Introduction to Fault-Managed Power

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***Abstract*— Fault-Managed Power systems revolutionize power distribution by integrating advanced fault detection, energy limitation, and functional safety. This paper provides an overview of Fault-Managed Power including origins, benefits over traditional AC power distribution, infrastructure applications, hazard mitigation, and functional safety mechanisms. Compliance with standards like UL 1400-1, UL 62368-1, ATIS-0600040, and IEC 61508 is also covered highlighting Fault-Managed Power's safety, efficiency, reliability, and advantages in modern power infrastructure applications.**

Keywords*— *Fault-managed Power, UL 1400-1, UL 1400-2, UL 62368-1, ATIS-0600040, IEC 61508, Hazard-Based Safety Engineering (HBSE), Class 4, Functional Safety, National Electrical Code, NFPA 70, Article 726

I. Introduction

Fault-Managed Power (FMP) systems represent a transformative advancement in power distribution, offering a safer, more efficient alternative to traditional methods. Defined under standards such as UL 1400-1 [1] and National Electrical Code (NEC) Article 726 [2], FMP systems enable the transmission of higher voltages (up to 450 V) while maintaining stringent safety measures [3]. By incorporating real-time fault detection, fault-energy limitation, and rapid shutdown mechanisms, these systems mitigate risks of fire, electric shock, and equipment damage. FMP leverages innovations such as Packet Energy Transfer to ensure safe operation even in fault scenarios. By addressing safety and efficiency challenges, FMP is poised to redefine power distribution across industries.

A. Definition of FMP as a Class 4 power system

The official definition of FMP, as introduced in the 2023 NEC Article 100 [2], is: "*A powering system that monitors for faults and controls current delivered to ensure fault energy is limited*". This definition aligns with NEC Article 726 [2], governing Class 4 circuits. Unlike Class 2 and Class 3 systems that limit power output, FMP systems allow higher power delivery, such as up to 2,000 W, while actively monitoring circuits in real time for faults. Upon detecting faults such as improper wiring, short circuits, or human contact, FMP systems immediately halt power transmission, limiting the energy transferred into the fault to mitigate risks of fire or electric shock. This combination of high-power capacity and advanced safety mechanisms makes FMP ideal for long-distance power distribution in applications like smart buildings, data centers, and telecom networks.

B. NEC Classifications: Class 1, 2, 3, and 4

The NEC [2] defines four classes of power systems with distinct safety profiles. Class 1 circuits operate at up to 600 volts and rely on overcurrent protection rather than inherent power limitations, presenting significant shock and fire hazards that require stringent installation practices. Class 2 circuits are inherently power-limited to 100 VA with maximum voltages of 30 VAC or 60 VDC, minimizing electrical hazards and making them suitable for direct user contact in applications like doorbells and thermostats. Class 3 circuits maintain the 100 VA power limitation but allow higher voltages up to 150 V, presenting increased shock hazards that necessitate additional safeguards against direct contact.

Class 4 circuits represent a new category of FMP systems that transmit energy with continuous fault monitoring. One way this is done is by employing transmitter circuitry that periodically connects the source to transmit energy in discrete packets and disconnects the source during monitoring to verify the absence of faults before sending the next packet. This sophisticated approach enables the delivery of higher power levels while maintaining safety through millisecond fault detection and immediate transmission halting when abnormalities are detected.

C. Key benefits: high power capacity, long-distance transmission, and enhanced safety

FMP offers numerous benefits, making it a transformative solution for modern power distribution. It enhances safety through real-time fault detection and rapid shutdown, reducing risks of fire and shock. FMP enables efficient, high-voltage transmission over long distances, minimizing energy losses and material costs. Its flexibility and scalability support diverse applications, from smart buildings to industrial automation. Cost savings stem from reduced cabling needs and simpler installations. Additionally, FMP contributes to sustainability by lowering energy waste and resource usage, aligning with environmental goals for large-scale infrastructure projects.

D. Potential challenges and limitations of FMP systems

FMP systems face several challenges despite their advantages. Regulatory restrictions in the NEC [2] prohibit residential installations and mandate separation from other electrical systems. Interoperability issues arise as transmitters and receivers typically require same-manufacturer compatibility, creating vendor lock-in concerns. Market resistance exists, particularly from manufacturers of traditional components that FMP systems replace. Potential adopters may exhibit caution toward this relatively new technology.

E. Fault-Managed Power versus traditional AC power distribution and Power over Ethernet

FMP systems offer several key advantages over traditional AC power distribution and Power Over Ethernet (PoE) methods. While conventional systems rely on circuit breakers and fuses for protection, FMP actively monitors circuits in real-time and can shut down power within milliseconds of detecting abnormalities. Over a single pair of #16 AWG conductors, FMP can deliver hundreds of Watts over distances of 2 km or greater as well as deliver over 2 kW at distances of several hundred feet, where these power and distance limitations are only dictated by the factors such as the maximum permitted power dissipation of the cable and the maximum voltage drop that can be tolerated. This far exceeds the limitations of traditional PoE which is restricted to 100 W over 100 meters. The system uses lightweight, thinner-gauge cables and allows for simpler installation methods like cable trays and j-hooks, reducing both material and labor costs compared to traditional conduit-based AC distribution. Additionally, FMP systems include built-in power monitoring capabilities without requiring supplemental devices or equipment, offering significant cost savings over traditional systems that need separate power management infrastructure. NEC [2] requires the separation of traditional AC power distribution from data circuits, where FMP can travel in the same channel or cable as data.

F. Infrastructure applications of Fault-Managed Power

Smart Buildings have seen significant advancements in power distribution technology. Building automation systems, including sensors, lighting controls, and IoT devices, can now be efficiently powered across large facilities using innovative solutions. A prime example of this is the Sinclair Hotel in Texas, which has implemented FMP as its primary power backbone infrastructure. Similarly, the 35-story Circa Casino & Resort in Las Vegas utilizes Digital Electricity™ for powering lights, switches, in-room climate control, and wireless access points, showcasing the versatility of these new power distribution methods in smart building applications.

For Data Centers and Telecommunications, FMP and similar technologies are proving to be game-changers. These systems can power edge computing devices and 5G infrastructure over long distances, enabling efficient power delivery to remote servers and network equipment. The implementation of such technologies can result in substantial cost savings, potentially amounting to multiple millions of dollars for a 6-megawatt data center compared to traditional AC power distribution methods.

Industrial and Commercial sectors are also benefiting from these advanced power distribution systems. Factory floors are leveraging integrated control and power delivery to remote machinery, while warehouses and distribution centers utilize FMP for operational equipment. These technologies are particularly valuable in supporting industrial automation systems, sensors, and control systems in harsh environments, where traditional power distribution methods may face challenges.

In the Transportation and Public Infrastructure sector, FMP and similar technologies are finding diverse applications. Airports are implementing these systems for various power distribution needs, while shipping ports are utilizing the technology for equipment power delivery. Additionally, these advanced power distribution methods are being employed to power traffic control systems and roadway infrastructure, contributing to smarter and more efficient urban environments.

Security systems are significantly enhanced by advanced power distribution technologies, which enable reliable power distribution for security cameras and access control systems across expansive areas. This ensures continuous surveillance and secure access control, even in large and complex environments.

II. ORIGINS

The origins of FMP systems are closely tied to the pioneering work of Stephen S. Eaves, founder and CEO of VoltServer. With patents related to energy storage, power conversion, and fault detection, Eaves revolutionized power distribution by introducing the concept of Packet Energy Transfer technology, laying the foundation for FMP. These innovations involve transmitting power in discrete packets combined with real-time fault monitoring, enabling immediate shutdown upon detecting hazards like short circuits or human contact [4]. Eaves incorporated VoltServer in 2011 and launched the first commercial FMP systems in 2015, transforming power distribution for large-scale applications like stadiums, office buildings, and telecom networks. By combining safety, efficiency, and scalability, his work established FMP as a new standard in modern electrical systems.

A. Packet Energy Transfer

Packet Energy Transfer (PET) is a novel power distribution technology that delivers significant electrical power over long distances while maintaining safety through sophisticated fault management.

The system operates by splitting energy into discrete packets that are transmitted hundreds of times per second from a transmitter to a receiver. Each PET system consists of a Transmitter with semiconductor switches that periodically disconnect the source from the power transmission lines, effectively isolating the load from stored energy through isolation diodes.

The technology continuously monitors line conditions after every packet transmission; if a fault such as improper wiring, short circuit, or human contact is detected, the system halts transmission within milliseconds. This fault management capability allows PET systems to deliver up to 20 times more power than Power over Ethernet while using low-voltage pathways and wiring practices.

The architecture typically employs staggered or interleaved packet transmission across multiple channels to minimize power system impact, with transmission lines operating at voltages similar to RFT-V (±190VDC) but without imposed power limits per circuit. PET systems must be tested as complete units—including power sourcing equipment, transport cables, and powered devices—to ensure precise control of fault energy transfer during human contact events.

B. *Adoption of Fault Managed Power*

FMP adoption began in 2020, spearheaded by the Alliance for Telecommunications Industry Solutions (ATIS), with support from Underwriters Laboratories (UL) and the NEC [2]. ATIS developed the initial technical requirements, culminating in ATIS-0600040 [5], which defined fault energy limitations and testing protocols. UL advanced the effort by drafting UL 1400-1 [1], providing safety guidelines for FMP systems. In parallel, the NEC [2] incorporated Article 726 into its 2023 update [2], establishing Class 4 circuits as a new standard. Collaboration among industry leaders and standards bodies ensured FMP's safe deployment, enabling high-power, fault-limited systems for modern infrastructure applications.

III. FUNCTIONAL SAFETY

Functional Safety in FMP systems represents a comprehensive approach to ensuring safe and reliable power delivery. UL 1400-1 [1] Section 4, Functional Safety, mandates that FMP systems meet Functional Safety requirements. Specifically, "*4.1.1 To ensure a device's fail safe mechanisms are operating correctly and risks are reduced to as low as reasonably practical (ALARP), these assessments are vital to qualify or quantify the safety integrity level of safety functions.*"

The system incorporates multiple layers of protection, including hardware and possibly software components, working in concert to detect, manage, and mitigate potential hazards. At its core, FMP systems rely on sophisticated monitoring and control systems that continuously evaluate operating conditions through software algorithms and/or electronic circuits.

These systems are complemented by physical protection measures such as cable insulation, mechanical safeguards, and safety interlocks. The implementation must adhere to one or more of the following standards: IEC 60812 [6], IEC 61025 [7], SAE J1739 [8], MIL-STD-1629A [9], IEC 61508-1 [10], IEC 61508-2 [11], IEC 61508-3 [12], ISO 13849-1 [13], ISO 13849-2 [14], or IEC 62061 [15]. These requirements mandate specific protections against electrical and mechanical hazards while emphasizing thorough software fault analysis.

Critical testing protocols ensure system response times remain under the shock-duration curve, which is typically under 10 milliseconds for low impedance human contact scenarios, with all fault test results required to fall within specific AC or DC zones similar to IEC 60479-1 [16] and IEC 60479-2 [17] standards. The integration of these various safety components creates a robust system where no single point of failure can compromise overall safety.

IV. HOW FAULT MANAGED POWER MITIGATES HAZARDS

FMP systems prevent hazards by combining advanced fault detection, fault-energy limitation, and rapid shutdown mechanisms. These systems continuously monitor circuits for abnormalities, such as short circuits, ground faults, or human contact with live wires. Upon detecting a fault, power transmission halts or limits typically within milliseconds, minimizing the risk of fire, electric shock, or equipment damage. Unlike traditional systems that limit power output (Class 2 and Class 3), FMP (Class 4) limits fault energy during incidents, ensuring safety even at higher voltages (up to 450 V). This real-time response makes conductors safe to touch ensuring safe power delivery.

A. *NFPA 70 Class 2 and Class 3 circuits limitations*

FMP, classified as Class 4 circuits, prevents hazards by addressing the limitations of Class 2 and Class 3 systems. Class 2 circuits limit power to 100 VA and focus on safety by restricting energy to prevent fire or shock risks. Class 3 circuits allow higher voltages but still rely on power-limiting mechanisms. In contrast, Class 4 systems do not limit power output but instead actively monitor for faults in real time. FMP systems immediately halts power transmission typically within milliseconds upon detecting abnormalities such as line-to-line faults, arc faults, or human contact. This rapid response limits fault energy to levels comparable to Class 2 systems, ensuring safety even at higher voltages (up to 450 V). By mitigating risks of fire and electric shock through advanced fault detection and energy control, FMP enables safe high-power delivery over long distances, making it ideal for modern infrastructure applications.

B. *Fault Managed Power System operation*

UL 1400-1 [1] allows flexibility in designing a FMP System. One FMP system implementation operates by converting standard AC or DC power into small, digitally controlled energy packets [18]. Each packet consists of a 1.5-millisecond high-voltage DC power pulse (350 V) followed by a 0.5-millisecond gap, with approximately 500 packets transmitted every second.

The transmitter continuously monitors these packets for potential faults. If any abnormal condition is detected - such as improper wiring, short circuits, or human contact - the system immediately stops sending the next packet. This intelligent packet-based approach allows for safe power distribution at high levels while enabling transmission distances up to 2 km or even longer using standard low-voltage cables while simultaneously exchanging data within the packet for monitoring and control functions. Fig. 1 details the operation of a FMP System.

At the receiving end, the packets are converted back into standard AC or DC power to serve end devices. All safety related functions are in control of the transmitter alone and do not rely on receiver or communications functionality. The system has proven highly reliable and efficient, capable of delivering up to 1.5 kW per channel while maintaining safety standards comparable to low-voltage systems. Fig. 2 shows a Class 4 system block diagram.

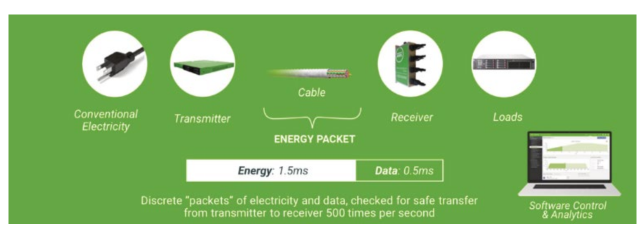

Fig. 1. Fault-Managed Power System Operation

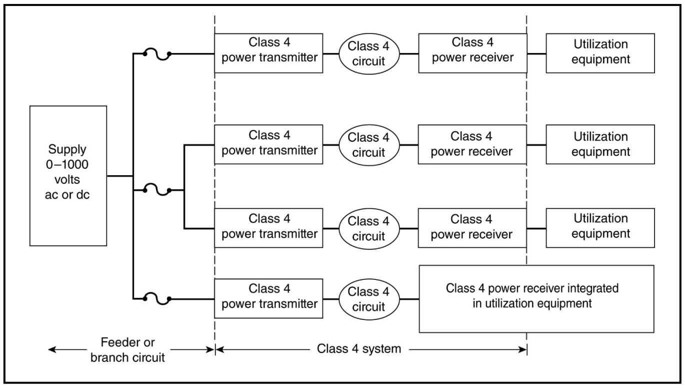

Fig. 2. Informational Note Figure 726.121 Class 4 Circuits - NEC [2]

Power Transmitter - The transmitter, also known as Power Sourcing Equipment (PSE), converts standard AC or DC power from the grid, UPS, or other power source into a Class 4 power source (up to 450 V). This process ensures efficient power delivery over long distances.

The transmitter continuously monitors the circuit for faults such as short circuits, ground faults, or human contact; or continuously monitors for communication from the receiver indicating any such faults were detected. If any fault is detected, it halts or typically limits power transmission within milliseconds to prevent hazards.

Class 4 Cabling - The power is transmitted over specialized Class 4 cables, which are designed to meet UL 1400-2 [19] standards for insulation and safety. These cables allow high-voltage transmission while maintaining a safety profile comparable to Class 2 circuits.

Class 4 cabling can be installed alongside data cables and does not require conduits in most cases, simplifying installation and reducing costs.

Power Receiver - The receiver, also known as a Powered Device (PD), receives the Class 4 power from the transmitter and converts it to another AC or DC format for use by any connected loads.

In one implementation, the receiver converts the high-voltage DC back into usable voltages, i.e., 48 VDC for end devices like IoT systems, lighting, or telecom equipment.

The receiver may communicate with the transmitter to confirm a safe connection before power transmission beings. The receiver may also integrate fault detection to ensure safety at the load level.

This system's fault management capabilities ensure that only a limited amount of energy is delivered during faults, effectively mitigating risks of fire or electric shock while enabling efficient delivery of high power over long distances [20].

C. *Human body's response to electrical current*

The human body's response to electrical current is governed by both the magnitude of current and the duration of exposure. When the body is exposed to voltage, the resulting current flow is influenced by total body impedance, of which the skin resistance can be a negligible or significant amount depending on various contact conditions. For shorter durations under 10 ms, the effects are mainly determined by specific energy and charge transfer, with defined thresholds for physiological responses like perception and pain from impulse currents. When considering a 400 VDC conductor-to-conductor exposure with a hand-to-hand current path, the heart-current factor is 0.4, and the body resistance typically ranges from 1,000 Ω to 1,300 Ω under dry conditions.

This exposure scenario can lead to strong involuntary muscular reactions and potential cardiac disturbances. Beyond these direct electrical effects, serious non-electrical injuries can occur, including falls from heights, involuntary muscle reactions, loss of balance, and secondary trauma. These indirect injuries can be particularly severe in workplace situations involving elevated positions or hazardous environments, where the consequences of electrical shock can be compounded by environmental factors.

The relationship between IEC 60990 [21], IEC 60479-1 [16], and ATIS-0600040 [5] Annex A presents a comprehensive framework for human body resistance modeling in electrical safety testing. The foundation begins with IEC 60479-1's [16] empirical data on human body impedance, which establishes baseline physiological responses to electrical current. This standard provides detailed impedance values for various body paths and contact conditions, with particular emphasis on hand-to-hand and hand-to-foot current paths.

ATIS-0600040 [5] Annex A builds upon this foundation by implementing a simplified resistance model that adopts two critical boundary conditions from IEC 60990 [21]: a 500 Ω lower boundary representing worst-case scenarios where skin impedance is eliminated, and a 2,000 Ω upper boundary representing typical body resistance with intact skin impedance. These values are validated through empirical measurements showing the lowest hand-to-hand resistance of 575 Ω and hand-to-foot resistance of 553 Ω.

The standard introduces important modifications to account for different contact scenarios. For hand-to-hand paths, it adds 1,000 Ω to account for index finger to thumb contact with both hands. For hand-to-foot paths, it adds 500 Ω for index finger to thumb contact with one hand and calculates the total at 90% of the adjusted hand-to-hand resistance. These adjustments create a more practical testing model while maintaining safety margins established in IEC 60479-1 [16].

The model specifies testing parameters for DC voltages between 60 and 400 V, with additional testing required at resistance values corresponding to a 25 mA heart current. This ensures that electric shock exposure remains within DC zone 2 (DC-2) [Fig. 3] for continuous contact scenarios. The framework assumes body insulation from ground for hand-to-hand contact and grounded feet for hand-to-foot contact scenarios.

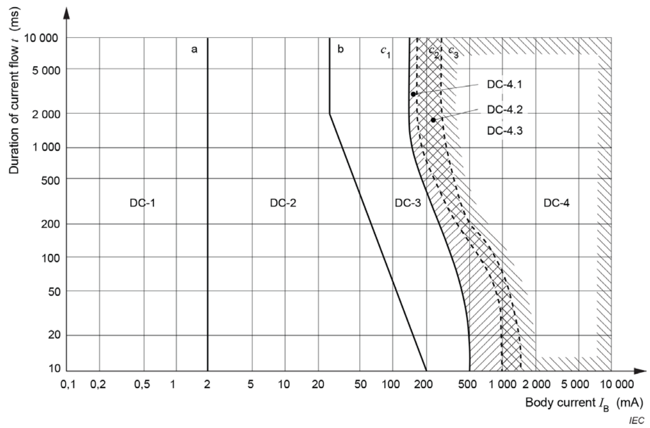

Fig. 3. IEC 60479-1 [16], Figure 22, Conventional time/current zones of effects of DC currents on persons for a longitudinal upward current path

FMP also addresses let-go limits, as a line-to-line fault or a line-to-earth fault that requires mitigation is defined as any fault that exceeds the let-go limits for AC, DC, or AC+DC in combination. Faults are not considered mitigated until the fault is below an appropriate let-go limit and remain under this let-go limit for approximately 3 seconds to ensure cumulative heart effects cannot continue and to allow recovery of muscle control.

This integrated approach provides a standardized methodology for electrical safety testing that combines theoretical understanding of human body impedance with practical testing requirements, ensuring consistent and reliable safety assessments across different applications.

D. UL 1400-1 – Annex A and Annex B

When it comes to in-line resistive faults for fire hazards, Class 4 devices must meet 1 of 2 mitigation options. One option, described in Annex A of UL 1400-1 [1], mitigates the risk of fire due to in-line resistive faults through strict connector requirements covering insulation requirements, thermal factors, mechanical performance such as crush test resilience, security of blades, and other similar requirements to reduce the probability of fault occurrences at the connector. The other option, described in Annex B of UL 1400-1 [1], mitigates the risk of fire due to in-line resistive faults by limiting in-line resistive faults to less than 100 W similar to Class 2 systems. This negates the need for more restrictive connector requirements since the failure modes addressed by those requirements can be detected. This permits a cost savings for the manufacturer and the customer by avoiding the expense of the connectors required by Annex A. Additionally, such fault detection in accordance with Annex B can further mitigate faults that are not addressed by Annex A, such as mid-cable faults, poor splices, or any other possible fault location not at the end connectors.

E. Hazard-Based Safety Engineering

IEC/UL 62368-1 [22] plays a crucial role in Fault Managed Power Systems by establishing fundamental safety requirements that must be integrated into the system design. In Class 4 FMP Systems, compliance with IEC/UL 62368-1 [22] is mandatory as part of the UL 1400-1 [1] standard requirements. The standard employs a hazard-based safety engineering (HBSE) approach, requiring appropriate safeguards between energy sources and potential points of contact. These safeguards are organized in a hierarchy ranging from basic to reinforced, with each level providing increasing protection against electrical hazards. For power supplies within these systems, the standard imposes specific testing requirements, including enhanced voltage testing for basic and reinforced insulation, as well as strict capacitor discharge specifications to ensure safety. This comprehensive approach to safety certification helps ensure that FMP Systems can deliver higher voltages while maintaining robust protection against shock and fire hazards.

V. CONCLUSIONS

FMP systems, also known as Class 4 power systems, provide comprehensive fault protection through sophisticated monitoring and control mechanisms. Unlike traditional GFCI and AFCI systems, FMP systems can detect and respond to all types of faults: line-to-earth, line-to-line, in-line arcing, parallel arcing, and resistive faults [TABLE I] .

The system actively monitors for human contact faults and controls power delivery to ensure fault energy remains within safe limits.

TABLE I. FAULT-MANAGED POWER PROTECTIONS

Hazard	Fault	GFCI	AFCI	Class 4
Shock	Line-to-Earth	YES	YES	YES
	Line-to-Line	NO	NO	YES
Fire	In-Line Arc	NO	YES	YES
	Parallel Arc	NO	YES	YES
	Line-to-Line resistive	NO	NO	YES
	In-Line Resistive	NO	NO	YES

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REFERENCES

[1] UL 1400-1, UL LLC Outline of Investigation for Fault-Managed Power Systems - Part 1: Safety Requirements

[2] NFPA, (2023), NFPA 70: National Electrical Code (NEC) (2023 Edition). Quincy, MA: National Fire Protection Association

[3] T. Sarkar, J. Casey and N. Lutz, "Modeling MOSFETs for fault-managed power systems: a transient analysis based on capacitance dynamics," 2023 IEEE Energy Conversion Congress and Exposition (ECCE)

[4] S. S. Eaves, “Network remote powering using packet energy transfer” Telecommunications Energy Conference (INTELEC), 2012 IEEE 34th International

[5] ATIS-0600040, Fault Managed Power Distribution Technologies – Humatisan Contact Fault Analysis

[6] IEC 60812, Failure modes and effects analysis (FMEA and FMECA)

[7] IEC 61025, Fault tree analysis (FTA)

[8] SAE J1739, Potential Failure Mode and Effects Analysis (FMEA) Including Design FMEA, Supplemental FMEA-MSR, and Process FMEA

[9] MIL-STD-1629A, Procedures for Performing a Failure Mode, Effects and Criticality Analysis

[10] IEC 61508-1, Functional safety of electrical/electronic/programmable electronic safety-related systems - Part 1: General requirements

[11] IEC 61508-2, Functional Safety of Electrical / Electronic / Programmable Electronic Safety Related Systems – Part 2: Requirements for Electrical / Electronic / Programmable Electronic Safety Related Systems

[12] IEC 61508-3, Functional Safety of Electrical / Electronic / Programmable Electronic Safety Related Systems – Part 3: Software

[13] ISO 13849-1, Safety of machinery — Safety-related parts of control systems, Part 1: General principles for design

[14] ISO 13849-2, Safety of machinery — Safety-related parts of control systems, Part 2: Validation

[15] IEC 62061, Safety of machinery - Functional safety of safety-related control systems

[16] IEC 60479-1, Effects of current on human beings and livestock - Part 1: General aspects

[17] IEC 60479-2, Effects of current on human beings and livestock - Part 2: Special aspects

[18] T. Sarkar and J. Casey, "Switching transient induced skin effect in Packet Energy Transfer systems," SoutheastCon 2024

[19] UL 1400-2, UL LLC Outline of Investigation for Fault-Managed Power Systems - Part 2: Requirements for Cables

[20] T. Sarkar, A. Mills and J. Casey, "Soft start optimization using NTC resistors in fault managed power systems," 2024 IEEE/IAS 60th Industrial and Commercial Power Systems Technical Conference (I&CPS), Las Vegas, NV, USA, 2024

[21] IEC 60990, Methods of measurement of touch current and protective conductor current

[22] UL 62368-1, Audio/Video, Information and Communication Technology Equipment— Part 1: Safety Requirements