Digital Protective Relays Demonstrate Superior Reliability and Improve System Performance

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ABSTRACT

Digital protective relays have more than 40 years of successful operating history. Reliability data, recorded over this period, have shown continuous and dramatic improvements. This paper publishes the latest reliability data to highlight the improvements made in the past 20 years. A comparison to electromechanical relaying technology is explored in this paper, including methodologies for comparing reliability and availability.

The existing fleet of commercial nuclear plants relies heavily on electromechanical and analog technology, and the industry has been reluctant to transition to intelligent electronic devices due to reliability concerns and additional complexity and failure modes. The industry is now facing aging reliability and obsolescence concerns with electromechanical devices, and has made strides in providing guidance for the acceptance of digital technology. Moving to digital technology addresses these concerns as well as improves performance and protection for plant electrical systems.

Digital devices introduce an attribute of embedded firmware, which must be analyzed for reliability performance in addition to the hardware. This paper provides a detailed analysis of accepted standards for evaluating reliability and unavailability of electrical protective relays. Using these approaches, this paper then examines the reported reliability and availability of digital relays over decades of operating experience, considering overall failure rates and firmware failure rates. The paper explains how self-diagnostic capabilities of digital relays allow for significant improvements in unavailability compared to electromechanical relays. Formal data are examined for mean-time-between-failure (MTBF), reliability and failure rates, unavailability, and design life. Significant improvements in reliability performance over the past 20 years are presented.

The results of this analysis provide the industry with justification to transition from electromechanical relays to modern digital relays with the conclusion that reliability is as good as or better than their electromechanical counterparts.

Keywords: digital relays, electromechanical relays, reliability, unavailability, MTBF

1. INTRODUCTION

This paper describes the benefits of digital relay performance and capabilities that exceed previous protective relaying technologies and highlights the dramatic improvements in reliability over the past two decades. These benefits are drawn from decades of transmission, distribution, generation, and industrial

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operating experience gained as the power industry has been transitioning much of its protective relaying from electromechanical to digital. This is an important consideration for nuclear generation facilities that are currently faced with aging electromechanical and solid-state protective relaying equipment and the corresponding equipment malfunctions, misoperations (accidental tripping), or labor-intensive maintenance. Although digital relays have been commercially available for more than 40 years, the nuclear industry tends to be reluctant to embrace digital technology for mission-critical applications, such as nuclear safety-related. This reluctance is due in part to reliability concerns with unfamiliar equipment and the added complication of qualifying firmware, a step that is not needed for electromechanical relays.

In 2006, the paper "Microprocessor-Based Protective Relays Deliver More Information and Superior Reliability with Lower Maintenance Costs" [1] described an approach to analyzing reliability and maintenance costs associated with digital relays compared with electromechanical relays. That analysis included reliability and availability metrics collected over 20 years of operating experience to justify the transition from electromechanical to digital technology. This paper updates digital relay reliability and unavailability data presented in [1] to further justify the move to digital technology for nuclear applications.

Technical and marketing literature may refer to digital protection and control equipment using terms such as "microprocessor-based relays," "multifunction relays," or "numerical relays." Generally speaking, these terms refer to the same equipment: intelligent electronic devices that receive current and voltage inputs, which are used to make decisions about the protection of the electrical system, using a microprocessor for logic functions. For consistency, this paper will refer to these devices as digital relays to differentiate them from their predecessor electromechanical and solid-state equivalents.

2. RELAY RELIABILITY

2.1 Electromechanical Versus Digital

Performing a direct comparison of the reliability of electromechanical relays to digital relays is a challenging task, as the reliability data for electromechanical relays are difficult to quantify. When an electromechanical relay is found to be inoperable (e.g., through testing or in response to a system disturbance), both when the relay failure occurred or how long the electrical system had remained unprotected are impossible to determine. With a digital relay, self-diagnostics and additional in-service checks mitigate this lack of awareness.

Electromechanical and solid-state relays both have the potential to lose calibration, or "drift," over time. While the electromechanical relay may not have failed in the traditional sense, if calibration is lost to the point that the device no longer performs its intended function, it should be considered a failure. An out-of-calibration relay could fail to trip for an event, resulting in a miscoordination and causing a more widespread system outage. If the relay is being relied upon for arc-flash protection, it could result in an increase in incident energy, creating a hazard. This failure mode is eliminated in digital relays as they inherently do not drift, removing the need for periodic calibration.

As the units currently in service age, concerns about increased failure rates grow. Nuclear plants that are still using primarily electromechanical devices, are faced with maintaining and repairing equipment that is approaching 40 years old or older. One utility examined their system electrical protection and determined many of their protective devices were 25 to 40 years old. They assessed their performance and concluded that out of all system misoperations associated with relays, nearly 35 percent of them were due to incorrect operation of electromechanical relays [2].

Nuclear plant operators are faced with the challenges of maintaining and replacing aging electromechanical relays and the associated constraints: availability of replacement parts, skilled technicians to perform repairs, and more frequent failures. Given the many benefits of moving to digital technology the justification for replacement is straightforward. However, electromechanical relays have performed quite reliably over their long operating life. To solidify the case for replacement, it must be demonstrated that digital relays are as reliable, if not far more, than existing electromechanical relays.

2.2 Information From Reliability Standards

There are a few IEEE standards that address relay reliability:

- IEEE 493 includes reliability data specifically for protective relays in the 1997 edition. However, the data were from a 1974 survey, which included a caveat that the sample size of actual failures recorded was so small that the data should be excluded from reporting. The standard also clearly notes that no attempt was made to report on reliability of different types of protective devices. The 2007 edition of IEEE 493 removed the specific table entry for protective relays but kept all the caveats about small sample sizes and aggregation of all protective device types [3].

- IEEE 3006-2012 includes equipment reliability for individual power system components (transformers, breakers, switchgears, motors, etc.) but does not include data specifically for protective relays. Some inferences could be made by the data tables, which categorize causes such as the malfunction of protective devices, however, no further details are given as to what types of protective devices are in the system. All the reliability data in this standard are from 1976 or before [4].

- IEEE 500-1984, which compiled equipment reliability data for nuclear-power generating stations, includes a chapter on circuit breakers, interrupters, relays, switches, and fuses. Failure rates are provided for given systems, but there are no rates provided specifically for relays. Some information could be inferred from some of the failure modes such as “failed to open/close on command” or “open/close without command.” The standard includes a disclaimer that the data are not taken from a random sample but rather collected through a Delphi survey, either as recorded data or the collective judgement from a group of specialists [5].

In 1989, an electromechanical relay manufacturer published reliability numbers for electromechanical and solid-state relays. The manufacturer published a failure rate of 0.1 percent for electromechanical relays, and at that time noted a significantly higher failure rate for digital relays (referred to in the paper as “electronic relay systems”). This paper includes a discussion on IEEE 493 and also observes the data presented in IEEE 493 are from too small a sample size to provide meaningful inferences [6].

In 2015, the IEEE I22 Working Group published a report on the *End-of-Useful Life Assessment of Protection and Control Devices*. It provides a detailed analysis for determining a device’s end-of-useful life in comparison with its “end of life.” It considers factors such as age, obsolescence, maintenance, availability, and maturity of replacement technology, etc. The report begins by stating that the protection and control industry has moved from electromechanical to microprocessor-based platforms [7].

2.3 Self-Diagnostics

An immediate differentiator between electromechanical and digital relays is the ability to perform self-diagnostics, providing instant feedback on the functionality of a relay and alarming if the relay is suspect.

One governing body, the North American Electric Reliability Corporation (NERC), recognizes the gains and increased visibility in its standard. NERC Standard PRC-005-2, *Protection System Maintenance*, prescribes maximum maintenance intervals for different relay types protecting the bulk electric system. Electromechanical relays fall under the category described as unmonitored protective relays that have no self-diagnostics or alarming capabilities. PRC-005-2 requires a maximum maintenance interval of six years, which must include testing and calibration. For digital relays that include self-diagnostic and alarming capabilities, the maximum maintenance interval is extended to 12 years, and recalibration is not required [8].

An important benefit of a digital relay is the ability to continuously run self-diagnostics to confirm that all functions are operating within the intended specification. An analysis of field return data notes that of all failures, over 75 percent of them were detected by self-diagnostics [9]. Reference [9] explains that through monitoring and testing of input/output contacts, analog inputs, and periodic front-panel checks, 100 percent coverage can be achieved. Unlike electromechanical relays that may get checked on an annual (or longer) basis, digital relays check themselves thousands of times each minute, greatly improving availability.

2.4 Firmware Reliability

An intelligent electronic device such as a digital relay includes a microprocessor for logic functions, using embedded firmware to enable and control the functions of the device. This introduces a new layer of complexity not found in electromechanical and solid-state counterparts. The tradeoff is the enhanced performance of an intelligent device capable of processing multiple inputs and responding much more quickly and accurately to system events than its counterparts. Just like hardware components, the firmware must be developed under a robust quality assurance program to ensure reliability. For nuclear applications, commercial off-the-shelf digital devices undergoing commercial-grade dedication must include an analysis of the firmware development process and operating experience to conclude that the firmware can operate reliably with a sufficiently low likelihood of failure.

Fortunately, two key factors are providing a successful path. First, the industry has developed guidance, which has been endorsed by the Nuclear Regulatory Commission (NRC) to aid in the acceptance of commercial digital devices. Historically, commercial-grade dedication and equipment qualification activities focused on the performance of the hardware (e.g., a motor, pump, piping, etc.) validated by physical testing and analysis of the manufacturing and design process. Applying this approach to firmware qualification was ambiguous and laborious, resulting in few nuclear plant operators being willing to expend the effort to accept a digital device. Additionally, introducing microprocessor-based devices introduces cybersecurity concerns and the need to comply with 10 CFR 73.54 *Protection of Digital Computer and Communication Systems and Networks* [10]. To address these concerns, industry groups such as the Electric Power Research Institute (EPRI) and the Nuclear Energy Institute (NEI) began publishing guidance specifically aimed at providing manageable criteria to facilitate the acceptance of digital devices running embedded firmware [11] [12]. The NRC has formally endorsed much of this guidance [13], along with issuing supplemental clarifications on how to apply it [14], and this guidance is cited as the basis of qualification methods by dedicating entities.

The second factor to consider when qualifying firmware is the long use history of digital devices and accumulated operating experience of embedded firmware. Analyzing product return data, a relay manufacturer found that the resulting failure rates associated with firmware-related returns were only a fraction of the total returns. Data analysis by the relay manufacturer suggests firmware-related issues are 100 times less likely than a hardware-related return. Exploring the data further revealed that of the entire

population of firmware-related returns, only a small fraction of those resulted in a momentary impact to the protective functions of the relay.

Improved industry guidance coupled with documented firmware reliability allows a dedicating entity to reach a conclusion of a sufficiently low likelihood of failure. This analysis can be provided by the dedicating entity in a qualification report or qualitative assessment. For a device manufacturer (i.e., original equipment manufacturer or OEM) with a robust quality assurance program, the dedicating entity can implement a commercial-grade survey of the OEM and give credit for much of the OEM's quality assurance program [11]. This is critical in firmware lifecycle management and facilitating necessary firmware revisions to address vulnerabilities or latent errors, reducing the efforts needed to accept a new version of firmware.

3. REVIEW OF RELIABILITY MEASUREMENT PRACTICES

Reference [1] describes several methods for determining reliability data and explains that actual observed field reliability performance as providing the most insight into the expected reliability of equipment. The paper also provides measured reliability data collected as of the time of publication. Since then, nearly two decades of additional data have been collected and analyzed. The result is a definitive demonstration that reliability continues to significantly improve as digital relay technology matures.

An operating nuclear plant looking to upgrade their safety-related relays to digital relays must evaluate that the replacement relays have a "sufficiently low likelihood of failure" per the NRC [15]. Reference [15] describes three primary criteria for assessing a design change, such as a relay upgrade, one of which is operating experience of the component. The critical metric for concluding a relay will have a sufficiently low likelihood of failure is mean-time-between-failure (MTBF). Reference [1] provides a detailed explanation of this metric, and a summary is provided here for context.

3.1 MTBF

A relay manufacturer started recording a MTBF measure in 1989 and continues to compile data based on product return and product-in-service data for the prior 12-month period, assuming that products are put into service six months after shipping and removed from service after 20 years. A measurement of reliability, MTBF includes electronic component, hardware design, and manufacturing assembly defects. From [1], the related annualized failure rate (based on MTBF failures) is

$$\lambda = \frac{1}{MTBF} \tag{1}$$

where λ is the constant MTBF annualized failure rate. Suppose the MTBF is 300 years and the corresponding failure rate is $\lambda = 0.3333$ percent per year for a particular protective relay model. If a facility had 300 of those devices, then they would expect $300 \bullet \lambda = 300 \bullet 0.003333 = 1$ device failure per year, or with a facility of 900 devices, they would expect three device failures per year.

3.2 Reliability Trends

Table I shows digital relay MTBF from one relay manufacturer, which includes updated data from 2025, compared to the metric values originally published in [1]. Since this metric was first published nearly 20 years ago, MTBF has nearly tripled, meaning relays manufactured in the past 20 years are almost three times as reliable as those manufactured in the previous 20 years. This significant MTBF improvement is

due to the increased reliability of electronic components and consistent dedication to continuous improvement.

Table I. Observed MTBF

Measure	2006 Data (Years)	2025 Data (Years)	Improvement
MTBF	300	1,140	280%

Based on the MTBF in Table I, the calculated failure rate for digital relays is

$$\lambda = \frac{1}{1{,}140} \tag{2}$$

or 0.0877 percent per year. Reference [6] notes failure rates of 0.1 percent for electromechanical relays. Comparing these failure rates concludes that digital relays are actually performing more reliably than their electromechanical counterparts. Comparing digital relay failure rates published in [6] (1989) and [1] (2006) to the data shown above in Table 1 demonstrates significant improvements in relay reliability. In addition, the electromechanical relay's lack of self-diagnostics has a significant impact on unavailability metrics as described in Section 4.

3.3 Design Life

In the United States, commercial nuclear plants were initially licensed to operate for 40 years. This was selected based on economics and antitrust considerations rather than the life expectancy of equipment at the time [15]. Despite the somewhat arbitrary 40-year design life, electromechanical relays have enjoyed many years of reliable service throughout the initial 40-year operation of the plant. As plants obtain 20-year license extensions, many are still using the original electromechanical relays. Moving to a digital relay raises the question of design life, particularly as it fits into extending the life of an operating nuclear plant.

Coincidentally, the intended design life of a digital relay is a minimum of 20 years. Similar to the 40-year original license period, a 20-year design life is somewhat arbitrary to the user, as it has been found that many end users choose to replace their digital technology after 20 years based on availability of later technology developments, improved performance, and added features. Analysis of the reliability metrics discussed in the previous sections is limited to a 20-year window, as most end users do not return or report relay replacements after 20 years. Reference [16] provides compelling evidence that a digital relay can continue to perform reliably well beyond 20 years. One utility plans for their digital relays to last 24 years and implements the NERC Standard PRC-005-2 twelve-year maintenance requirement, resulting in the relay only needing to be maintained once in its service life [16].

4. THE UNAVAILABILITY OF ELECTROMECHANICAL RELAYS

4.1 The Advantage of Self-Diagnostics in Nuclear Applications

In addition to information mentioned in Section 2.3, reference [9] provides a detailed model for determining unavailability based on many factors, including MTBF, time to repair, time to replace, and time to test (i.e., perform maintenance). Given operating nuclear plants are most likely to perform relay maintenance (and subsequently repair and replacement) during a refueling outage, unavailability for these activities is not as critical of a factor when evaluating overall performance. The availability of a relay when it is needed to

perform its intended function, i.e., during a system fault event, is critical, particularly considering its role in a nuclear safety-related electrical system.

Given the opportunity to detect near 100 percent of all failures, unavailability of a digital relay is limited to the time to replace upon failure detection. This is an important factor to consider when comparing to an electromechanical relay's unavailability. Given an electromechanical relay has no self-diagnostic capability, failures are only discovered during regularly scheduled maintenance, which could occur as infrequently as once every six years [8].

4.2 Quantifying Unavailability

Factors impacting unavailability include the time it takes for a relay to be repaired, maintained, or tested, as well as the likelihood of a relay malfunctioning. Industry standards and numerous technical publications have provided models and formulas for calculating unavailability, including the model described in [9]. Most of this analysis can trace its roots to [17], which provides a formulaic approach for calculating unavailability of a component by considering failure rates, average downtime per failure, average time to repair, and the test interval.

Reference [17], published in 1981, had the foresight to consider the advantages of a component whose functionality was monitored. In modern digital relays, self-diagnostics with output contacts that can be externally monitored, serve the purpose of a monitored component as intended in the unavailability formulas. From [18], the simplified unavailability (q) formula for a monitored (i.e., digital with self-diagnostics) relay is

$$q = \lambda \cdot T_D \tag{3}$$

where λ = failure rate (failures per year) and T_D = average downtime per failure (in years). However, for an electromechanical relay, which is dependent on periodic testing to determine functionality, the formula changes to

$$q = \lambda \cdot \frac{T}{2} \tag{4}$$

where T = test interval. The adjustment to include the test interval as a factor (1/2) considers the probability that the failure occurred prior to being tested and assumes on average the relay was unavailable to perform its intended function for half of the period between scheduled tests.

Both digital and electromechanical relays are considered highly reliable devices with low failure rates. However, the difference in unavailability provided by self-diagnostics is significant. Consider the failure rate for a monitored relay of 0.000877 (taken from the reciprocal of MTBF = 1,140 as shown in Table 1) and for an unmonitored relay of 0.001 [6]. These data do not reflect the aging population of relays that end users are experiencing today.

Assume a time to replace or repair of 24 hours (or 0.00274 years) for either relay and a test interval of six years for the electromechanical relay. Using the two formulas results in $q = 0.000877 \cdot 0.00274 = 0.00000240$ for the monitored relay, and $q = 0.001 \cdot \frac{6}{2} = 0.003$ for the unmonitored relay. The gains provided by a monitored relay results in an unavailability improvement over 1,000 times better. Shortening the test interval to every refueling outage (e.g., every 18 months), which

would require testing 100 percent of the plant's relay population during every outage, results in $q = 0.001 \quad \frac{1.5}{2} = 0.00075$, which is still nearly 300 times more unavailable than a monitored digital relay.

This approach to calculating unavailability based on testing interval was added to IEEE Std 338, *Standard Criteria for the Periodic Surveillance Testing of Nuclear-Power Generating Safety Systems* in the 2006 edition, primarily for the context of performing probabilistic risk assessments and determining optimal testing intervals. This edition also acknowledges the presence of self-diagnostics and lays out the criteria for implementation of self-diagnostics on digital devices, which allow for exemption of periodic testing [18].

The NRC acknowledges self-diagnostics in Branch Technical Position 7–17 but establishes the criteria that self-diagnostics do not interfere with the critical (safety) function of the component [19]. It also takes the conservative position that periodic testing, to verify the self-test functions, is still required but does not offer specific guidance on extension of intervals, unlike NERC PRC-005-2, which extends the maximum interval from six years to 12 years for relays with self-diagnostic capability [8].

5. CONCLUSION

Digital relays have a long use history, having been introduced over 40 years ago, and revolutionized the power industry and electrical system protection. Concerns about reliability, as well as the complexity of accepting devices running embedded firmware, have posed a barrier to acceptance by the nuclear industry, particularly for safety-related applications, which require a higher degree of rigor and reliability. The industry is evolving with guidance to improve the efficiency in qualifying digital devices for safety-related applications.

Extending the life of today's nuclear plants involves addressing aging and obsolete components that are no longer manufactured, or made by suppliers that have dropped their nuclear-specific quality assurance programs (e.g., Appendix B, NQA-1). This includes the population of electromechanical relays protecting much of the plant's electrical system and equipment. Industry groups have formed to address equipment obsolescence, with relays and digital acceptance being a topic of discussion in recent meetings [20] [21]. Despite an excellent track record for reliability, concerns still exist about aging electromechanical relays becoming less reliable, and the inability to repair or replace failed relays due to obsolescence.

Meticulous tracking of decades worth of reliability data have demonstrated tremendous improvement in the failure rates for digital relays. Accounting for the self-diagnostic capabilities of digital relays leads to the unavailability metrics to be magnitudes better than electromechanical relays with no self-diagnostic capability. The analysis of these data and operating experience enable a successful conclusion of a sufficiently low likelihood of failure of the device to perform its intended safety function.

Newly developed industry guidance, demonstrated reliability, and the need to address obsolescence are compelling factors for nuclear industry acceptance of digital relays. The additional features and information available in these devices provide greater insights into plant performance and equipment health, enabling plant operators to take advantage of the latest technology and successfully operate their plants for many years to come.

NOMENCLATURE

The following list provides some important terms and their definitions, as used in the paper.

Quality: "The totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs" [22].

Reliability: The probability that a product or system will perform its specified function over a specified period in a defined environment [22].

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" [22].

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)" [22].

Failure rate: The average number of failures over a specified period, expressed in failures per year [22].

Mean Time Between Failures (MTBF), observed: For a specified population of devices, MTBF is defined as the combined operating experience during a specified time period divided by the hardware or manufacturing process field failures that occur during that same time period. Both population and failure criteria shall be clearly specified. MTBF is the reciprocal of the observed failure rate during the period [22] [23].

Induced Failure: Failure attributable to the application of stresses beyond the stated capabilities of the item. Reference [2] also uses the term misuse to describe this type of failure [22] [23].

Useful Life or Service Life: The intended operational lifetime of a device [22] [23].

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