IAES Journal of Electrical and Electronics Engineering
Vol. 9, No. 1, June 2022, pp. 6~10
ISSN: 2338-7432, DOI: 10.11591/jeee.v9i1.pp6-10

Advanced electrical protection in smart plugs: a review of overcurrent detection, thermal protection, and electrical fault mitigation

Tole Sutikno[1], Tri Wahono[2], Hendril Satrian Purnama[2]
[1]Faculty of Industrial Technology, Universitas Ahmad Dahlan, Yogyakarta, Indonesia
[2]Embedded Systems and Power Electronics Research Group, Yogyakarta, Indonesia

Article Info

Article history:

Received Apr 6, 2020
Revised Nov 28, 2020
Accepted Dec 9, 2020

Keywords:

Arc-fault detection
Electrical safety
Fault mitigation
Overcurrent protection
Smart electrical plugs
Thermal monitoring

ABSTRACT

Smart electrical plugs are evolving from remotely controlled outlets into potential components of intelligent electrical safety systems. Their integration with current sensors, temperature sensors, embedded controllers, and communication interfaces creates opportunities to detect abnormal operating conditions and disconnect hazardous loads. This review examines three protection priorities: overcurrent detection, thermal monitoring, and electrical fault mitigation, with particular attention to residential, commercial, laboratory, and light industrial applications. Relevant literature published up to 2021 is synthesized from research on arc-fault detection, high-impedance faults, connector degradation, electrothermal protection, and low-voltage distribution systems. The review identifies current measurement as an effective basis for overload detection, while temperature and contact-resistance monitoring can reveal developing thermal hazards that may not immediately produce excessive current. Arc-fault detection requires additional signal analysis because some series faults generate currents below conventional protection thresholds. An integrated protection architecture is proposed, combining sensing, fault classification, decision logic, and controlled disconnection. The review also highlights limitations involving sensor accuracy, nuisance tripping, switching-device ratings, communication reliability, and certification. Smart plugs should complement, rather than replace, certified circuit breakers and residual-current protection.

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1. INTRODUCTION

Electrical safety at the appliance connection point remains an important concern in residential, commercial, laboratory, and industrial environments. Overloaded outlets, deteriorated contacts, damaged insulation, and abnormal appliance operation can produce excessive heating or hazardous electrical faults. Conventional protective devices are essential, but they generally operate at the circuit or distribution-board level rather than providing detailed information about the condition of each connected appliance. This creates an opportunity for smart electrical plugs to provide additional appliance-level monitoring and early warning.

A smart electrical plug combines a socket interface with electronic measurement, switching, processing, and communication functions. Depending on its design, it can monitor load current, voltage, power, and local temperature, then respond to abnormal conditions through alarms or automatic disconnection. Such functions can improve visibility of developing hazards, particularly when abnormal behavior occurs at an individual appliance or plug connection. However, a smart plug must be designed as a supplementary protection device and must not be treated as a substitute for certified overcurrent, short-circuit, or residual-current protective equipment.

The main challenge is that electrical hazards do not always produce the same measurable symptoms. Overloads usually cause sustained current above an acceptable operating level, while poor contacts can generate localized heating without a large increase in total load current. Series arc faults may also produce

irregular electrical signatures without activating conventional overcurrent protection. This review therefore examines overcurrent detection, thermal protection, and fault mitigation as complementary functions within an integrated smart-plug architecture.

2. REVIEW SCOPE AND SMART-PLUG PROTECTION ARCHITECTURE

This review synthesizes research on low-voltage electrical protection, arc-fault detection, thermal behavior, connector reliability, and intelligent fault diagnosis. Because peer-reviewed studies specifically evaluating complete smart-plug protection products are relatively limited, relevant research on electrical connectors, miniature circuit breakers, and distribution-system faults is also considered. These studies provide the physical principles and detection methods that can inform smart-plug design, although their results should not be interpreted as direct validation of a particular smart-plug product. The discussion consequently distinguishes established protection principles from potential smart-plug implementations.

A practical protection architecture consists of five functional elements: electrical sensing, thermal sensing, fault assessment, switching, and user notification. Current and voltage sensors provide electrical measurements, while temperature sensors monitor the plug body, contact region, or internal switching components. A microcontroller evaluates the measurements against protection thresholds and time-dependent operating rules. When a hazardous condition is identified, the system can disconnect the load and communicate an alarm through a local indicator or networked application.

The sensing arrangement must reflect the physical location of the hazard. A current sensor can identify overload conditions in the connected load, but it may not detect a high-resistance contact that heats locally while carrying an otherwise normal current. A temperature sensor can identify abnormal heating, although its response depends on sensor placement, thermal coupling, ambient conditions, and enclosure design. Combining electrical and thermal measurements therefore provides a more comprehensive basis for protection than relying on a single sensor.

3. OVERCURRENT AND SHORT-CIRCUIT DETECTION

Overcurrent protection is the first essential function of a safety-oriented smart plug. An overload occurs when a connected appliance or group of loads draws current beyond the permitted operating level for a sufficient period, whereas a short circuit can produce a much larger fault current requiring rapid interruption. Current transformers, Hall-effect sensors, and shunt-based measurement circuits can provide the information needed to identify abnormal current conditions. The detection logic should consider both current magnitude and duration because brief starting currents may be normal for motors, compressors, and other appliances.

Conventional miniature circuit breakers use thermal and magnetic operating principles to respond to overloads and short circuits. Lyu and Zong [1] investigated an electrothermal current-prediction method for miniature circuit breakers, demonstrating the relevance of temperature-related information to overload protection. Their work suggests that thermal behavior can supplement current measurement when estimating the operating condition of protective components. In a smart plug, similar principles could support warning functions or coordinated disconnection, provided that the electronic control does not compromise the independent operation of certified protection devices.

Overcurrent thresholds must be selected according to the plug rating, conductor capacity, switching-device rating, and applicable electrical standards. A threshold that is too high may permit dangerous heating, while a threshold that is too low can cause nuisance disconnection during normal appliance startup. Time-current behavior is therefore important when designing protection logic for different load categories. Mahindara *et al.* [2] discussed coordination challenges in overcurrent protection, emphasizing that protective devices must operate selectively and reliably under different fault conditions.

4. THERMAL MONITORING AND OVERHEATING PROTECTION

Thermal monitoring is necessary because not all dangerous electrical conditions are accompanied by excessive load current. Loose contacts, oxidation, mechanical wear, and degraded connector interfaces can increase contact resistance and produce localized heating. Research on connector health monitoring has shown that electrical resistance and temperature can provide useful indicators of developing connector degradation [3], [4]. These findings are relevant to smart plugs because the plug blades, socket contacts, internal terminals, and switching components are potential locations of abnormal heat generation.

A temperature-based protection function can use thermistors, resistance temperature detectors, or integrated temperature sensors placed near critical components. The controller can compare measured temperatures with defined warning and disconnection limits, while also considering the rate of temperature increase. A gradual rise may indicate progressive contact deterioration, whereas a rapid rise can suggest an

acute overload or component failure. However, a sensor located far from the actual contact interface may respond too slowly to prevent damage, making thermal design and sensor placement essential.

Thermal protection should therefore combine temperature thresholds with electrical operating information. For example, a high temperature accompanied by sustained excessive current may indicate an overload, while a high temperature under moderate current may suggest poor contact or internal resistance growth. Connector degradation research supports monitoring resistance and temperature together rather than relying exclusively on a single thermal reading [3], [4]. This combined approach can improve early warning, although laboratory testing is still required to establish reliable thresholds for different plug designs and environmental conditions.

5. ARC FAULTS AND OTHER ELECTRICAL FAULT CONDITIONS

Arc faults represent a particularly difficult protection challenge because they may not produce the high current expected from a conventional short circuit. A series arc can occur at a damaged conductor or loose connection, and its current may remain limited by the connected load. Chu *et al.* [5] investigated series AC arc-fault detection using a high-frequency coupling sensor and convolutional neural networks, illustrating how signal characteristics can support fault recognition. Other studies have examined arc detection using signal processing, machine learning, and image-based feature extraction [6]–[8].

The distinction between series and parallel arc faults is important when selecting detection methods. Parallel arcs may produce substantial fault current, while series arcs can be more difficult to identify using simple current thresholds. Saeed *et al.* [6] examined series and parallel arc-fault detection in electrical buildings, while Ferracuti *et al.* [7] investigated arc-fault detection and appliance classification in AC home electrical networks. These studies indicate that signal patterns, frequency-domain characteristics, and load-dependent behavior can help distinguish abnormal arcing from normal switching transients.

High-impedance faults and ground faults introduce additional detection difficulties. Their current levels may be insufficient to activate conventional overcurrent protection, even though they can create hazardous conditions. Research has investigated signal decomposition, feature extraction, and data-driven methods for identifying high-impedance faults [9]–[12]. Although many of these studies address distribution networks rather than individual smart plugs, their findings show why intelligent fault detection may require more than a fixed current threshold.

6. FAULT MITIGATION AND PROTECTION COORDINATION

Fault mitigation involves more than detecting an abnormal condition because the system must also interrupt the hazardous current safely. A smart plug may use a relay, contactor, or semiconductor switching element to disconnect the load, but the selected device must be rated for the expected voltage, current, fault duty, and switching frequency. The interruption mechanism must also account for contact welding, switching transients, and the possibility that the fault current exceeds the device's breaking capability. Consequently, a low-cost relay should not be assumed to provide short-circuit protection simply because it can switch a load under normal operating conditions.

Table 1 summarizes the principal hazards, measurable indicators, and possible smart-plug responses. It also shows why no single sensor can reliably identify every fault category. Current measurement is central to overload detection, but temperature and signal-pattern analysis are needed for other developing hazards. A coordinated design should therefore combine sensing and protective actions while retaining independent, certified safety devices.

Table 1. Electrical hazards and potential smart-plug protection functions

Hazard	Typical indicators	Potential smart-plug response	Important limitation
Overload	Sustained excessive current; rising temperature	Time-dependent current assessment and disconnection	Must tolerate legitimate startup current
Short circuit	Very high current and rapid electrical transient	Rapid fault interruption and alarm	Switching element must have adequate breaking capacity
Poor contact	Localized temperature rise; increasing contact resistance	Thermal warning and disconnection	Sensor must be thermally coupled to the contact region
Series arc	Irregular current and high-frequency signatures	Signal-based arc detection and isolation	Load variation can cause false alarms
Parallel arc	Abnormal current and voltage signatures	Rapid fault recognition and interruption	Detection must be coordinated with circuit protection
Ground or leakage fault	Residual-current or insulation-related indicators	Warning and coordination with residual-current protection	A smart plug sensor does not replace a certified RCD

A robust smart-plug design should coordinate its functions with upstream circuit breakers, fuses, and residual-current devices. Overcurrent protection should address overload and short-circuit conditions, while residual-current protection should address applicable leakage-current and electric-shock hazards [13]-[15]. Arc-fault detection may provide another layer of protection where supported by appropriate hardware and standards. The smart plug's role is to add local monitoring, early warning, and supplementary disconnection rather than replace the protective functions of the electrical installation [16]-[18].

7. RESEARCH CHALLENGES AND FUTURE DIRECTIONS

The first major challenge is reliable detection across diverse appliance types and operating conditions. Motors, heaters, power supplies, and electronic devices exhibit different startup currents, switching patterns, and harmonic characteristics. A detection algorithm trained on a limited set of loads may misclassify normal operation as a fault or fail to recognize an unfamiliar fault signature. Future studies should therefore use diverse appliance datasets and evaluate detection sensitivity, false-alarm rates, and response time under realistic operating conditions.

The second challenge concerns thermal sensor placement and long-term reliability. A sensor embedded in the plug enclosure may not accurately represent the temperature at a deteriorated electrical contact, particularly when heat transfer is affected by the enclosure material and airflow. Repeated insertion, removal, mechanical stress, dust, and environmental temperature changes can also affect contact performance. Research on connector degradation and condition monitoring provides a foundation for developing more representative thermal and resistance-based assessment methods [3], [4].

The third challenge is safe integration of intelligent electronics with certified protective equipment. Smart-plug manufacturers must consider insulation coordination, creepage and clearance distances, enclosure temperature, switching endurance, electromagnetic compatibility, and fail-safe behavior. Network connectivity should be treated as an additional monitoring function rather than a prerequisite for local protection, because communication failure must not disable essential safety responses. Future work should prioritize standardized test procedures, independent protection paths, and field validation in residential, commercial, laboratory, and industrial environments.

8. CONCLUSION

Advanced electrical protection can extend the role of smart plugs from remote switching to appliance-level safety monitoring and supplementary fault mitigation. Overcurrent sensing provides a practical basis for identifying overloads and abnormal current conditions, while thermal monitoring can reveal localized heating associated with poor contacts and component degradation. Arc-fault and high-impedance fault detection require more advanced signal analysis because hazardous conditions may not activate conventional current thresholds. An integrated architecture combining electrical sensing, temperature monitoring, fault assessment, and controlled disconnection offers a promising direction for future smart-plug development. Nevertheless, smart plugs must complement certified circuit breakers, fuses, and residual-current protection rather than replace them. Further research should validate detection performance, switching capability, thermal response, and long-term reliability under realistic operating conditions.

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