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MICROPROCESSOR-BASED PROTECTIVE RELAYS

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THIS ARTICLE DESCRIBES THE BENEfits of microprocessor (μP) relay performance and its capabilities beyond previous protective relaying technologies. This article also discusses a multiple quality-measurement approach to observing, measuring, and then calculating μP relay reliability and unavailability. This is an important consideration for industrial and commercial facilities that are being required to repair or replace old electromechanical or solid-state (analog and digital) protective relaying equipment because of equipment malfunctions, misoperations, accidental tripping, or obsolescent parts. Although μP relays have been commercially available for more than 20 years and researched for the past 40 years, industrial and commercial plant engineers tend to be more reluctant to embrace the μP technology. Electric power utilities in North America have aggressively selected to replace older protection equipment by upgrading and replacing the equipment with new μP relays whenever and wherever possible.

This article is useful for consulting engineers, industrial and commercial electric power plant engineers, and original equipment manufacturer (OEM) engineers who are interested in doing reliability and unavailability predictions for industrial electric power distribution systems that employ μP relays. Furthermore, this article assists those making μP relay cost-versus-reliability decisions when performing facilities studies to evaluate and improve the system reliability or capacity of an existing plant.

This article explores the benefits in performance (sensitivity and speed), reliability (security, selectivity, and

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dependability), availability, efficiency, economics, safety, compatibility, and capabilities of μP multifunction protective relaying technology over the previous existing technologies, namely electromechanical and solid state. The suggested typical values, quality measurements, and analysis of protective relaying performance, reliability, and unavailability are intended to be a recommendation of what could be used as a benchmark in our industry.

In 1988, the article "Practical Benefits of Microprocessor-Based Relaying" [1], presented at the 15th Annual Western Protective Relay Conference (WPRC), described the equipment hardware and how typical early-model μP-based protective relays perform the signal processing from inputs, logic manipulations, and calculations.

Later in 1991 and 1992, [2] and [3] provided good detailed explanations and examples of the increased operational flexibility and the additional features of μP relays that better accommodate system disturbances, relay failures, protection philosophies, and changing power system conditions.

MICROPROCESSOR RELAY SCHEMES ARE SIMPLER DESIGNS BECAUSE THEY USE LESS RELAYING COMPONENTS AND AUXILIARY EQUIPMENT.

With the significant cost and consequences of electric power system failures being increased, often a single forced outage can drastically exceed the replacement project cost of the failed electrical distribution equipment. Furthermore, managers and operators of industrial plants that have NASA's "failure is not an option" mindset regarding forced process outages will be required to look at the inherent reliability of a plant's electric power system, including the protective relaying devices and components of the electrical distribution equipment, to attempt to approach zero defects for uncleared electric system faults.

Definitions

With reference to [4], the following definitions of the terms used in this article are provided:

- *Quality*: The totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs.
- *Reliability (of a relay or relay system)*: A measure of the degree of certainty that the relay, or relay system, will perform correctly. Note: Reliability denotes certainty of correct operation (dependability) together with assurance against incorrect operation (security) from all extraneous causes.
- *Availability*: As applied either to the performance of individual components or to that of a system, it is the long-term average fraction of time that a component or system is in service and satisfactorily performing its intended function. An alternative and equivalent definition for availability is the steady-state probability that a component or system is in service.
- *Unavailability*: The long-term average fraction of time that a component or system is out of service due to failures or scheduled outages. An alternative definition is the steady-state probability that a component or system is out of service due to failures or scheduled outages. Mathematically, unavailability = (1 – availability).
- *Failure rate*: The mean number of failures of a component per unit exposure time. Usually, time is expressed in years, and failure rate is given in failures per year.
- *Mean time to failure (MTTF)*: The mean time until a component's first failure, for components with a wear out failure mode, such as incandescent light bulbs.
- *Mean time between failures (MTBF)*: The mean exposure time between consecutive failures of a component. It can be estimated by dividing the exposure time by the number of failures in that period, provided that a sufficient number of failures has occurred in that period.
- *MTBFs observed (repaired items)*: For a stated period in the life of an item, the mean value of the length of time between consecutive failures, computed as the ratio of the cumulative observed time to the number of failures under the stated conditions. 1) The failure criteria shall be stated; generally, the main criteria is failure to conform to specification. 2) Cumulative time is the sum of the times during which each individual item has been performing its required function under the stated conditions. 3) This MTBF is the reciprocal of the observed failure rate during the period. 4) MTBF does not indicate useful life.
- *Mean time between removals (MTBR) observed*: The mean value of the length of time between consecutive unscheduled unit removals, computed as the ratio of the cumulative observed service years of installed base to the number of hardware, unrepeatable, software, or manufacturing process field failures.
- *Removal rate*: The mean number of removals of a component per year, that is, 1/MTBR.
- *Outage*: The state of a component or system when it is not available to properly perform its intended function because of some event directly associated with that component or system.
- *Interruption*: The complete loss of voltage for a time period. The time base of the interruption is characterized as follows:
  - *Instantaneous*: 0.5–30 cycles
  - *Momentary*: 30 cycles to 2 s
  - *Temporary*: 2 s to 2 min
  - *Sustained*: greater than 2 min.
- *Induced failure*: Failure attributable to the application of stresses beyond the stated capabilities of the item.
- *Initial quality error rate (IQ)*: The number of failures occurring during the first two days of ownership of a unit, expressed as a percent of those units tested or placed in service.

- *Maintenance indicator (MI), observed*: The mean value of the length of time between consecutive unit failures, removals, and software upgrades, computed as the ratio of the cumulative observed service years to the number of failures, removals, and service-bulletin-related upgrades.
- *Useful life or service life*: The period from a stated time during which, under stated conditions, an item has an acceptable failure rate or until an unrepairable failure occurs.

Performing Traditional Functions Better

Microprocessor relay schemes are simpler designs because they use less relaying components and auxiliary equipment. These schemes use the same data inputs within the relay to perform additional relay functions using Boolean algebraic expressions. The improvements can be summarized as follows:

- Low-burden devices.
- More simple protection schemes and compact designs due to multifunction devices. For example, the transformer protection of primary differential relays and backup time- and instantaneous-overcurrent relays requiring ten electromechanical relays (EMRs) is reduced to a primary and a backup multifunction μP-based relay.
- Lower cost.
- Wider and continuous setting ranges.
- Greater sensitivity due to higher accuracy metering and repeatability of relay. Hence, 0.2 s coordinating time interval (CTI) instead of the typical 0.3 s can be used for coordination.
- Fault sensing and high-speed tripping, which provide improved system stability and power quality.
- Flexibility for designing or changing a protection scheme (not available with solid-state analog or digital relays) without installing additional equipmentlike control switches, because of user-programmable logic.
- Negative-sequence polarization.
- Negative-sequence overcurrent and differential elements.
- Three-pole subcycle current-differential protection.
- Built-in synchronism-check function to supervise breaker closing conditions.
- μP relays can be tested under load conditions to confirm phase angle and magnitude values using the metering command of the relay.

Providing More Information

A protective relaying system includes relays, voltage and current transformers, circuit breakers, a dc supply, control cables, and sometimes a communications channel to exchange data between relays. Hence, protective relaying reliability depends on all the system elements. In the past, EMRs were responsible for a high percentage of protection system operation failures or undesired operations. As shown in this article, μP relays are highly reliable devices that provide protection and fault recording and can monitor the status of some of the elements of the protection system.

IN THE PAST, ELECTRO-MECHANICAL RELAYS WERE RESPONSIBLE FOR A HIGH PERCENTAGE OF PROTECTION SYSTEM OPERATION FAILURES OR UNDESIRED OPERATIONS.

The information that these devices gather during system disturbances and faults is very important in understanding the power system behavior and evaluating the protection system performance. The importance of analyzing this information cannot be overstated.

Furthermore, many of the new features are not available in previous technologies, such as the following:

- multiple settings groups
- built-in event reporting shows voltage and current levels and relay element, contact output, and contact input status every one-fourth cycle (for a relay that processes its logic four times per power cycle)
- fault locating
- automatic self-testing
- sequence-of-events (SOEs) record
- built-in metering that eliminates transducers and meters
- remote communications access for setting, monitoring, and control
- all relay event and SOE information for entire plant timestamped to 1-ms accuracy, using a standard global positioning system (GPS)-synchronized time signal, making postfault and interruption investigations that involve multiple events in different relays easy to correctly reconstruct for root cause analysis.

Increased Reliability

The features built into μP relays make a power system safer, more reliable, and more economical. We design and test μP relays to operate reliably in the toughest environments. After all, the less maintenance a relay requires, the less time the relay is out of service. Out-of-service relays reduce the protection of the system. The reliable operation of μP relays ensures that the system is operating within design limits.

With EMRs, the only way to know if the relay was working was to remove it from service and test it. The test would verify only whether the relay worked during testing. You could not be sure the EMR would work when you returned it to service.

An important benefit of a μP relay is the ability to constantly run self-checks to confirm that all functions are operating properly. μP relays have 75–85% coverage in self-diagnostics, as explained further in [5]. The enable light in front of a μP relay assures electricians and operators that the relay is functioning and protecting the system. Unlike the EMRs, which may get checked on an annual (or longer) basis, μP relays check themselves thousands of times each minute. Additionally, if the self-test finds an anomaly, the relay automatically signals an alarm condition through fail-safe contacts. Operators and electricians can then check and repair the problem before a fault occurs, especially when the alarm contact status is remotely monitored by a control system.

THE LESS MAINTENANCE A RELAY NEEDS, THE LESS TIME THE RELAY IS OUT OF SERVICE.

Review of Reliability Measurement Practices

Reliability engineers typically use one or more of these practices to measure product reliability.

1) *Reliability prediction based on individual component failure rates:* Prediction methods assume that all components have a constant failure rate. Component failure rates are added to obtain a total system failure rate (the inverse of MTBF).

   Two methods are offered in MIL-HDBK-217, "Reliability Prediction of Electronic Equipment" (1992): the parts count method and the parts stress method. A total of 19 component categories cover failure rates derived from historical data; models employ empirically derived factors that adjust for temperature, environment, and quality level.

   Reliability prediction does not ensure that the reliability values will be achieved and is not a demonstration of the way that a power consumption prediction, being based on physical laws, would be. Rather, it is best used as a basis for setting the objective, to be attained only if there is a personal commitment to it.

2) *Product reliability testing:* Reliability testing is an essential part of engineering development to address risks and determine whether designs are reliable. The key element of reliability testing is applying stress over time. Accelerated tests may include temperature, temperature cycling, humidity, and vibration, or combinations of these stresses.

   For highly reliable products, demonstrating that a specific MTBF goal is achieved during product development is difficult because several hundred unit years of testing are required. Extrapolating accelerated test results to normal use conditions is complex because of the wide variety of failure modes and corresponding acceleration factors involved.

3) *Observed field reliability performance:* Reliability monitoring can continue beyond the development process throughout the life of the product. Logging product shipments by serial number and recording all warranty failure service actions enables reliability engineers to calculate observed MTBF under field conditions.

   We use all three measures of product reliability at appropriate points in our process. Reliability prediction models provide an initial estimate based on product complexity and type of components.

   We employ highly accelerated life testing (HALT) during the development process to force failures and improve designs.

   Our no-questions-asked ten-year, worldwide warranty brings products back for analysis and repair. We monitor results of warranty service to provide the following:

   - calculation of observed reliability in the field
   - opportunity to detect unexpected failure mechanisms quickly and initiate corrective action
   - input to improve the design, process, or materials of current and future products.

The following subsections explain the probabilistic but quantitative understanding of μP relay reliability by observing μP relay failure rates and unavailability. Typically, manufacturers looked primarily at hardware failures as the key indication of μP relay product reliability. As we explain in the following subsections, and as illustrated in Table 1, we use four quality measurements to measure product quality and reliability.

TABLE 1. FOUR QUALITY MEASURES.

Category	MTBF	MTBR	MI	IQ
Hardware and manufacturing process	✓	✓	✓	
Firmware and no trouble found		✓	✓	
Firmware service bulletins			✓	
Hardware service bulletins			✓	
Any failure in first 48 h of use				✓
Induced failure				

✓ means this category of failure is counted for the specific measure.

Mean Time Between Failures

In 1988, we started recording MTBF statistics. This observed approach is better than a theoretical calculation, such as MIL-HDBK-217F parts count procedure [6], as it incorporates manufacturing and design quality.

Theoretically,

$$\text{MTBF} = \text{MTTF} + \text{MTTR}. \tag{1}$$

But since MTTF $\gg$ MTTR, where MTTF is of the order of 300 years and MTTR is of the order of 48 h or 0.000228 years

$$\text{MTBF} \cong \text{MTTF}. \tag{2}$$

Also the related failure rate (based on MTBF failures) is

$$\lambda_F = \frac{1}{\text{MTBF}}, \quad (3)$$

where λ_F is the constant MTBF failure rate.

For repairable products, such as μP relays, MTBF in years does not indicate useful life of a single unit in years. To understand what the MTBF measure is, consider the failure rate is $\lambda = 0.3333\%$ per year for a particular unit. If a facility had 900 units, then we would expect $900\lambda = 3$ unit failures per year. Because the unit's MTBF is the reciprocal of failure rate, the MTBF reliability of the unit would be

$$\frac{1}{\lambda} = 300 \text{ years},$$

or, in other words, a MTBF of 300 years. The 300 years MTBF is a useful reliability or quality measure that is valid during the useful life (typically, 30 years) of the unit. Stated another way, for an MTBF of 300 years, you might experience one failure per year due to hardware or manufacturing process for a μP relay population of 300 installed units for a total of 30 total failed units over the 30-year life of the units.

AN IMPORTANT BENEFIT OF A μP RELAY IS THE ABILITY TO CONSTANTLY RUN SELF-CHECKS TO CONFIRM THAT ALL FUNCTIONS ARE OPERATING PROPERLY.

The MTBF quality duration is increased by selecting reliable components that are specified for high-temperature operation, establishing operating limits of μP relay components well below the published specification, designing μP products for a wide operating temperature range (−40 °C to +85 °C), and, lastly, applying HALT to verify operating margins and force failures well beyond normal specification levels to improve reliability.

Mean Time Between Removals

We introduced the MTBR measure in 1998 to include hardware failures (part of MTBF), manufacturing process errors (part of MTBF), firmware errors, or no problem found on a returned unit. For a 240-year MTBR, one of every 240 relays can be expected to have a defect each year.

Figure 1 shows how product failures occur over the life of a μP relay. At unit receipt, the customer installs or tests the unit and may find some IQ errors in the first few days of use, which we consider IQ errors. During the stable failure period, the product has a relatively constant failure rate, mainly because of our 100% burn-in on each product, which eliminates nearly all of the abnormal early-life component defects. We calculate the removal failure rate by dividing observed removal failures by the number of products in service. The MTBR is then the inverse of the removal failure rate

$$\lambda_R = \frac{1}{\text{MTBR}}, \quad (4)$$

where λ_R is the constant removal (MTBR) failure rate.

The time at which failure rates start to rise significantly from the stable failure rate region is called the wearout failure period (see Figure 1). For μP relays, the wearout failure mechanism is usually a reduction in capacitance of aluminum electrolytic capacitors in the power supply. Our units are designed for a 30-year life. However, with a power supply replacement, μP relays can continue to function well beyond 30 years.

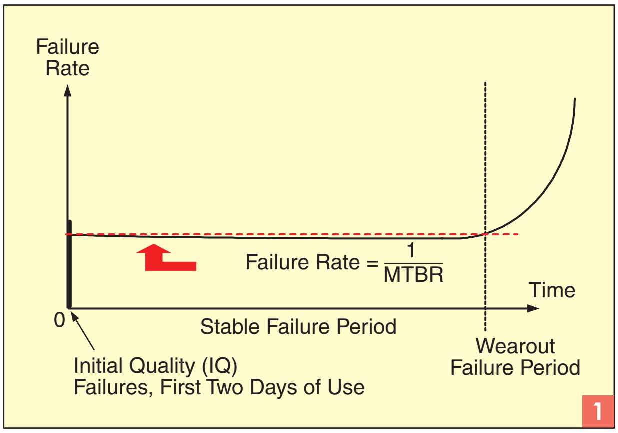
Observed MTBF and MTBR based on the actual reliability of field-installed units are better measurements: the correlation of laboratory testing conditions to field-use conditions is eliminated by obtaining the measurements from units experiencing field conditions. In addition, to obtain significant and useful results from laboratory testing, one must test a large number of units for an extended period of time. For instance, to demonstrate a field reliability of a 100-year MTBF, one would need to test 1,000 relays for about 2,000 h.

Nevertheless, as part of our development process, we test units at high-stress conditions to determine any significant life-limiting failure modes. We also analyze any failures to root cause and implement appropriate design, material, or process corrective actions.

The early-life failures are considered to be those failures that occur after two days but during the first year of a unit's in-service life, whereas the useful life failures are considered to be those failures that occur after the first year of a unit's in-service life. Both the early and useful life failures (or defects) are included in the MTBF and MTBR measurements.

Initial Quality

In 2003, we introduced the IQ measurement, which measures observed out-of-box errors detected by our customers at receipt or initial testing of a unit. These errors or failures can be due to incorrect order entry, performance, configuration, documentation, accessory, or shipping damage. These unit failures are included in the IQ measurement but not in the MTBF and MTBR measurements. Our observed IQ measurement for all products is approximately 0.6%.



Product failure rate pattern.

Maintenance Indicator

In 2003, we also introduced the MI measurement, which measures MTBR plus all service-bulletin-related upgrades. We capture data generated from detected unit concerns during inspections, reliability and manufacturing tests, field failure reports, and customer feedback. Once the concern is observed to be a significant trend and problematic, we issue a service bulletin to proactively inform customers of known failure mode(s). After looking at μP relay users' experience, we observed that the MTBF, MTBR, and IQ do not capture the impact of maintenance and service bulletins that are implemented by customers to fix firmware or hardware errors; hence, we added the MI quality measurement.

RELIABILITY TESTING IS AN ESSENTIAL PART OF ENGINEERING DEVELOPMENT TO ADDRESS RISKS AND DETERMINE THAT DESIGNS ARE RELIABLE.

The MI quality measurement is a method of measuring customer maintenance activity and the impact of our quality on customers. This measurement is the most stringent quality measure, because it includes an additional error, that of proactive service bulletin work (problem has not occurred yet, but may without intervention), in addition to observed MTBF- and MTBR-repeatable failures.

For an 80-year MI, one of every 80 relays (each year) can be expected to have a hardware defect, manufacturing process defect, firmware defect, no problem found return, or service-bulletin-related maintenance recommendation.

Table 2 shows our relay MTBF, MTBR, and MI statistics. These observed values are based on relays returned by customers to us under our no-fault ten-year, worldwide warranty for free repair service and are therefore accurate measurements of repair, removal, and maintenance experience. The failure rate is calculated by the method described in the "Mean Time Between Failures" section.

Unavailability

Typically, unless higher reliability is necessary, electric utilities' transmission and distribution (T&D) systems are planned, designed, and built using single ($n-1$) contingency analysis, which may or may not include breaker failure and bus failure analysis. For protection, this requires designing protective relay schemes that will not compromise the protection of the electrical equipment for a single protection component failure. Parts of industrial and commercial power systems are single-contingency reliable, but large portions of these power systems are radial, without parallel feeders. In these cases, a single equipment component failure causes a significant sustained interruption that renders the downstream power system and industrial process unavailable.

TABLE 2. OBSERVED MTBF, MTBR, IQ, AND MI.

Measure	Years	Failure Rate[1]
MTBF	300	0.33%/year
MTBR	240	0.42%/year
IQ	—	0.6% of new units
MI	80	1.25%/year

[1]Percent of units installed that would experience a failure in one calendar year of continuous operation, except IQ, which is percent of units installed that experience a failure within the first two days of use.

The failure rate of a μP relay is useful in predicting equipment maintenance costs, but does not indicate whether a μP relay will be available to perform its protective function when required to during a power system fault condition. Hence, there is a need to consider the unit's unavailability.

To determine a unit's unavailability from its failure rate, we need to know the time it takes to detect and repair a unit's failure or defect. From [7], we have a simple method to determine unavailability (q).

$$q = \lambda r = \frac{r}{\text{MTBF}}, \tag{5}$$

where r is MTTR, expressed in years, and q is unitless. Note that 1 h equals 0.000114 years.

Considering the 300-year MTBF unit (0.33% failure rate) that detects, through self-tests, a defect in seconds but requires two days to repair ($r = 0.005479$ years) without a spare unit to immediately replace the failed unit, then

$$q = 0.003333 \times 0.005479 = 18.3 \times 10^{-6}. \tag{6}$$

Based on 525,600 min/year, unavailability is about 9.6 min/year.

Or if $r = 5$ h, as stated in P.217 of [8], with spare unit replacement, then

$$q = 0.003333 \times 0.0005708 = 1.9 \times 10^{-6} \tag{7}$$

or 1 min/year. If failed relay and spare are the connector type, then $r = 2$ h could be used.

Alternatively, substituting a 240-year MTBR unit (0.42% failure rate) into (6) and (7) would give us unavailability numbers of 22.8×10^{-6} (12 min/year) and 2.4×10^{-6} (1.25 min/year), respectively.

Using a spare unit, the MI measure will have an unavailability impact of

$$q = 0.0125 \times 0.00057078 = 7.13 \times 10^{-6} \tag{8}$$

or 3.75 min/year.

However, the MI would require only a forced outage consequence if the relay maintenance could not be done during the next planned and scheduled process outage.

Compare this to an EMR that cannot be monitored but is serviced every two years and repaired the same day it is tested. If a defect is detected, then this relay was down on average for one year. Hence, using data from P.217 of [8],

$$q = 0.0002 \times 1 = 200 \times 10^{-6} \quad (9)$$

or 105 min/year.

Although unavailability is useful information, it does not have a direct cost impact to the occurrence of a forced outage until an electric power system fault occurs during the period the unit is unavailable, which results in an uncleared fault and makes the forced outage more extensive because backup protection interrupts more of the system than necessary.

THE MI QUALITY MEASUREMENT IS A METHOD OF MEASURING CUSTOMER MAINTENANCE ACTIVITY AND THE IMPACT OF OUR QUALITY ON CUSTOMERS.

Frequency of Faults

Assuming that faults are random and independent of protective relaying failures, we can say that relay unavailability is the likelihood that the protective relaying is not available when a power system fault occurs. For example, we assume that an industrial plant consists of 500 protective zones that each experience, on an average, two faults per year. If the plant is a radially configured system and uses μP relays with only single primary protection throughout, with an average unavailability of all protective relays from (8) being 7.13×10^{-6}, then the number of faults for which the protection will be unavailable would statistically be

$$\mathrm{NUF} = 2 \times 500 \times 7.13 \times 10^{-6} = 0.00713, \quad (10)$$

where NUF is the uncleared faults per year.

Albeit oversimplified, this example shows that the uncleared faults each year in an industrial plant due to μP relay reliability are significantly less than one, and that uncleared faults are more likely to be the result of some other equipment failure, such as a circuit breaker.

Using redundant and independent primary and secondary (in addition to backup) relaying throughout the plant (not typically done) would require that both the primary and secondary relays must fail to operate for a relay misoperation and, hence, the unavailability will be the product of their respective unavailabilities, $(7.13 \times 10^{-6})^2$ in this case, and NUF reduced to 1.1×10^{-7}.

The total protective system unavailability, which includes relays, voltage and current transformers, circuit breakers, a dc supply, control cables, and communications channel for an industrial plant, could be in the neighborhood of $1{,}000 \times 10^{-6}$ to $2{,}000 \times 10^{-6}$, based on [7]. Reference [7] clearly shows that, given the high-availability numbers of μP relays, industrial and commercial facilities need to focus their attention on the design, operation, and maintenance of the other components of the protective system to achieve better protection, because the μP relays' reliability improvements will have little effect on the protective system's total unavailability.

Using the earlier information and knowing the direct and consequential costs of an uncleared fault, one could determine the cost of this level of unavailability. Using the time value of money, one could then compare the cost benefit of the do-nothing option to determine the benefit and payback period of any proposed electrical equipment protective system improvement.

Cost of Ownership

For the purpose of this article, we have used our known μP relay costs and durations but have had to estimate some EMR costs and durations. We have confidence in the μP relay reduction in maintenance frequency due to the self-checking.

Table 3 summarizes our comparison of the total ownership costs over a ten-year period for a single μP relay and a single-function EMR. The key data that are required for this analysis include purchase price, warranty period, annual removal rate, engineering labor cost, measured reliability data, service call cost, and repair fees, as detailed in Table 4. This simple comparison reveals that several other items of key significance should be considered beyond just the purchase price of protective relaying equipment.

Conclusions

Electric power utilities have found that even distribution μP relays offer considerable advances in protection coupled with reduced capital, operation, and maintenance costs. In contrast, industrial and commercial users of electric power usually do not upgrade their existing protective relaying equipment but often choose to keep the existing protective equipment until it eventually fails. However, on new equipment purchases for new projects, industrial and commercial facilities are accepting the use of μP relay technology over electromechanical or solid-state (analog and digital) protective relaying equipment, which may suggest that some plant engineers and users at least view this new technology as only an updated equivalent.

TABLE 3. SUMMARY OF COST-OF-OWNERSHIP COMPARISON.

Cost Element (Over a Ten-Year Period)	μP Relay	EMR
Purchase price	US$4,000	US$6,000
Cost of settings labor	US$1,000	US$1,000
Cost of service calls (per ten years)	US$120	US$1,200
Cost of repairs (per ten years)	US$0	US$600
Sum	US$5,120	US$8,800

TABLE 4. BASIS OF COST-OF-OWNERSHIP COMPARISON.[1]

Item	Element	µP Relay Unit	µP Relay Cost	EMR Unit	EMR Cost
1	Purchase price		US$4,000		US$6,000
2	Warranty (years)	10		2	
3	Cost of settings labor (one device)		US$1,000		US$1,000
4	Annual removal rate	0.004		0.04	
5	Service calls in ten years, Item 4 × 10	0.04		0.4	
6	Cost of one service call	US$3,000		US$3,000	
7	Cost of service calls (per ten years), Item 5 × Item 6		US$120		US$1,200
8	Cost of repair (one device)	US$0		US$1,500	
9	Cost of repairs (per ten years), Item 5 × Item 8		US$0		US$600
10	Total cost of ownership		US$5,120		US$8,800

[1]Data are from the authors' 2006 survey of relay manufacturers and users.

It is the authors' opinion that the reluctance to upgrade outdated existing protective relaying equipment is not based on actual µP relay performance or experience, but it is more founded in the personal preference to stay with familiar equipment. Contributing factors are the poor quality of early-static relays, the reluctance of an aging industry's workforce to embrace the technology change, the hurdle of an associated learning curve for the new technology, and the perception that µP relays are too difficult to configure and set.

With these industrial cultural issues understood, we believe that, similar to the transition to the µP relay that has occurred in the electric utility T&D industry, industrial and commercial users will find that

1) using the capabilities of µP relays has significant benefits over the former protective relaying technologies
2) µP relay reliability is predictable and known from disclosed observed MTBF, MTBR, IQ, and MI quality measurements for all units and even specific customer units
3) as determined and described in [9], the use of µP relay-to-relay communications-assisted protection and control schemes for distribution circuits will reduce trip and load transfer times
4) µP relay manufacturers need to continue to communicate to power plant and industrial plant engineers that this newer technology is indeed better and more economical
5) based on unavailability analysis in this article, it appears that the unavailability of EMRs may be from 10 to 80 times that of µP relays, depending on the repair time.

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