IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received December 4, 2017, accepted January 24, 2018, date of publication February 7, 2018, date of current version March 15, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2803298

Molded Case Circuit Breakers - Some Holes in the Electrical Safety Net

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ABSTRACT Test results presented in this paper demonstrate that some brands of residential molded case circuit breakers do not operate properly within the limits specified by the applicable standard. The samples tested are both used, from homes, and new, purchased at retail sources. The minimum trip current is determined for each breaker. The test procedure encompasses the basic overload trip requirements of the applicable standard. Breakers that do not open the circuit at or below 135% of rated current fail to meet the requirements of the standard. Test results vary substantially from brand to brand. The best brands are essentially failure free. The failure rate of the worst-case brands is in the order of 50% for both used breakers from homes and new breakers recently purchased. Some samples, primarily multi-pole breakers, do not open the circuit at any level of applied current. Failure of a circuit breaker in a home to operate properly when required poses an increased risk of fire and injury.

INDEX TERMS Circuit breaker, electrical fires, electrical safety, failure, quality control, residential, test data, test method, test results.

I. INTRODUCTION

Circuit breaker panels were installed in most housing constructed in the USA from about 1960 onward. Panels with screw-in Edison base fuses were more common in earlier construction. Either type satisfies the overcurrent protection requirement of applicable building codes. They are fundamental safety devices that help prevent electrical fires. This paper reports test results for molded case circuit breakers used to supply 15A to 70A circuits in 120/240V AC residential applications. In this paper "breaker" and "circuit breaker" are used interchangeably.

Circuit breakers have advantages of convenience and safety. There is no need to stock and replace "blown" fuses. The use of circuit breakers eliminates two unsafe practices; substituting a higher-amperage fuse ("overamping") to eliminate frequent outages in an overloaded circuit, and putting a penny in the socket behind a blown fuse to restore power if a spare fuse is not available.

The safety advantage of circuit breakers is negated if they do not operate properly. A breaker that trips (opens the circuit) only at higher current than it should for its rating presents the same hazard as overamping. A breaker that jams (does not trip at all - at any current) poses the same hazard as the penny behind the fuse.

Proper performance of residential circuit breakers is assured to a limited extent by our system of "listing" and "labeling". A nationally recognized testing laboratory (NRTL) examines samples of a breaker type submitted by a manufacturer and puts it on a list of acceptable equipment if it meets the applicable requirements.

Subsequently, quarterly or less often, an inspector from the NRTL visits the manufacturer's facility to check that the breakers being manufactured and shipped at that time are the same as described in the listing. The inspector also witnesses the manufacturer's tests of some breakers taken from the production line.

As long as the listing is maintained, the NRTL permits the manufacturer to "label" each listed breaker that it ships. The labeling of a breaker with the NRTL's logo is the manufacturer's certification that the breaker conforms to the applicable standard, which is UL489 [1]. Distributors, installers, inspectors and the general public take the NRTL logo as assurance that each and every breaker so labeled will perform properly in the event of an electrical malfunction. Circuit breaker manufacturers contract with the NRTL for the listing service, for the follow-up inspection services and for the labels that are applied to the breakers. The manufacturers are clients of the NRTLs.

The listing and labeling system works properly provided that manufacturers consistently maintain a suitable level of quality control for breakers that are shipped. That is not rigorously audited by the NRTL or any other entity, however. There is no systematic random sample testing of breakers obtained from the normal supply chain. There is no test data available to specifiers, installers, public safety agencies or homeowners by which to judge the relative quality of the various brands that are already installed or available for new installations.

One particular circuit breaker brand did capture public attention due to poor quality [2]. The tests reported in this present paper were originally initiated to quantify the defect level of that particular brand and make the results available to persons involved in decisions as to their replacement. A method was subsequently developed to link circuit breaker defect statistics to electrical fire statistics so as to quantify the resulting injuries and losses attributable to the substandard performance of that particular brand [3]. "Brand X", as it is identified in [3], is estimated in that paper to be a causative factor in about 2,800 fires in the USA every year, resulting in an estimated 116 injuries, 13 fatalities and $40 million in property damage. Those are fires that would not occur if the Brand X breakers performed correctly.

From time to time there have been recall notices for some defective production lots of various circuit breaker brands and for breakers with counterfeit labels [4], [5]. These notices typically include a statement to the effect that, "if the breakers do not operate correctly there is an increased risk of fire and injury." This reflects general agreement that substandard breaker performance poses an increased electrical fire hazard.

Brand X was assumed to be a unique outlier when [3] was published. Subsequent testing of a variety of brands of circuit breakers from homes has shown that assumption to be false. There are several brands with a high defect level that have been installed in homes over the years.

The most recent tests in this study have been of new breakers purchased from retail sources. Three of the available brands demonstrate substandard performance. This indicates that the present listing, labeling and independent quality auditing protocols for this type of product fall short of the goal of assuring the required level of electrical fire safety.

II. TEST METHOD

The tests are performed using computer controlled systems that utilize commercially available data acquisition and control hardware and software. Applied current is either AC or DC, as permitted by UL489. The results are the same at the relatively low current thermal trip range for the breakers being tested. Fig. 1 and Fig. 2 are block diagrams of the test systems.

Each system includes a calibrated shunt and a digital voltmeter (DVM) for independent verification of the data acquisition system calibration. The data acquisition system calibration is offset low by 0.5A, so that the actual current is always slightly higher than the indicated current. The offset

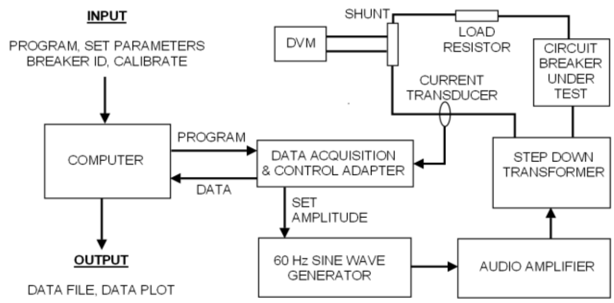

FIGURE 1. AC Test System. The step down transformer and the load resistor in the AC system accommodate the output impedance requirement of the high power audio amplifier.

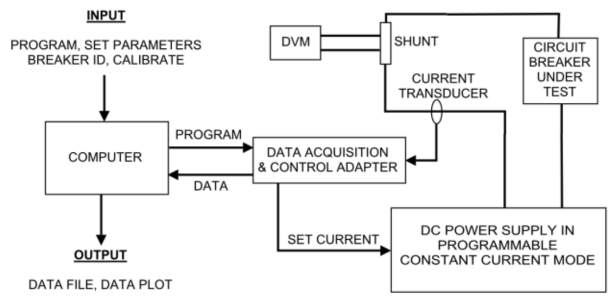

FIGURE 2. DC Test System.

assures that a breaker that actually performs within the allowable limit will not be classified as a failure due to measurement system tolerances.

Computer control provides the ability to program the applied current in various ways. Most of the tests performed in this study are conducted by starting the application of current at slightly below 100% of the breaker's rating and then increasing the current linearly to 135% over a period of one hour. If the breaker has not tripped by that time, the 135% current is held for one hour.

Breakers that do not trip by the end of the hour at 135% have failed to meet the UL489 requirement. When that happens, the current is ramped up further at the original linear rate until the breaker trips or the current reaches 200% of the breaker's rating. The current is held at 200% until the breaker trips or for at least six minutes. Fig. 3 and Fig. 4 show representative current traces for a circuit breaker that passes and for a breaker that fails the 135% must trip requirement.

Some breakers trip quickly at the start of the test, at a current close to 100% of rating. In that event they may be retested at a constant 100% current level. UL489 requires that a breaker should not trip at 100% of rated current. Failure to meet this criterion results in possible nuisance tripping in service, which is not considered to be a fire safety issue.

The test procedure most often used therefore includes the three UL489 calibration current levels: must not trip at 100%, must trip at 135% within one hour, and, for breakers that do not trip prior to that point, must trip at 200% within two, four, or six minutes depending on the rating. In some instances breakers are tested for compliance with the

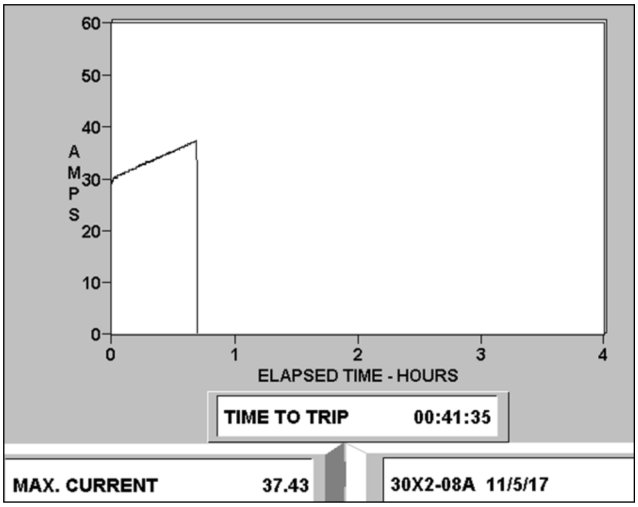

FIGURE 3. Data Record for a 30A Circuit Breaker that Passes the 135% (40.5A) Must Trip Requirement.

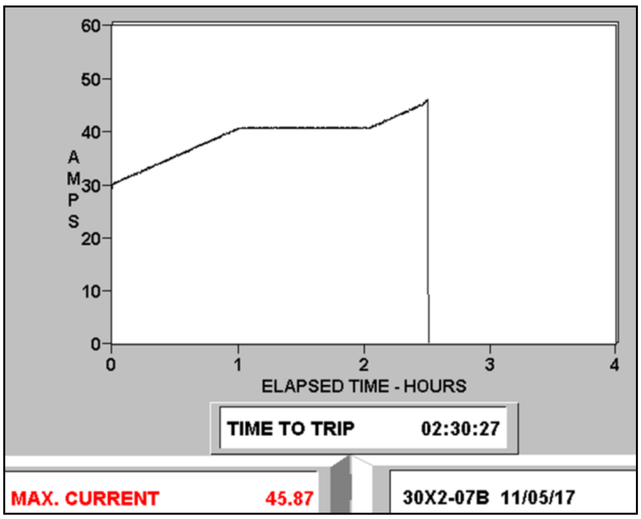

FIGURE 4. Data Record for a 30A Circuit Breaker that Fails the 135% (40.5A) Must Trip Requirement.

UL489 135% "must trip" limit by applying current at that level for up to one hour and measuring the time to trip. That procedure yields a pass/fail result in less time, but the actual minimum trip current is not determined by that method.

III. TEST SPECIMENS

Both used and new branch circuit breakers with ratings up to 70A are tested. The used breakers were originally installed in homes and were removed during upgrades or renovations. Used breakers were provided by property owners and electricians from regions across the country. About 4,000 used breakers have been tested so far, almost 3,000 of which are the Brand X type.

The detailed history of the used breakers is generally not known. The property owners and electricians considered them to have been in satisfactory working condition when removed from the original installation. They had no reason to suspect that the breakers (other than Brand X) would not have operated properly if they had remained installed at the residence. The installation date of these breakers (when they were new) ranges from the late 1950s to 2014. Breakers with signs of corrosion or damage are not tested.

The new circuit breakers tested were purchased recently from retail sources. Five of the brands tested are commonly stocked in the Capital Region of New York State. The samples for each of these brands were purchased off-the-shelf from several sources in the region and at different times. They contain product with a range of production dates. The sixth brand tested, Brand 10 (X), is available from retail sources on special order or from internet vendors. Two samples of that brand were obtained through a local retailer and the rest from internet sources. All were in sealed "point of sale" packages.

The various brands tested are identified by number in the following sections. A letter in parenthesis following the brand number indicates a particular type of construction. Brands with the same letter are essentially identical. Brands 1 (X), 9 (X) and 10 (X) are versions of the same circuit breaker design produced at different times under different corporate ownership. Brand 9 (X) is the generation of breakers that is identified in [3] as Brand X.

IV. TEST RESULTS

A. USED CIRCUIT BREAKERS

Fig. 5 presents test results for twelve brands of circuit breakers from homes. Brand to brand differences in performance are apparent. About half of the brands trip reliably at or below 135% of rated current, aside from a few outliers. The remaining brands have a relatively high rate of failure to trip correctly at or below the 135% limit.

The failures fall into two categories: breakers that trip at some level above 135% and breakers that do not trip at any current. Typically, breakers that do not trip at 200% of rated current are mechanically jammed. These are most often 2-pole breakers.

Brand 9 (X) has been studied in detail regarding the jamming failure. The cause was determined to be excessive friction in the common trip mechanism, which links the two poles of the breaker to assure that both poles open their respective circuit when one pole trips.

B. NEW CIRCUIT BREAKERS AND FUSES

Fig. 6 presents test results for new samples of six brands of circuit breakers and for an assortment of Edison-base fuses. The breakers were recently purchased from among the various brands and types presently on the market. The fuses are an assortment of old and new stock.

V. DISCUSSION

The results for the new breakers show brand to brand differences, just as they did for the used breakers. Further, to a reasonable extent, the same brands that performed well in the new breaker tests also performed well after many years

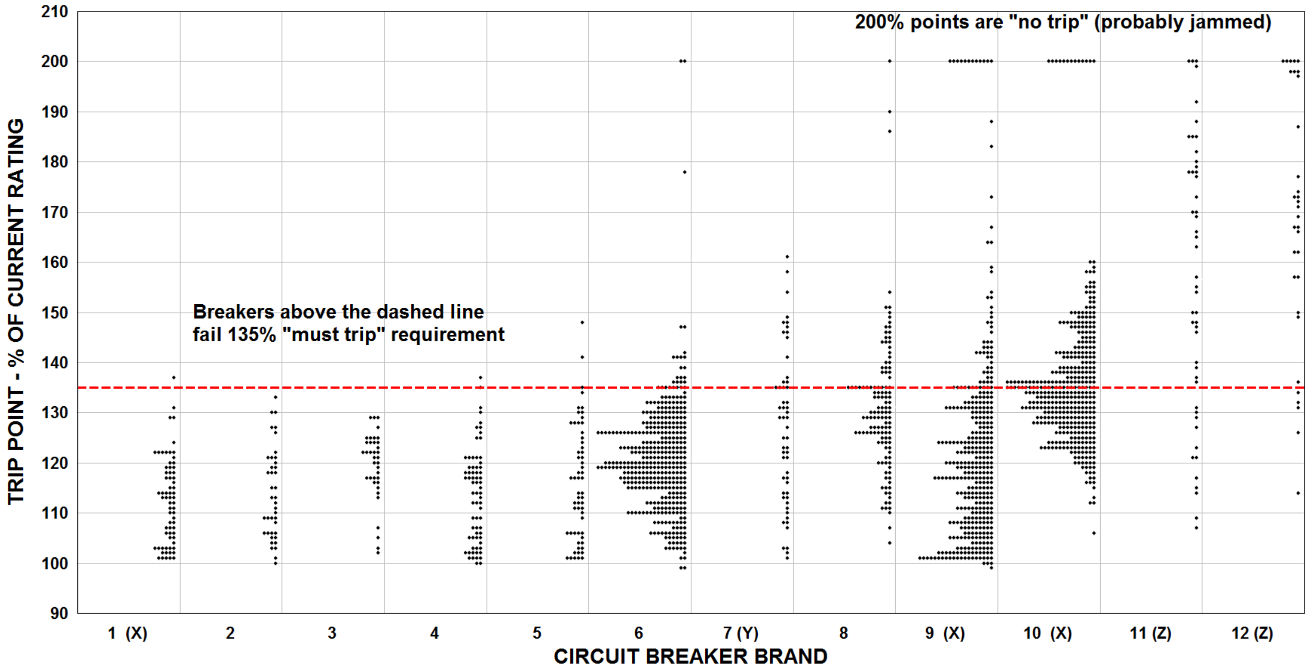

FIGURE 5. Test Results: Trip Point for Circuit Breakers From Homes – Various Brands Notes: 1. These used breakers are field samples that were removed from homes during upgrades or renovations. 2. Data points on this and subsequent charts are 1-pole breakers and individual poles of 2-pole breakers. 3. Brand 9 (X) data is typical of 2,240 breakers of this brand that have been tested.

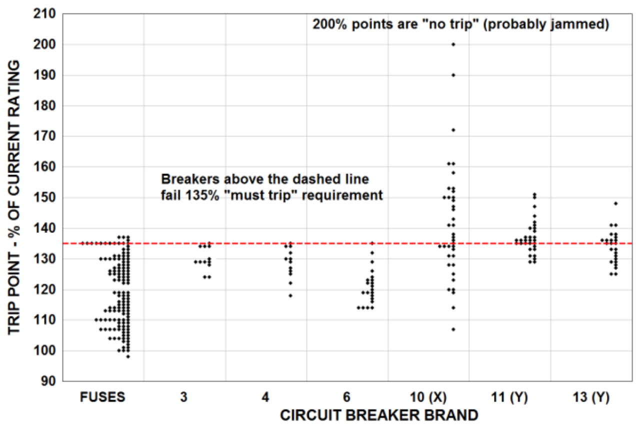

FIGURE 6. Test Results: Fuses and New Circuit Breakers Brands 11 (Y) and 13 (Y) are identical breakers from the same manufacturer and marketed under two brand names.

of service in buildings. The similarity of results for new and used breakers of the same brand reflects the manufacturers' general level of quality control. Breakers of the poorly performing brands that do not meet the standard when removed from long term service most likely did not meet the standard when they were new. The buildings they were installed in were exposed to an increased risk of fire ignition and the occupants lived with an increased risk of injury. It is estimated from the data and results of [3] that homes equipped with Brand X breakers have a 20% increased risk of electrical fire relative to homes with properly operating breakers. The additional risk is about one electrical fire (above the average) per 6,000 homes per year for those equipped with Brand X breakers.

A. THE FIRE HAZARD

The role of a circuit breaker is to open the circuit in the event of excessive current flow. This interrupts some – but not all – electrical malfunctions that could otherwise result in fire ignition. The level of safety provided by a circuit breaker is inversely related to its minimum trip current. Breakers with high minimum trip current provide a lower level of protection, since the energy available for fire ignition at a point of failure or along a conductor varies with the current squared and the time that the current is sustained. Breakers that jam provide no protection at all. This can be particularly hazardous in so-called "split bus" residential panels, which do not have a main breaker [6].

A breaker is sized according to the building's circuit wiring. It provides overcurrent protection for the circuit wiring and for the utilization equipment that it feeds. For example, the power cord of a common lamp rated to take a 60W bulb is much larger than required for the bulb's 1/2A current draw. It is sized to assure that a short circuit in the lamp's socket or power cord will cause the circuit's 15A or 20A breaker to trip in time to minimize the chance of fire ignition. The increased risk of fire due to substandard breaker performance (or fuse overamping) is primarily associated with the effects of overcurrent in utilization equipment. The building's circuit wiring generally has a higher overcurrent safety factor.

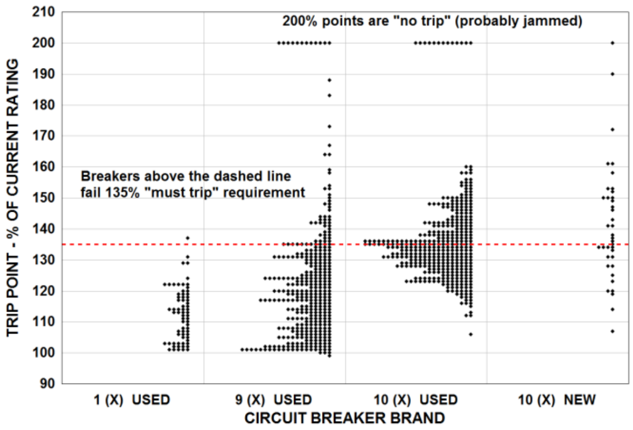

FIGURE 7. Side-by-Side Comparison of Test Results for Three Brands of Type X Circuit Breakers.

FIGURE 8. Brand 10 (X) 15A 2-Pole Breaker, Jammed, Tested to 60A.

B. BRAND X TYPE BREAKERS

Test results for Brand X type breakers from three different manufacturers, previously shown in Fig.5 and Fig.6, are presented side-by-side in Fig.7. The three brands share the same basic design.

Brand 1 (X) is the original, manufactured prior to 1960. The product line was then sold to another company and marketed as Brand 9 (X) until the early 1980s. That company ceased manufacturing operations a few years after it was publicly disclosed that it had cheated on circuit breaker testing for about 15 years. Yet another company ultimately obtained the rights to the design and continues marketing this type of breaker as Brand 10 (X). Their product today has a unique case color and style, so that from the outside it appears to be different. Inside the case, however, is essentially the same mechanism as Brands 1 (X) and 9 (X).

The Brand X type mechanism is unique in that there is no provision for calibrating the breakers once they are assembled. The internal mechanism must be calibrated before being placed into the case by bending a metal piece of the mechanism at a specific point.

The favorable test results on the more than 60 year old Brand 1 (X) breakers suggest that the original manufacturer had the production and calibration processes under control and that their breakers resist serious deterioration in service. Note that the common trip mechanism that sometimes jams in the brand X type multi-pole breakers did not exist when Brand 1 (X) breakers were manufactured.

Test results for Brand 9 (X) breakers are poor, reflecting that company's known manufacturing quality deficiencies and the jamming tendency of their 2-pole breakers. The Brand 10 (X) breakers, whether used field samples or purchased new, are no better. Fig. 8 shows a field sample of a Brand 10 (X) 2-pole 15A breaker that jammed and did not trip when tested up to 60A (400% of rating).

The burn mark on the side of the case corresponds to the position of the severely overheating bimetallic element of the internal mechanism. The toggle face of this breaker, as seen by a person looking at the load center, has a perfectly normal appearance and the breaker's toggle action feels normal.

The sample shown in Fig. 8 was manufactured in 2004 and installed in a condominium complex the following year. It is one of about 3,000 of that brand in the complex that replaced the original Brand 9 (X) breakers for safety reasons. All of the replacement breakers are now being replaced, once again for safety reasons. Of the 420 Brand 10 (X) breakers from this complex that have been tested, 177 (43%) failed to trip at or below 135% of rated current as required and 14 of the 104 2-pole breakers jammed.

The condominium owners have now replaced two brands of substandard circuit breakers. They are exposed to the possibility that the new breakers that they are installing are also substandard. Brand 10 (X) is not the only one marketed today that performs poorly in the tests.

C. BRAND Y TYPE BREAKERS

Test results for used and new type Y circuit breakers sold under different brand names are presented side by in Fig. 9. This same product line of breakers has been sold under at least three different brand names.

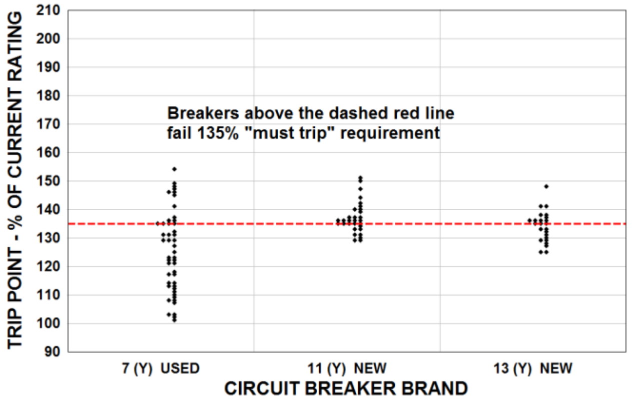

FIGURE 9. Test Results for Type Y Circuit Breakers, Used and New. These are identical breakers sold under different brand names.

Brand 7 (Y) is the original. Breakers with this original brand name are no longer on the market since a change in corporate ownership. The same breaker design is currently manufactured and marketed under two brand names, Brand 11(Y) and Brand 13 (Y), which are identical down to the same NRTL listing number. They have essentially the same substandard performance as the original.

D. BRAND Z BREAKERS

The two brands of breakers of type Z shown in Fig.5 show very poor performance. They are identical breakers coming out of the same factory before and after a change in corporate ownership and brand name. They are no longer being manufactured, but they remain installed in many homes across the country.

E. FUSES

The fuses that were tested represent a cross section of brands, ratings and types. Within each type and brand, individual fuses were very closely matched in performance. The range of trip points reflects different types of fuses with slow or fast response to suit the characteristics of the utilization equipment on the circuit. Only the best-performing brands of circuit breakers provide reliable circuit protection equal to these fuses.

F. PAST AND FUTURE

Testing in this study has been focused only on the basic overcurrent trip requirements. This is important from a fire safety standpoint, since the energy available for fire ignition at a point of failure or along a conductor varies with the current squared. To conform to the requirements of UL489, breakers must also meet test requirements for mechanical endurance, dielectric integrity, interrupting capacity and other factors related to electrical safety.

The broader scope of circuit breaker quality problems is well illustrated by test results reported at an industry association committee meeting in 1979 [7]. A sample of 55 breakers including a variety of brands was obtained from distributors by the NRTL that listed them. Five of the samples failed to trip as required at 135% of rated current, 25 samples failed the dielectric test and only two of the samples passed all of the UL489 performance requirements.

Three years later, a published article reported on the results of in-situ testing of circuit breakers in homes by engineers from Underwriters Laboratories Inc. [8]. Two of the six brands tested in homes demonstrated high failure rates, 8.6% and 33% respectively for the brands identified as "A" and "D" in that article. One of the brand D breakers failed to trip at 200% of rated current.

This is a long-standing manufacturing quality issue for the brands that have high defect rates, and there are substantive electrical fire safety consequences. No new industrial engineering or quality control breakthroughs are required for the manufacturers to correct the problem or for the NRTLs to independently detect it. For many decades our system of standards, listing, labeling and periodic inspections by an NRTL has fallen short of assuring the expected and required level of performance for all brands of residential molded case circuit breakers that are marketed.

It is the authors' opinion that the more than half-century old residential thermal-magnetic breaker technology may have run its course. Solid-state power electronics can now be used to create residential overcurrent protection that has precise current-time trip characteristics, that is sealed from environmental moisture and corrosives, that is tamper proof, not temperature sensitive, and that has a multi-pole common trip function that will not jam. All that and more is possible with today's solid state logic and power electronic technology, which is already employed in switching and control applications at higher current and voltage levels than those present in residential load centers [9].

Modern electronics can employ precise current sensing along with ease and speed of calibration and self-testing. These attributes can lead to substantive improvement in quality control for residential circuit protection equipment.

By contrast, the process of calibrating and verifying the trip characteristics of thermal-magnetic breakers is cumbersome and time-consuming for the manufacturers. This contributes to the performance problems described above. Some manufacturers do not test all breakers that they produce for the UL489 135% must trip requirement [7]. Instead, to minimize test time and cost, they test at 200% of rated current or higher and rely on an assumption that there is a dependable current-time trip relationship. That assumption may be erroneous for some circuit breaker product lines.

A paradigm shift from molded case thermal-magnetic breakers to solid state current management and circuit protection is probably inevitable. The sooner it occurs, the greater the electrical fire safety benefit will be.

REFERENCES

[1] *Molded-Case Circuit Breakers and Circuit Breaker Enclosures*, Underwriters Laboratories Standard UL489, 2016 and prior editions.
[2] "Exxon buys a scandal along with a company," *Business Week*, p. 66, Jul. 1980.
[3] J. Aronstein and R. Lowry, "Estimating fire losses associated with circuit breaker malfunction," *IEEE Trans. Ind. Appl.*, vol. 48, no. 1, Jan./Feb. 2012, p. 45.
[4] U.S. Consumer Product Safety Commission, Recall No. 14-134, Mar. 2014.
[5] U.S. Consumer Product Safety Commission, Release No. 07-036, Nov. 2006.
[6] J. Aronstein. (Nov. 2017). *Hazardous FPE Circuit Breakers and Panels*. [online]. [Online]. Available: www.fpe-info.org/
[7] J. Palmer *et al.*, *Report on First Meeting of Circuit Breaker Follow Up Program Ad Hoc Committee*, W. Camp, Ed. GTE Sylvania, Jun. 1979.
[8] R. W. Eckert, "Molded case circuit breakers—Oldies but goodies," *Elect. Construction Maintenance*, Apr. 1982.
[9] J. M. Maza-Ortega, E. Acha, S. García, and A. Gómez-Expósito "Overview of power electronics technology and applications in power generation transmission and distribution," *J. Mod. Power Syst. Clean Energy*, vol. 5, no. 4, pp. 499–514, Jul. 2017.

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