also prevents circulating AC or DC current in the EPS and/or spacecraft structure.

3.1.1.4 Reverse Current

The power system shall not be required to accept reverse current flow under normal operation for a fixed interface voltage.

Rationale: Loads will be designed to prevent current to out-flow into the power system under normal load operation, on/off where the EPS voltage remains constant. Loads, mainly motors and other inertial loads need to be designed as to not normally supply reverse currents (re-gen) into the distribution system and potentially raise the bus voltage to unacceptable levels causing the unintended tripping from other devices within the system.

3.1.1.5 Stability

Power system stability is the ability of an electric power system to return to a state of operating equilibrium within a specified time after being subjected to a physical disturbance. The EPS will remain stable over the entire range of power generation, energy storage, and load conditions in all operating modes, temperatures, and orbital phases or conditions over the power system's design life to maintain power quality. The following section addresses the requirement to assure bus stability Interface.

3.1.1.5.1 Small Signal Stability - System Stability

A complex system impedance margin shall be maintained for the source impedance/load impedance ratio that remains outside the hatched area (Forbidden Zone) shown in Figure 1.

Rationale: This Nyquist Criteria was adopted as a system level stability verification. This criteria uses design data from both the supply and load as an ultimate overall stability check. This approach is based on the significant relationship between source and load impedance and the effect of this relationship on system stability. The stability criteria establish that by maintaining a 3 dB (0.707) impedance margin between unity gain and the ratio of source and load impedance provides system stability. When the margin for impedance magnitude is less than 3 dB, then the phase margin cannot enter the Forbidden Zone shown in the Nyquist Stability Plot of $|Z_S/Z_L|$ figure over the span of frequencies from 30 Hz to 100 kHz. The application of the stability criteria should consider all possible source and loads combinations that may occur, including the failure of any equipment connected to the bus. On the Nyquist plot, the phase margin is specified only at the cross-over points where $|Z_S/Z_L|$ intersects the unit circle. The stability criteria are discussed further in the General Discussion appendix of this document. Maintaining stability is specifically important in maintaining power quality in a multiple load and multiple channel system because instability in any part of the system will cause degradation, if not a total loss, to the power quality delivered to any other part of the system.

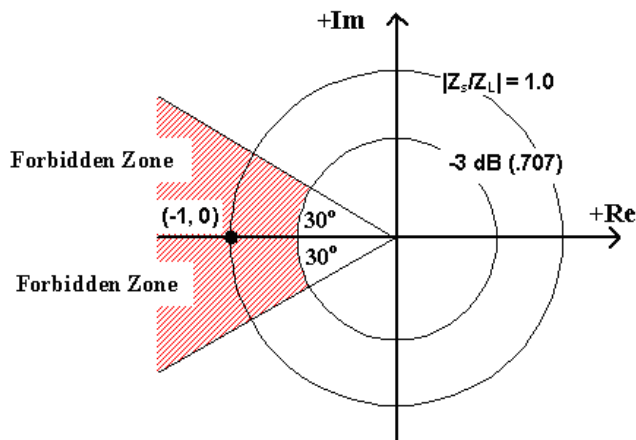


Figure 1 - EPS Nyquist stability criteria

NOTES:

1. Z_S is the output impedance of the source subsystem.
2. Z_L is the input impedance of the load subsystem.

3.1.1.6 Electromagnetic Compatibility

An EPS EMI control plan shall be established for the power system in accordance with the vehicle mission requirements.

Rationale: Adopt a common Electromagnetic Interference (EMI) requirement for the power system.

3.2 EPS Electrical Requirements

The following requirements are imposed on the electric power system to guarantee the required power quality is supplied to the spacecraft loads.

3.2.1 Normal Operation

The electrical power system shall provide the following system power quality in the absence of failures or fault conditions.

3.2.1.1 Steady-State Voltage

The EPS shall supply the steady-state voltage within the range defined in Table 1 for load conditions from no load to rated capacity of the system.

Rationale: Establish a system voltage range for the EPS. The voltage ranges include the expected voltage swing for a power system that is comprised of batteries and either solar arrays or fuel cell power generation with nominal voltage losses due to the EPS distribution system.

3.2.1.2 Normal Load Step Transient Voltage

The electrical power system shall remain within the magnitude and duration limits for voltage transients shown in the figure specified in Table 1.

Rationale: Establish an acceptable normal operating magnitude limit for voltage transients at the EPS due to normal switching of loads. Extreme high and low bus voltages are assumed contingency cases, and while experiencing these conditions it is assumed that the power system will experience small changes in load steps. The rise and fall rates are not defined in the Transient Voltage figures although for test purposes the rate of change is defined for the test setups as 1 V/μs in Section 4.

3.2.1.3 Pulsed Loads

Operation with pulsed loads in the 1 to 30 Hz frequency range shall meet the ripple voltage requirements (see 3.2.1.4).

Rationale: Pulsed loads may cause repetitive voltage transients in excess of the ripple voltage limits. These transients can cause damage to filter components in other EPCE on the same power bus.

3.2.1.4 Ripple Voltage

Ripple voltages are superimposed on the power system and can dramatically affect instrumentation and other sensitive loads. The ripple voltage is a primary power quality parameter. The total system ripple voltage is comprised of the collective contributions from sources and loads. Ripple is defined by three requirements, peak voltage, ripple voltage amplitude, and ripple voltage spectrum.

3.2.1.4.1 Peak Ripple Voltage

The peak ripple voltage for the power system shall be less than the defined values in Table 1.

Rationale: Establish a worst-case peak system ripple voltage with the collective contributions from sources and loads. The requirement particularly targets ripple voltage contributions generated by pulses, doublet pulses and spike waveforms.

3.2.1.4.2 Ripple Voltage Amplitude

The power system ripple voltage amplitude shall be less than the defined values in Table 1.

Rationale: Establish a worst-case maximum system ripple voltage as a primary power quality parameter. This requirement limits the total rms voltage composite of all ripple harmonics. The requirement particularly targets ripple voltage contributions generated by low frequency, non-harmonic, and pulsed loads.

3.2.1.4.3 Ripple Voltage Spectrum

The frequency distribution of the power system ripple voltage shall remain within the limits shown in the figure specified in Table 1.

Rationale: Establish a worst-case system ripple voltage characterized against a frequency range with collective contributions from sources and loads. This system ripple spectrum defines power quality for the electromagnetic emissions and susceptibility requirements. This spectrum requirement limits ripple voltage contribution generated by periodic waveforms such as sine, square and triangle waves.

3.2.1.5 Inrush/Surge Current Transients

The EPS shall support load inrush/surge currents of:

- 0.012 ampere-seconds/ampere for loads ≤ 10 A,
- $(0.00252 + 0.096/A)$ ampere-seconds/ampere for loads from $10\text{ A} < I \leq 200\text{ A}$.

Rationale: Establish inrush/surge capability that the power source can support. EPS designers must allow for inrush/surge conditions while maintaining nominal system voltage. While this inrush/surge requirement does not take into account source/load margin, the EPS designers need to determine sufficient margins to avoid nuisance tripping of source switchgear from protection circuits. Designers should consider minimum values of margin of 120% of rated output when connecting loads that are not predetermined. The ampere-seconds/ampere are normalized inrush ampere-second current divided by the source current rating of the source. The first equation covers circuits up to 10 A and the second equation covers circuits from 10 to 200 A and carries an offset constant. The value of 0.012 A-s/A is equivalent to a capacitance of 100 μF for a 1 A source at 120 V as determined by the equation $C = 0.012 \cdot 1\text{A}/120\text{V}$. An example of a 75 A circuit is $C = 0.00252 \cdot 75\text{A}/120 + 0.096/120$. EPS designs may require additional power conditioning for a large inrush condition to limit the bus voltage drop.

3.2.2 Source Impedance

The source impedance at the EPCE terminals shall be established for the power system from 30 to 150 kHz.

Rationale: The source impedance value is required to evaluate stability margin of the source/load combination at the user input terminals per 3.1.1.5. The source impedance can be determined by analysis supported by test or test for frequencies up to 150 kHz.

3.2.3 External Power Source

External electric power sources shall supply power having the characteristics as specified within this standard.

Rationale: External power must maintain the same ripple, transient, stability, isolation and fault coordination characteristics that the EPS maintains.

Table 1 - Power characteristics

Characteristic	28 V DC (Unregulated Battery Bus)	120 V DC (Unregulated Battery Bus)		
Steady State Voltage (Note 1)	23 to 36 V	98 to 136 V		
Voltage Transients	Figure 2	Figure 6		
Peak Ripple Voltage	1.5 Vp 30 Hz to 1 MHz	3.5 Vp 30 Hz to 1 MHz		
Ripple Voltage Amplitude	1.0 V rms 30 Hz to 1 MHz	2.5 V rms 30 Hz to 1 MHz		
Ripple Voltage Spectrum	Figure 3	Figure 7		
Large Signal Stability	Figure 4	Figure 4		
Abnormal Voltage Limits	Figure 5	Figure 8		
Emergency Voltage Limits	18 V	80 V		

Note 1 - Lower limit of steady state voltage may be tailored to accommodate wiring losses to remote loads.

3.2.4 Abnormal Operation

The electrical power system shall provide the following system power quality in the presence of failures or fault conditions.

3.2.4.1 Reverse Current during Voltage Droop

The EPS shall accept reverse currents under system events without damage.

- 0.012 ampere-seconds/ampere for loads ≤ 10 A,
- $0.00252 + 0.096/A$ ampere-seconds/ampere for loads from $10 \text{ A} < I \leq 200 \text{ A}$.

Rationale: Establish a minimum reverse current capability for switchgear servicing loads during an event causing voltage droop due to EPS transients or a system fault condition to avoid damaging the switchgear. The normalized ampere-seconds/ampere units are defined as the reverse ampere-second current divided by the source current rating. The first equation covers circuits up to 10 A and the second equation covers circuits from 10 to 200 A and carries an offset constant. The value of 0.012 A·s/A is equivalent to a capacitance of 100 μF for a 1 A source at 120 V as determined by the equation $C = 0.012 \cdot 1A/120V$. An example of a 75 A circuit is $C = 0.00252 \cdot 75A/120 + 0.096/120$.

3.2.4.2 EPS Electrical Faults

The EPS power distribution system shall provide overcurrent protection to branch circuits to limit fault currents and isolate faults.

Rationale: The requirement establishes a consistent fault mitigation method for the EPS. Faults in any load branch must be cleared and not cause any other loads supported by other branch circuits to become disabled. The protection should limit/clear the overcurrent condition to maintain the EPS power quality.