FUSES OUTSHINE CIRCUIT BREAKERS IN COST, RELIABILITY

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INTRODUCTION

The debate sparked around fuses versus circuit breakers seems to travel around an endless path. Overcurrents are inevitable in electrical systems, so which is the best overcurrent protection method?

People often prefer fuses to circuit breakers because they can open the flow of interrupting power faster than circuit breakers and are not as costly to maintain. Compared to circuit breakers, fuses

- are less expensive;
- are more reliable (due to the lack of mechanical components that can wear down over time);
- react more quickly to overloading;
- are physically smaller in size, requiring much less panel space;
- provide a time delay feature that allows for a closer sizing to load, thus providing better protection (whereas circuit breakers must be oversized to accommodate inductive loads);
- can provide as close as 1.5:1 coordination, preventing the need to oversize upstream protection devices (whereas circuit breakers require detailed coordination studies, and coordination under short circuit conditions is difficult);
- do not require annual maintenance, unlike circuit breakers, which require annual adjustment and calibration maintenance (per the manufacturer's recommendations); and
- cut off the fault current long before it reaches its first peak, typically within the first half of an electrical cycle [1].

Circuit breakers trip both on overload fault and a short-circuit fault. Once the circuit breaker trips, it must be checked, which is a step people tend to skip. Instead, users simply reset the breaker, enabling it to be reused without knowledge as to whether the circuit breaker was damaged during the trip. If there is damage, then the breaker must be repaired and recalibrated so that it can safely perform to its original specifications. Circuit breakers also release up to ten times more let-through energy than fuses when operating during a fault condition.

This paper outlines how the use of fuses can be more beneficial than circuit breakers in an electrical system's design. For the purposes of this paper, "circuit breaker" will refer to a molded case circuit breaker (MCCB).

FUSES ARE SIMPLER IN DESIGN AND CONSTRUCTION

CIRCUIT BREAKERS

A circuit breaker is a mechanical device that consists of many moving components (see **Figure 1**). A typical MCCB contains a frame, an operating mechanism, an interrupting structure, a trip unit, and terminal connections. When the trip unit senses abnormal current flow, it causes the operating mechanism to open the contacts. When the contacts open, the interrupting structure (including the arc chute and all current-carrying parts) interrupts the arc, typically within 1.5 to 2 cycles.

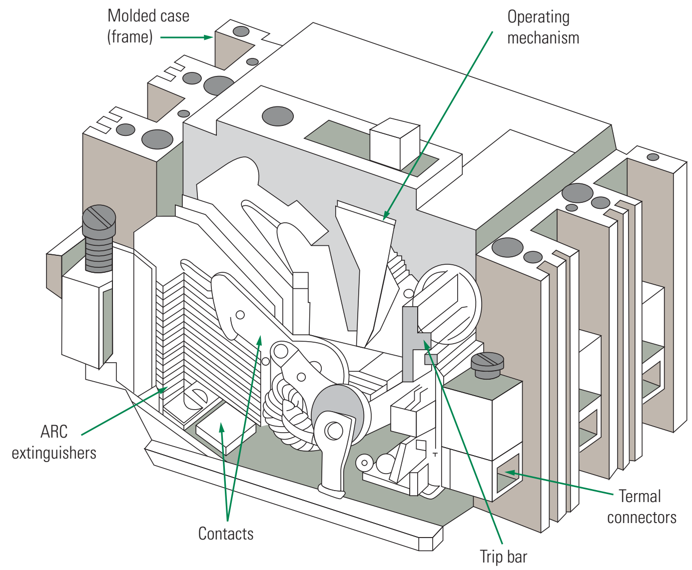

Figure 1. Components of a molded case circuit breaker.

Circuit breakers are intricately constructed, which makes them more susceptible to malfunctioning. NFPA 70B Section 17.10 [2] recommends periodic manual operation of the circuit breaker to help keep the contacts clean and lubrication properly performing. NEC also recommends operating any manual push-to-trip buttons (if applicable), which exercises the tripping mechanisms that are internal to the breaker that is otherwise not exercised by manual operation alone.

Grease often solidifies when it is exposed to heat over an extended period. It is therefore imperative to ensure that the lubrication performs properly. This solidification can slow down the internal mechanisms enough to prevent the circuit breaker from opening the circuit in accordance with its specifications.

In addition to grease solidification, a circuit breaker can have mechanical issues with its operating mechanism. The operating mechanism contains an opening and a closing set of springs, one of which holds tension. Over time, these springs can become fatigued and the linkages can lose adjustment due to vibration and wear. This can also slow down the internal mechanisms outside of its intended specifications.

Many of the mechanical operations within a circuit breaker can wear down over a period of time, which may cause issues with its performance. If a circuit breaker does not work properly, then the arc-flash incident energy can be much higher than what was assessed during any previous arc-flash hazard assessments. This can cause a worker to unknowingly be exposed to an incident energy that is higher than what their personal protective equipment was designed to protect against. The severity of this hazard can be fatal.

FUSE

By comparison, fuses do not contain any moving parts that need to be operated or periodically lubricated (see **Figure 2**). The fusible elements that are internal to the fuse are precisely designed to continuously carry a specified amount of current without opening. When electric current flows through the element, heat is generated. As long as there is a balance in heat transfer (where the heat generated equals the heat dissipated) the fuse element will continue to carry the current as intended. Once an imbalance in heat transfer is reached (typically due to an overcurrent condition) the element will then start to melt and break, thus resulting in an interruption of current flow.

Figure 2. Interior of a Littelfuse QS series high-speed fuse.

Once a fuse has opened a circuit, the blown fuse is replaced by a new fuse. This allows the circuit to have the same protection every time, unlike a circuit breaker which can deteriorate over time if it experiences too many operations. The potential for any arc-flash hazard will typically remain the same and thus workers will never unknowingly be exposed to an electrically hazardous situation.

FUSES SIMPLIFY SELECTIVE COORDINATION

NEC Article 100 defines selective coordination as:

> Localization of an overcurrent condition to restrict outages to the circuit or equipment affected, accomplished by the selection and installation of overcurrent protective devices and their ratings or settings for the full range of available overcurrents, from overload to the maximum available fault current, and for the full range of overcurrent protective device opening times associated with those overcurrents [3].

NEC Article 708.54 [3] requires that critical operations power system(s) overcurrent devices are selectively coordinated with all supply-side overcurrent protective devices. Selective coordination must be selected by a licensed professional engineer or other qualified persons engaged primarily in the design, installation, or maintenance of electrical systems.

The NEC began to require selective coordination in electrical systems in 1993. Selective coordination is required for applications such as elevator feeders (Article 620) and healthcare facilities (Article 517) as well as in emergency (Article 700) and legally required standby systems (Article 701). Selective coordination helps to ensure that if one circuit is overloaded or faulted, it will not cause a blackout or other circuits to lose power in places where losing power could be hazardous. Although not required for all systems, selective coordination is a best practice for helping a facility minimize work stoppages and speed up the troubleshooting process.

In a selectively coordinated system, only the protective device that is immediately on the line side of an overcurrent fault location opens. Any other upstream protective devices remain closed. All other equipment remains in service which simplifies the identification of faulted device and fault location during an event of overcurrent condition.

An overcurrent protection device’s datasheet provides a time-current curve that details the amount of time the device will take to clear a fault at a given value of fault current. When designing the circuit, these specifications are used to place the fastest-clearing devices closest to the load.

Circuit breakers can be used in a selectively coordinated system. However, the time-current curves of all upstream (line side) and downstream (load side) breakers must be overlaid to ensure that the downstream circuit breaker will open under a short-circuit condition before the upstream circuit breaker has a chance to operate. The time-current curves must not overlap any fault currents for the electrical system to be selectively coordinated with circuit breakers.

TABLE 1. Fuse Coordination Table

LINE-SIDE FUSES			LOAD-SIDE FUSES									
			TIME-DELAY FUSES AMPERE RANGE, UL CLASS AND CATALOG NO.						FAST ACTING FUSES AMPERE RANGE, UL CLASS AND CATALOG NO			
AMPERE RANGE	UL CLASS	LITTELFUSE CATALOG NUMBER	601-6000	601-4000	30-600	30-600	30-600	0-30	30-600	30-1200	30-600	1-60
			L	L	RK1	J	RK5	CC	RK1	T	J	G
			KLPC LDC	KLLU	LLNRK LLSRK_ID	JTD_ID JTD	FLNR_ID FLSR_ID IDSR	CCMR	KLNR KLSR	JLLN JLLS	JLS	SLC
601-6000	L	KLPC	2:1	2:1	2:1	2:1	4:1	2:1	2:1	2:1	2:1	N/A
601-4000	L	KLLU	2:1	2:1	2:1	2:1	4:1	2:1	2:1	2:1	2:1	N/A
601-2000	L	LDC	2:1	2:1	2:1	2:1	4:1	2:1	2:1	2:1	2:1	N/A
30-600	RK1	LLNRK	N/A	N/A	2:1	2:1	8:1	2:1	3:1	3:1	3:1	4:1
30-600	RK1	LLSRK_ID	N/A	N/A	2:1	2:1	8:1	2:1	3:1	3:1	3:1	4:1
30-600	J	JTD_ID	N/A	N/A	2:1	2:1	8:1	2:1	3:1	3:1	3:1	4:1
30-600	RK5	IDSR	N/A	N/A	1:5:1	1:5:1	2:1	2:1	1:5:1	1:5:1	1:5:1	1:5:1
30-600	RK5	FLNR_ID	N/A	N/A	1:5:1	1:5:1	2:1	2:1	1:5:1	1:5:1	1:5:1	1:5:1
30-600	RK5	FLSR_ID	N/A	N/A	1:5:1	1:5:1	2:1	2:1	1:5:1	1:5:1	1:5:1	1:5:1
30-600	RK1	KLNR	N/A	N/A	3:1	3:1	8:1	N/A	3:1	3:1	3:1	4:1
30-600	RK1	KLSR	N/A	N/A	3:1	3:1	8:1	N/A	3:1	3:1	3:1	4:1
30-1200	T	JLLN	N/A	N/A	3:1	3:1	8:1	N/A	3:1	3:1	3:1	4:1
30-1200	T	JLLS	N/A	N/A	3:1	3:1	8:1	N/A	3:1	3:1	3:1	4:1
30-600	J	JLS	N/A	N/A	3:1	3:1	8:1	N/A	3:1	3:1	3:1	4:1
1-60	G	SLC	N/A	N/A	3:1	3:1	4:1	N/A	2:1	2:1	2:1	2:1

Ratios are expressed as line-size fuse to load-size fuse.

With fuses, selective coordination is easier to achieve (assuming that the manufacturer's recommended ratios are maintained). **Table 1** is an example of a coordination table for Littelfuse brand fuses. **Table 1** indicates that Class L fuses need a 2:1 amperage-to-amperage ratio to be considered selectively coordinated with other Class L fuses. In **Figure 3**, the 3000 A Class L main fuses are more than twice the rating of the 1500-, 1200-, and 1000-amp Class L feeder fuses, which means that these fuses will properly coordinate. Table 1 also shows that the LLSRK_ID Series time-delay Class RK1 feeder and branch circuit fuses coordinate at a 2:1 ratio with the Class L feeder fuses, so the entire system shown in **Figure 3** is considered selectively coordinated.

Coordination tables make it easier to define what will be selectively coordinated. This also prevents the system designer from needing to overlay the time-current curves, which is a tedious and time-consuming task.

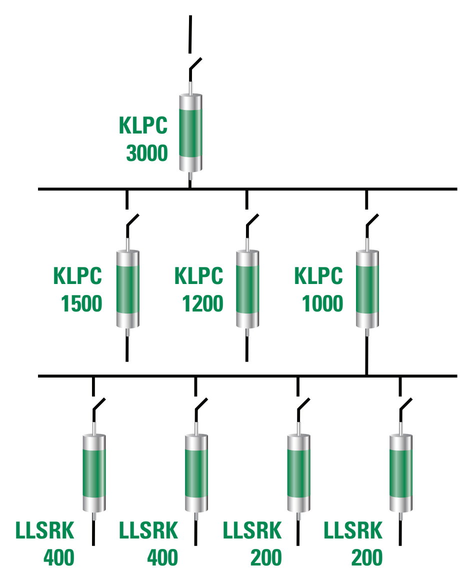

Figure 3. Example of a selectively coordinated fuse system.

CIRCUIT BREAKERS ARE SUSCEPTIBLE TO MISAPPLICATION

TAMPERING

Circuit breakers are the only method of overcurrent protection that is capable of being tampered with by an unqualified person. Any unauthorized modification of an MCCB may render the breaker incapable of providing protection from overcurrents [4].

The NEC addresses this issue in Article 240.82 [3] stating, "a circuit breaker shall be of such design that any alteration of its trip point (calibration) or the time required for its operation requires dismantling of the device or breaking of a seal for other than intended adjustments."

If a person or a maintenance worker does not know what they are doing and adjusts the breaker, which frequently occurs, then the effects can be catastrophic.

SLASH RATING

A slash rating specifies the maximum line-to-ground voltage rating with a maximum line-to-line voltage rating. NEC Article 240.85 addresses slash voltage ratings for circuit breakers and restricts their use, stating:

> A circuit breaker with a slash rating, such as 120/240V or 480/277V, shall be permitted to be applied in a solidly grounded circuit where the nominal voltage of any conductor to ground does not exceed the lower of the two values of the circuit breaker's voltage rating and the nominal voltage between any two conductors does not exceed the higher value of the circuit breaker's voltage rating [3].

Unlike fuses, which have straight voltage ratings that allow them to be installed in any system independent of its grounding, slash-rated MCCBs can only be installed on solidly grounded Wye systems. Slash ratings mean that MCCBs do not offer the flexibility that a fuse can and—most importantly, are susceptible to misapplication.

Misapplication is common with slash-rated MCCBs because when a person does not understand the higher and lower ratings, it can result in its application falling outside of its voltage rating. Should a person misapply the slash rating and an overcurrent occurs, then the MCCB's protection could be rendered useless.

INSPECTIONS, TESTS, AND PREVENTATIVE MAINTENANCE COME WITH A COST

Circuit breakers are the least cost-effective method of overcurrent protection. MCCBs are drastically more expensive than fuses in both initial and reoccurring costs (as well as a replacement should it break). An 800-A circuit breaker, for example, costs an average of more than $11,700. Fuses, however, cost significantly less; an 800A Class L fuse costs less than $800.

It is expensive to install a circuit breaker, which is a cost that typically does not payoff as a long-term investment. Between inspections and recurring maintenance costs, circuit breakers will always cost more than reliable and replaceable fuses. By comparison, when a fuse blows, it is simply replaced with a brand-new fuse.

Preventative maintenance and inspections are a critical consideration in an electrical system's design. A solid, preventative maintenance plan can maximize the life of equipment and detect troubles before they escalate. Circuit breakers and fuses should be inspected for serviceability at least once a year [2].

When deciding between circuit breakers and fuses, consider the number of circuit breakers the facility will require, as the extended time for these annual inspections and maintenance tests multiplies with every MCCB within the facility—and reoccurs every year.

Fuse inspections are simple. Fuses only need to be visually inspected by simply looking for discoloration on the fuse terminals and clips which might indicate corrosion. If there is evidence of corrosion or if overheating is detected, then the root cause of the problem must be determined, and the affected fuse and fuse clips must be replaced.

The inspection of circuit breakers, however, is not as quick and easy as fuse inspections. A circuit breaker's mechanical nature is a result of its toggle mechanism that opens and closes the circuit.

A dusty, dirty, or corrosive atmosphere may cause a circuit breaker to become inoperative or malfunction if it should attempt to interrupt a fault that is well within its capacity. The frequency of preventive maintenance, inspection, and cleaning must be high to ensure the integrity of operation [5]. The optimum testing and maintenance frequency typically ranges from 6 months to 3 years [2] [5].

NFPA 70B requires a functional test as part of a circuit breaker's annual inspection.

MCCBs involve multiple time-consuming inspection procedures: exposed face temperature check, inspection of the enclosure interior, electronic trip unit check. In addition to these inspection procedures, MCCBs also involve several multi-step test procedures:

- **Mechanical operation tests:** involves several steps that require an indicating device—such as an ohmmeter or a continuity tester.
- **Insulation resistance test:** requires an insulation resistance tester capable of applying a direct-current voltage of at least 500 VDC.
- **Individual pole resistance test:** consists of a lengthy test that should be conducted using a 24-volt or less direct current power supply that is capable of supplying the rated current of the circuit breaker. If unavailable, then a micro-ohmmeter or a 4-point tester capable of 10 to 100 amperes must be used.

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1 Based on Grainger's book prices for Square D (MG series and MJ series), General Electric (SK series), Eaton (MDL series), and Gordon circuit breakers.

2 Based on Mouser Electronics' single unit price for a Littelfuse KLLU800 fuse.

- **Inverse-time overcurrent trip test:** requires a variable low voltage power supply, including an RMS reading ammeter capable of delivering the required test current for the maximum test duration.
- **Instantaneous overcurrent trip test:** requires a pointer-stop ammeter, a calibrated image-retaining oscilloscope or a sampling rate digital ammeter, and/or a variable low voltage power supply, including an RMS reading ammeter capable of delivering the required test current for the maximum test duration.
- **Rated hold-in test:** requires a low voltage power supply, including an RMS reading ammeter capable of delivering the required test current for the maximum test duration [4].

These extensive tests are problematic to a facility's bottom-line. Properly functioning overcurrent protective devices are paramount, and time and money are critical factors when selecting the best method to ensure that equipment is—and will continue—to work. A circuit breaker's operational tests require skill and special equipment to perform the test. The accuracy of each test result also requires a meticulous level of precision, which can be time-consuming and difficult to achieve [1].

With the exception of mechanical operation tests, the MCCB must be removed from the equipment to conduct all of the operational tests and then reinstalled once the test is complete. These two steps are also time-consuming, but more importantly, can be incredibly hazardous if not properly performed.

Operational testing for MCCBs can take hours. For example, conducting a circuit breaker's rated hold-in test requires the power supply to be adjusted until the circuit breaker's temperature stabilizes. This test alone, as with all MCCB testing, must be performed by a qualified person and can take several hours. NEMA AB-4 states:

> Temperature stabilization usually occurs within one hour for breakers rated 100 amperes or less but will take several hours for breakers of a higher rating. Stabilization may be verified by taking three successive temperature measurements at intervals of 10 to 20 minutes between measurements at the same location on one or more of the circuit breaker connectors utilizing a temperature probe or thermocouple instrument [4].

As stated, this test alone takes several hours. When maintenance tests and annual inspections are extensive, reoccurring costs are expensive. To ensure the safety of people and the electrical system, each of these tests should be performed on each circuit breaker within the facility. There are multiple tests to perform, most of which are extensive. These tests are conducted by qualified technicians who charge by the hour—typically around $50 per hour. These costs accumulate with each circuit breaker within a given facility, and then also reoccur with every annual inspection.

Visual inspections can detect only a couple of the issues that will require the circuit breaker to be replaced. If an MCCB has a cracked case when inspected, the circuit breaker should be replaced because stresses on the breaker can occur when interrupting a fault, which could cause "a catastrophic failure of the case."

Tracking is another issue that visual inspections present:

> Tracking is an electrical discharge phenomenon indicated by a leakage path that is directionally erratic (similar to the pattern of a lightning strike). This phenomenon forms from electrical stress over a long period of time, especially in unclean environments, and it will eventually lead to a flashover. As a result, the cause of the tracking should be determined and corrected. The circuit breaker should be inspected for degradation and cleaned, and if the stress markings are still visible, the circuit breaker should be replaced [2].

Inoperable or damaged circuit breakers should be destroyed or returned to the manufacturer for disposal, which avoids them being inadvertently returned to service [4]. This additional step, which not only costs further time and money, is critical because unlike fuses, damaged or inoperable circuit breakers cannot always be visually detected. For this reason, it is easy for a person within the facility to inadvertently return a destroyed circuit breaker to service, which can result in a catastrophe.

CONCLUSION

Fuses are simple, reliable, and stable in nature. With their simple construction, fuses are neither fragile nor prone to wearing down over time as commonly found with circuit breakers. The straightforward design of fuses not only helps to ensure reliability but also cuts down drastically with the costs of maintenance and annual inspections. Without cause to worry about slash ratings, designing fuses into a system is uncomplicated. Finally, fuses are tamperproof; they do not possess the hazards that circuit breakers present if an unqualified person tries to adjust the breaker.

Both circuit breakers and fuses effectively protect against potentially dangerous overcurrents. Therefore, the cost is the most distinguishing factor between the two methods. High reoccurring costs of inspections and maintenance are tough on the bottom line, and the protection of a circuit breaker comes at a high cost. It is to this end that fuses outshine other methods of overcurrent protection.

[3] A qualified person is defined by NFPA 70 Article 100 as "one who has skills and knowledge related to the construction and operation of the electrical equipment and installations and has received safety training to recognize and avoid the hazards involved.

TERMS AND DEFINITIONS

Ampere Squared Seconds (I^2t): A means of describing the thermal energy generated by current flow. When a fuse is interrupting a current within its current-limiting range, the term is usually expressed as melting, arcing, or total clearing I^2t.

- Melting I^2t is the heat energy passed by a fuse after an overcurrent occurs and until the fuse link melts. It equals the rms current squared multiplied by the melting time in seconds. For times less than 0.004 seconds, melting I^2t approaches a constant value for a given fuse.
- Arcing I^2t is the heat energy passed by a fuse during its arcing time. It is equal to the rms arcing current squared multiplied by arcing time.
- Clearing I^2t is the I^2t through an overcurrent device from the inception of the overcurrent until the current is completely interrupted. Clearing I^2t is the sum of the melting I^2t plus the arcing I^2t.

Arcing Fault: A short-circuit that arcs at the point of fault. The arc impedance (resistance) tends to reduce the short-circuit current. Arcing faults may turn into bolted faults by welding of the faulted components. Arcing faults may be phase-to-phase or phase-to-ground.

Fault Current: The current that flows when a phase conductor is faulted to another phase or ground.

Heating: Heating occurs in every part of the system as the electrical current passes through the system. If the overcurrent is large enough, this will almost instantaneously occur. The energy in such overcurrents is measured in ampere-squared seconds (I^2t). An overcurrent of 10,000 amperes that lasts for 0.01 seconds has a thermal energy of 1,000,000 I^2t. A current of only 7,500 amperes can melt a #8 AWG copper wire in 0.1 seconds and within 8 ms (0.008 seconds or one-half electrical cycle). A current of 6,500 amperes can raise the temperature of an AWG THHN thermoplastic-insulated copper wire from its operating temperature of 75°C to 150°C. Currents higher than 150°C can immediately vaporize organic insulations.

Magnetic Stress: A function of the peak current squared. Fault currents of 100,000 amperes can exert forces of more than 8,000 lb/ft of a bus bar. Stresses of this magnitude may damage insulation, pull conductors from terminals, and result in forces and stress that will significantly damage equipment terminals.

Overcurrent: Any current larger than the equipment, conductor, or devices are rated to carry under specified conditions.

Overload: An overcurrent that is confined to the normal current path (i.e., not a short-circuit). If allowed to persist, will cause damage to equipment and/or wiring. Operation of equipment in excess of normal, full-load rating, or of a conductor in excess of rated ampacity that, when it persists for a sufficient length of time, would cause damage or dangerous overheating. A fault, such as a short circuit or ground fault, is not an overload.

Rating: A designated limit of operating characteristics based on definite conditions such as current rating, voltage rating and interrupting rating.

Selective Coordination: In a selectively coordinated system, only the protective device immediately on the line side of an overcurrent opens and the upstream protective devices remain closed. All other equipment remains in service, which simplifies the identification and location of overloaded equipment or short-circuits.

Short Circuit: Any current in excess of the rated current of equipment or the ampacity of the conductor. This may result from overload, short circuit, or ground fault. A current flowing outside its normal path, which is caused by a breakdown of insulation or by faulty equipment connections. In a short-circuit, current bypasses the normal load. Current is determined by the system impedance (AC resistance) rather than the load impedance. Short-circuit currents may vary from fractions of an ampere to 200,000 amperes or more. If not removed promptly, large overcurrents associated with a short-circuit can have three profound effects on an electrical system: heating, magnetic stress and arcing.

Voltage Rating: The maximum rms AC voltage and/or the maximum DC voltage at which the fuse is designed to operate. For example, fuses rated 600 volts and below may be applied at any voltage less than their rating. There is no rule for applying AC fuses in DC circuits such as applying the fuse at half its AC voltage rating. Fuses used on DC circuits must have DC ratings.

To find out more about how fuses can simplify an electrical design and cut costs, visit Littelfuse.com or call the Littelfuse Technical Support line at 1 (800) 832-3873.

REFERENCES

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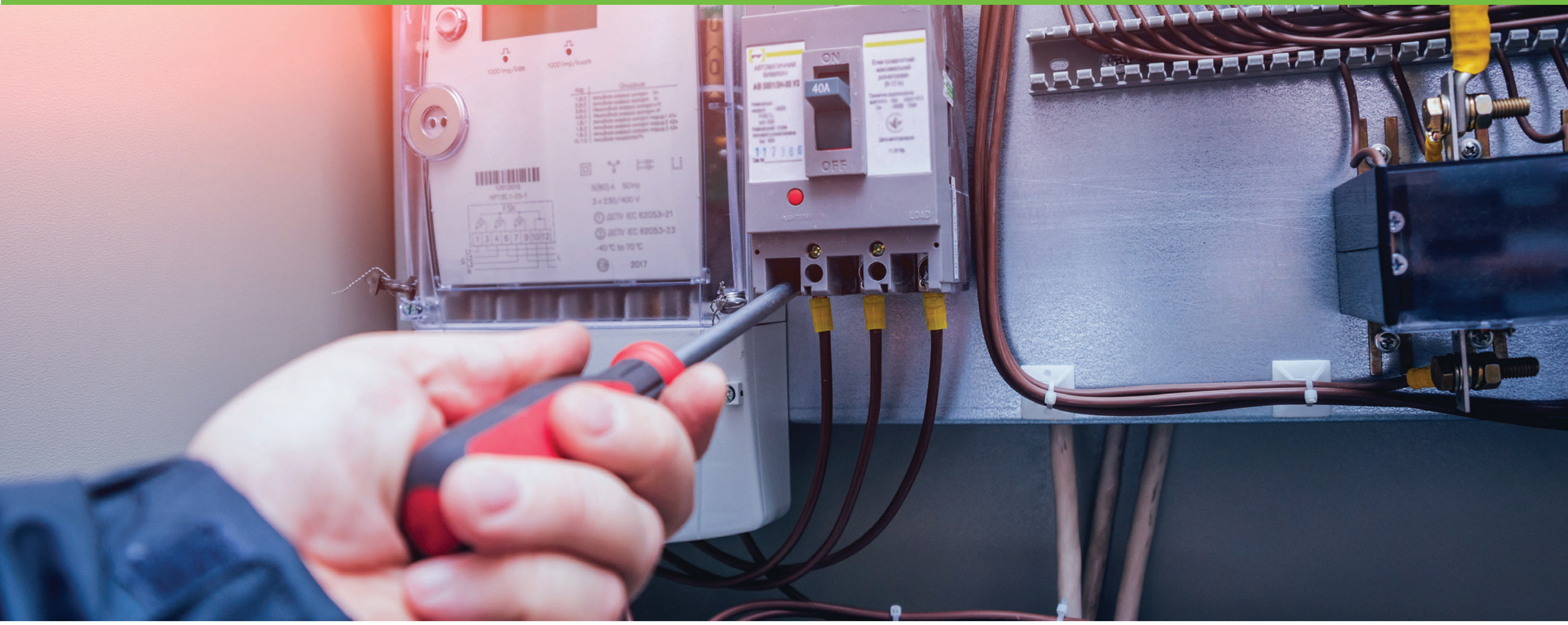

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