WHITE PAPER

# Arc-Fault Circuit Interrupter (AFCI) Technology

## History, Importance, and Current Challenges

### Executive Summary

Arc-Fault Circuit Interrupters (AFCIs) represent one of the most significant electrical safety advancements in residential construction in the past 30 years. Developed in response to persistent residential electrical fires that conventional overcurrent protection could not prevent, AFCIs were introduced into the National Electrical Code® (NEC®) in 1999 and have since expanded to cover nearly all 120V branch circuits in dwellings.

While AFCI adoption demonstrates great potential for reducing fires, injuries, and fatalities, the technology continues to face challenges related to load compatibility, nuisance tripping, legacy wiring, and public perception. This paper examines the history of AFCI development, why AFCIs are critical to modern electrical safety, and how Leviton has addressed the current technical and market challenges for our customers.

### History of AFCI Technology

By the late 20th century, U.S. fire data revealed a troubling trend:

- Electrical failures and electrical distribution equipment have long represented a significant residential fire hazard in the United States. While residential fire patterns have changed substantially over time, electrical distribution and lighting equipment continue to contribute to tens of thousands of home fires each year. NFPA data cited by the Electrical Safety Foundation International indicate an average of 31,647 home fires annually from 2011–2023 involving electrical distribution or lighting equipment.[2]
- Research into residential electrical fire hazards evolved over several decades as the industry developed a better understanding of how arcing conditions could lead to ignition without necessarily activating conventional overcurrent protection. In the 1990s, UL conducted focused research into arc-fault detection circuit breakers, including studies of arc-current characteristics associated with ignition, unwanted operation, and building-wire impedance. This research helped form the technical basis for UL 1699, the Standard for Arc-Fault Circuit-Interrupters, whose first edition was published in 1999.
- Conventional circuit breakers are designed primarily to protect against overloads and short circuits and may not respond to dangerous intermittent arcing conditions that occur below their normal trip thresholds.

These findings established the need for a fundamentally new protection mechanism, which resulted in the development and eventual National Electrical Code® (NEC®) adoption of Arc-Fault Circuit Interrupter (AFCI) technology.

- **1999 NEC®:** AFCI protection was first required for 125-volt, single-phase, 15- and 20-ampere receptacle circuits serving dwelling unit bedrooms.
- 2002 NEC®: The requirement expanded to include all outlets in dwelling unit bedrooms.
- Subsequent NEC cycles expanded AFCI protection requirements to additional living areas, including family rooms, dining rooms, living rooms, hallways, kitchens, laundry areas, and similar spaces.
- UL developed **UL 1699, Standard for Arc-Fault Circuit-Interrupters,** establishing performance requirements, product classifications, and testing methods that enabled industry-wide adoption and standardization of AFCI technology.

Over time, AFCI technology evolved from **branch/feeder-type AFCIs** to **combination-type AFCIs,** which can detect both series and parallel arcing faults in fixed wiring and connected cord sets.

## Why AFCI Protection Is Important

Data consistently shows that AFCIs address a major category of fire hazards that legacy protection was not designed to detect:

- Electrical hazards continue to represent a significant residential fire-safety concern. According to NFPA, U.S. fire departments responded to an estimated annual average of 46,652 home structure fires from 2020–2024 in which an electrical failure or malfunction contributed to ignition or electrical distribution, lighting, or power-transfer equipment was involved in ignition.[2]
- Electrical failures, malfunctions, and electrical distribution equipment continue to represent a major residential fire safety concern, contributing to deaths, injuries, and property damage each year.
- The Electrical Safety Foundation International, citing CPSC estimates, states that **up to 50% of home electrical fires may be preventable** with proper AFCI protection.

Modern homes introduce risk factors that did not exist at the same scale when traditional breakers were designed:

- Increased use of cord-and-plug-connected electronics, power supplies, smart devices, and other connected loads can add more complex electrical signatures to residential circuits.
- Energy-efficient electronics, motor drives, LED drivers, and switching power supplies can introduce non-linear current behavior and electrical noise that must be distinguished from hazardous arcing.
- Aging wiring in remodels and expanded AFCI requirements mean more existing homes are being evaluated against modern code expectations when circuits are modified or extended.

AFCIs provide **preventive protection** by detecting electrical arcing characteristics and de-energizing circuits before an arcing condition can progress into an ignition event, representing a proactive rather than reactive safety model.

## Current Challenges Facing AFCI Technology

Despite proven benefits, AFCIs continue to face adoption and perception challenges, largely driven by nuisance tripping concerns, which remain a common contractor and homeowner complaint.

- Certain loads, including motors, dimmers, LED drivers, electronic power supplies, and other non-linear loads, can create electrical signatures that are more difficult for AFCIs to classify than simple resistive loads.
- While many trips can indicate legitimate wiring defects or unsafe conditions, users may perceive trips as nuisance events when the root cause is not immediately visible or easy to diagnose.
- As new appliances and connected devices enter the market, AFCI detection technology must continue evolving to distinguish normal load behavior from hazardous arcing conditions.

**Several factors continue to influence understanding and acceptance of AFCI technology:**

- Questions about unwanted tripping and compatibility with certain connected loads
- Confusion between GFCI and AFCI functions, even though GFCIs are intended to address shock hazards while AFCIs are intended to address fire hazards from arcing faults
- Inconsistent local code adoption and enforcement, which can create regional skepticism about AFCI requirements

## Technology Evolution Pressure

As homes continue to electrify and add EV infrastructure, energy management systems, smart loads, high-efficiency motors, and power electronics, AFCI technology must continue improving its ability to:

- Improve **signal discrimination** between hazardous arcing and normal load behavior
- Support more advanced, data-driven detection methods that can account for complex and changing electrical signatures
- Maintain fire-safety performance while reducing unwanted trips that create homeowner and contractor frustration

The broader electrical protection industry is beginning to address these challenges through embedded intelligence, edge-based machine learning, and firmware-based detection approaches designed to classify arc-fault signatures more accurately while minimizing false positives.

## How Leviton Is Addressing This with Updated AFCI Technology

AFCIs are not a finished technology. They are an evolving safety platform responding to a changing residential electrical environment.

As residential electrical loads continue to evolve, driven by electronics, high-frequency power supplies, energy-efficient motors, and connected devices, traditional rules-based arc-fault detection can face limitations. Fixed detection thresholds and static pattern libraries may struggle to keep pace with:

1. Rapidly changing load signatures
2. New appliance topologies entering the market after a device's original detection logic was developed
3. Increasing electrical noise from power electronics and switching power supplies

To sustain both fire **prevention performance and user acceptance**, AFCI technology must continue moving beyond static detection toward more adaptive, data-driven intelligence.

## Leviton's Machine-Learning-Based AFCI Platform

Leviton's next-generation AFCI technology integrates shunt-based current sensing with machine-learning-driven classification models embedded directly within the circuit breaker. Together, these elements are intended to enable higher-fidelity electrical measurement and deeper event classification, improving alignment between AFCI operation and real hazard conditions while maintaining the safety objectives established by UL 1699 and the NEC.

## Shunt-Based Current Sensing: Fidelity, Linearity, and Calibration Stability

A foundational advancement in this AFCI architecture is the use of shunt-based sensing for current measurement. Shunt-based current sensing provides a direct method of measuring circuit current and is commonly used in applications that require accurate, repeatable current measurement.

Key advantages of shunt current sensing include:

- High measurement accuracy and linear current representation across a defined operating range
- Stable calibration characteristics that support repeatable measurement performance over time
- High-fidelity temporal measurement, allowing more precise observation of how current behavior changes moment to moment

For arc-fault detection, the ability to observe changes in current magnitude, shape, timing, and continuity is critical because AFCIs must identify patterns associated with hazardous arcing while ignoring normal load behavior. Shunt sensing provides a stable measurement foundation that supports more consistent capture of electrical signatures.

This combination of linearity, calibration stability, and temporal fidelity enables a more realistic representation of residential electrical behavior, forming a reliable input foundation for advanced analytical techniques.

## Machine Learning Models: Deep Classification of Non-Linear Electrical Patterns

Building on this high-quality sensing foundation, Leviton AFCIs employ machine-learning algorithms whose primary advantage lies in the depth and resolution of classification they enable. Machine-learning techniques are increasingly being studied and applied for arc-fault detection because arc signatures can vary significantly across load types, operating conditions, and electrical environments.

Rather than relying only on a limited set of predefined rules or thresholds, machine-learning models can evaluate electrical behavior within a richer decision space. This allows the system to recognize and differentiate nonlinear, multi-factor patterns that are difficult to fully characterize using deterministic logic alone.

The models are designed to distinguish between:

- Electrical behavior consistent with true arc-fault hazards
- Legitimate but complex load interactions common in modern homes
- Normal operating variability that may appear severe when viewed in isolation

By operating at higher classification resolution, the algorithm can account for interactions between multiple electrical characteristics simultaneously, enabling more nuanced conclusions about whether an observed condition represents a genuine safety risk.

The result is greater fault decision depth, evaluating not only whether an event exceeds a threshold but also how closely it aligns with hazardous or non-hazardous electrical patterns.

## Data-Driven Model Development Reflecting Real Residential Complexity

The effectiveness of this classification depth is driven by exposure to real residential electrical behavior. Machine-learning-based arc-fault detection relies on broad and representative electrical signal datasets to support accurate classification across varied operating conditions.

Leviton's machine-learning models are developed using a broad and continuously expanding dataset that includes:

- Field-captured trip events collected over time
- Controlled laboratory data generated using representative residential loads
- Events correlated to known electrical conditions, appliance behaviors, and verified hazards

This dataset reflects the diversity and non-linearity of modern residential electrical systems, spanning different home vintages, installation practices, and appliance technologies. Training across this breadth allows the models to learn how electrical patterns vary and interact under real-world conditions.

As a result, the AFCI system can improve its ability to classify unfamiliar or emerging behaviors while maintaining safety margins and alignment with code and product safety objectives.

## Immunity to RF Noise and Nuisance Disturbances

An additional advantage of current-based sensing and advanced signal classification is improved ability to focus on electrical behavior associated with actual circuit current rather than reacting to unrelated high-frequency disturbances.

In modern residential environments, electronic loads such as switching power supplies, variable-speed drives, LED drivers, and digitally controlled appliances can introduce high-frequency electrical noise and non-linear current behavior onto residential circuits. While this activity may be present on the electrical system, it does not necessarily represent sustained current behavior associated with hazardous arcing.

Current-based arc-fault detection algorithms, when supported by high-fidelity sensing and advanced classification, can better distinguish between nonhazardous disturbances and coherent current signatures associated with actual arc-fault conditions.

This increased resistance to nuisance disturbances improves robustness in electrically noisy environments and reduces susceptibility to unwanted tripping caused by normal appliance operation or incidental electromagnetic interference. At the same time, sensitivity to genuine arc-fault conditions is preserved because true hazards produce electrical behavior that can be captured, classified, and acted upon by the AFCI device.

## Conclusion and Implications for the Industry

Machine-learning-enabled AFCIs signal a broader transition for residential electrical safety:

1. From reactive protection to **predictive pattern recognition**
2. From fixed algorithms to **evidence-based continuous improvement**
3. From installer troubleshooting burden to **smarter edge intelligence**

As homes become more electrified, connected, and electronically complex, adaptive AFCI technology offers a path to maintain NEC-level safety objectives while reducing friction for homeowners, contractors, and inspectors.

Leviton's ML-driven AFCI architecture demonstrates how field experience, higher-fidelity sensing, and modern data science techniques can address longstanding pain points without compromising safety fundamentals. As code requirements expand and home power systems grow more complex, intelligence at the circuit-protection level will play an increasingly central role in preventing fires while maintaining system reliability.

AFCI technology has already delivered measurable public-safety benefits by addressing a category of electrical fires that conventional overcurrent protection was not designed to detect. While challenges persist, particularly around nuisance tripping and legacy wiring, these issues reflect the **complexity of modern electrical systems,** not a failure of the AFCI safety concept.

The continued evolution of AFCI design, combined with improved education and realistic expectations, positions AFCIs as a cornerstone of residential electrical safety for decades to come.

1. World Intellectual Property Organization; WO2026060353 - MACHINE LEARNING-BASED ARC FAULT DETECTION AND NUISANCE TRIP AVOIDANCE
2. National Fire Protection Association (NFPA), Electrical Home Fire Safety, "Statistics," 2020–2024. Accessed October 28, 2026

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26-R-0566-sa

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