Balancing Substation Design Service Life to Meet Changing Service Conditions and Maximize Useful Life

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***Abstract*—Protective relay development teams focus on making devices smaller, less expensive, more durable, and less complicated while also making protection faster and more accurate, which reduces cost and supports new power system requirements. Utilities do not want to use precious resources to replace relays in perfectly good condition, but they understand that there is also value in enhancing the functionality of their systems with these innovations.**

IEEE defines the design life of a substation as "the time during which satisfactory substation performance can be expected for a specific set of service conditions, based on component selection and applications" [1]. Where service stability and unchanging applications are preferred, device useful life—based on availability metrics, including mean time between failures (MTBF)—is a helpful predictor of system durability service life. Substation protection system designs for stable, unchanging service conditions, built with long-lasting devices and components, often have a durability service life of 25 to 30 years. From a business planning perspective, the business service life of a design informs a utility how to depreciate the asset, plan operations and maintenance (O&M) expenses for its business service life, and plan capital expenses for replacement.

This useful durable service life is shortened only if the business needs require product replacement to meet new service requirements unmet by the previous design. As an example, technical advancements in process bus signal exchange methods produce new features every few years, including MIRRORED BITS® communications, Utility Communications Architecture (UCA) Generic Object-Oriented Substation Event (GOOSE), IEEE C37.118 synchrophasors, IEC 61158 EtherCAT®1, IEC 61850 GOOSE, IEC 61850-9-2 LE Sampled Values, time-domain technology messaging, and IEC 61869 Sampled Values. If the substation design were modified to incorporate each new method, the design itself would have a brief service life of only a few years, even though the components have a 25- to 30-year service life.

Adding the latest technology to designs for new and existing systems may help utilities adapt to new objectives and requirements, such as adopting Ethernet messages on shared bandwidth links in parallel with, or instead of, time-division multiplexed direct messaging on private bandwidth links to publish protection signals. Service resiliency and the ability to react to changing customer demands may create the need to change protection and control (P&C) system designs to add Ethernet. When the technical design is driven by financial and other benefits associated with technical advancements to devices and applications, the business service life of the system may be shorter than the durability service life.

This paper introduces metrics and methods to support utilities as they plan to capitalize on the benefits of advancements in protective relay technology and upgrade system designs as well as plan for O&M expenses and capital expenses for replacement and maximize useful life.

I. Introduction

There are multiple compelling business reasons for updating digital protective relays in the power system protection and control (P&C) design. The first, obvious reason is focused on the reliability of the relays and other programmable electronic devices in service and how that reliability corresponds to the overall reliability of the power system.

Another reason driving the decision to enhance P&C designs with different digital protective relays is to increase functionality. Every year brings substantial improvements in relay functionality, including faster operations, improved communications, better diagnostics, higher-quality fault resolution, and additional automation elements and security included in the relay.

Several business requirements prompt the decisions to update protective relays outside of a purely maintenance perspective. Maintenance costs are recovered in a significantly different process than capital expenditures (CAPEX). Executing system upgrades using capital funding provides a better return on investment for both the utility and the customer through system improvements.

A reasonable approach to update relays is to replace equipment toward the end of its useful life, but before it begins to become a reliability issue. These replacement programs transfer the costs from operating expenses (OPEX) to CAPEX by executing the work of replacement on a planned and scheduled timetable. The challenge is to identify when an asset has reached the end of its useful life.

The duration of time that a device used for protection, control, and metering remains functional and serves the purpose for which it was intended ends when any of the following situations is reached, according to the IEEE Power & Energy Society:

> 1. The device is no longer able to perform as per its design specification when first installed and it is not possible to repair it.
>
> 2. The device is no longer under warranty and the cost of repair outweighs the benefits of a newer device.

3. The device is no longer useful and no longer meets present functional requirements [2].

Service life based on usefulness is the lifespan used to predict when it is safe to rely on the product and is therefore related to reliability and product robustness. Emergency repair requests and unintended outages are recorded and compared to the overall installation base versus number of failures to calculate a mean time between failures (MTBF). Manufacturing, quality, support, design, and testing can significantly affect the useful life of a relay. Some digital protective relays are ready for replacement within only a couple of years from installation, as demonstrated by high failure rates [3].

Well-designed, well-constructed, and well-supported digital relays have not shown exponentially growing failure rates, even when they are in service for 20 years or more. Although all electronics have a useful life, many digital protective relays are still functioning with low failure rates. A simple asset tracking system will quickly identify equipment with high failure rates. Justifying these replacements is straightforward [4].

Information about device reliability and durability may be expressed as MTBF. The MTBF reflects the reliability lifespan and is different from the service life or useful life [5].

Service life can have many definitions. Financial calculations use depreciation schedules to match an asset's planned service life. The term "depreciation" refers to an accounting method used to allocate the cost of a tangible or physical asset over its service life or life expectancy. Depreciation represents how much of an asset's value has been used. Depreciating assets helps companies earn revenue from an asset while expensing a portion of its cost each year the asset is in use. Not accounting for depreciation can greatly affect a company's profits.

Often, an asset has reached the end of its service life while it is still adequately performing its original function and has a continued useful life. The authors observe in their own workplace that desktop computers tend to be replaced every 5 to 8 years. Laptop computers are typically replaced every 3 to 5 years. On average, cell phones are replaced between 11 and 18 months. Arguably, these devices are still functioning at the speed and performance levels they originally operated at when they were purchased. Larger software demands and increased functionality requirements drive the need for faster processors and more memory, pushing older hardware to the end of its service life more quickly. However, when mobile phones are replaced due to failed components or batteries, it is indicative of the end of their useful life.

Protective relays have seen similar growth in application demands and functional requirements. Electromechanical (EM) relays served the industry well for many years. To increase reliability, lower costs, and improve situational awareness, digital relays replaced their EM predecessors. The advantages of EM replacements have been well-documented in industry technical papers and reliability indices. The replacement of P&C designs that use older digital relays with energy control system (ECS) designs that leverage newer digital relays has a similar justification. Modern protective relays offer more processing power to provide improvements in safety, reliability, functionality, communication, automation, event reporting, asset management, security, and even regulatory compliance.

Increased communication and other systemic improvements or requirements may accelerate the end of the service life of standalone protective relays, even when they are functioning properly and remain useful. Additionally, changes in ECSs like renewables and energy storage can drive the need to replace older P&C installations with newer intercommunicating protective relays and acting as the digital secondary system (DSS) within the ECS. In addition to new communications capabilities, other enhanced functionality in newer protective relays can improve engineering design times, reduce maintenance time and costs, and provide better system-wide coordination. Programs to regularly replace programmable electronic devices across the entire ECS, including protective relays, may be the most cost-effective and profitable way to manage these assets. This uses capital to renew the service life of the protection system and uses the protective relays in the ECS while depreciating previously updated parts of the system. Periodic replacement programs, in which an entire fleet of intelligent electronic devices (IEDs), or systems of meters, relays, remote terminal units (RTUs), and fault recorders are all considered at the end of their service life and replaced simultaneously, often have financial benefits to the utility even though the relays may be far from the end of their useful life. This is frequently confirmed when microprocessor devices are removed from service based on operational decisions by electric utilities and are resold through the General Services Administration and eBay auctions based on their remaining useful life.

One strategy to understand the increased value of new standalone relays is to align required testing with relay maintenance activities in order to plan a periodic cycle of in-depth testing and evaluation, which will work in concert with a replacement cycle to replace in-service standalone relays with newer relays installed as standalone [6]. Matching a replacement program to the in-depth testing cycle could help optimize capital to extend useful life. This strategy would minimize maintenance costs by replacing some of the more costly maintenance testing on existing relays and, instead, performing the required tests when a replacement relay is commissioned. For example, if scheduled maintenance testing is set at six-year intervals, perform the maintenance testing at Year Six, but plan and schedule replacement at Year Twelve. This reduces the maintenance work and cost by 50 percent, transferring the costs to the capital replacement program. These CAPEX can be justified by taking advantage of the improvements mentioned above. Fig. 1 provides an example function evaluation chart to help justify the need for standalone relay replacements.

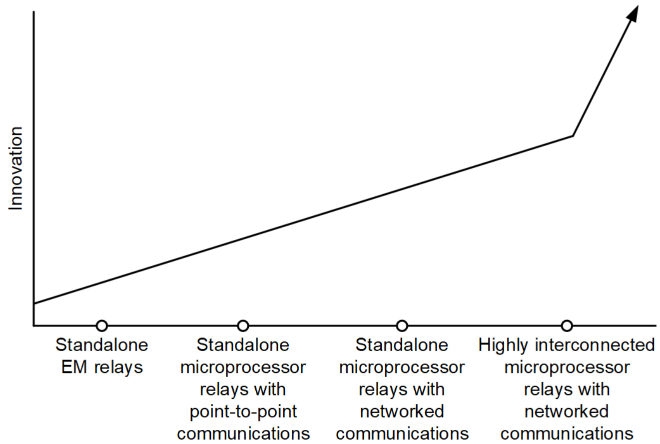

Fig. 1. Innovation enabled by technical advances to protective relays.

A. System Upgrade

Advancements in protective relays provide multiple advantages, as mentioned above. Taking the next technological step includes a system approach rather than a unit-for-unit replacement of standalone installations. The individual improvements from upgrading single relays can be amplified by upgrading with the end goal of building a system. Approaching protection system upgrade paths with a system view in concert with an ECS upgrade enables both the advantages of new, individual relays and the ECS improvements provided by advanced system-wide protection, control, and automation. Single relay events can easily be time- or location-coordinated with other events on the power system. Individual protection decisions can be linked to other current operating parameters for a system protection approach. Proper security actions can be implemented at the appropriate level instead of at every level of the system. Protection settings can accurately protect the system through various power flow configurations. Distributed energy resources applied throughout the distribution systems can be accounted for dynamically through a system-wide upgrade approach. System visibility can be improved by bringing the new, high-resolution system measurements that are missed by older, low-resolution systems. Events like breaker re-strike, system oscillation, and microfaults can now be identified and resolved.

As illustrated in Fig. 1, each advance in relay technology has enabled innovation within the P&C system. Systemic innovation comes largely from the distributed logic and decision-making enabled by communications. After standalone microprocessor relays began replacing EM counterparts, their programmability was quickly exploited for expected and unexpected innovations. Next, point-to-point supervisory control and data acquisition (SCADA) protocols and process bus protocols, including MIRRORED BITS communications and digitized thermal signals, created opportunities for innovative interlocking, asset management, and RTU replacement via interconnected distributed devices. The addition of networked communications to microprocessor relays enabled even more distributed innovation, while also introducing cyber risks to be mitigated. And finally, newer systems of highly interconnected programmable protective relays and controllers have created a platform for highly accelerating innovation in P&C and ECS designs.

B. End-of-Useful-Life Evaluation Matrix

Fig. 2 provides some evaluation criteria to help determine if the P&C have reached the end of their service life. Scores are determined with the best conditions scoring low and the poorest conditions scoring higher. The chart does not produce an absolute score indicating a replace or keep decision but is intended to help the evaluator make determinations on conditions beyond the simple failure rate of P&C devices. Weighting factors can also be applied to emphasize categories that have higher or lower implications on the power system under evaluation. Even application of the evaluation across the power system can aid in the determinization of the highest priority needs for upgrades.

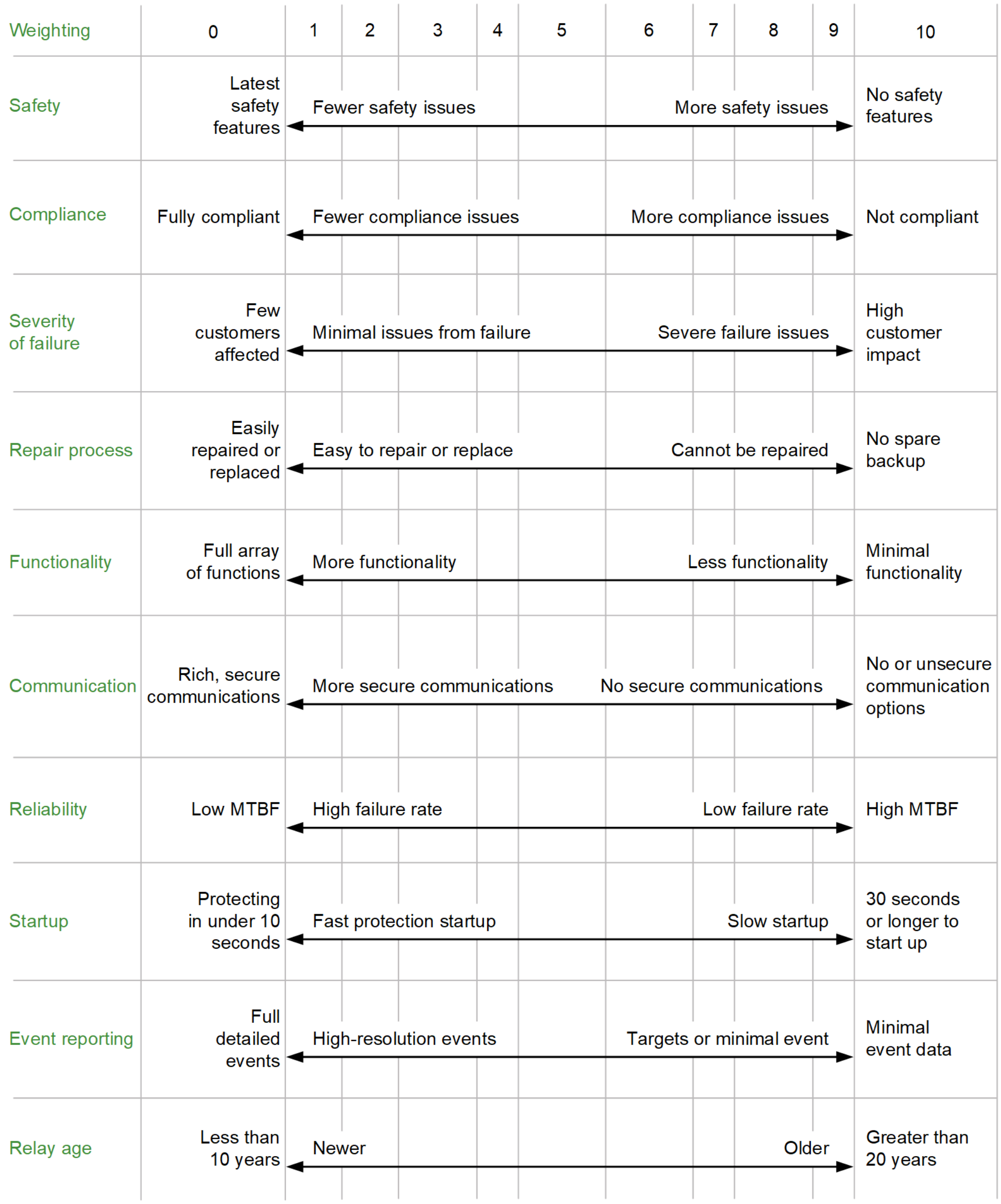

Fig. 2. This evaluation matrix can help assess priorities for replacement.

II. Example Benefits of a P&C Enhancement Program

As was true at a large Southeastern utility in 2001, ECS systems including P&C enhancement via the interconnection of programmable relays are often used in new stations [7]. Utilities often adopt a new P&C design and begin using it as part of the utility build out of the power system. Exceptions include station rebuilds where wholesale replacement of the ECS makes sense along with the primary system upgrade, replacement of EM relays, and systems where early programmable P&C are inadequate. Utilities often install early technical advances in important substations, and enhancements may be scheduled to improve these stations prior to the end of P&C service life. As was reported by the utility at the time, the relay upgrade project enhanced the performance of the utility through better availability and an automated data collection infrastructure. Engineers were quickly able to determine and document operations and events and improve power quality, voltage load profiling and voltage surveillance. Power factor monitoring, energy metering, and interval demand metering are additional benefits.

> Each new "drop-in control house" provides shareholder value through lowering the capital requirements for protection and control upgrades, retrofits, and new installations. Additional value is realized through real-time performance monitoring of substation assets; this allows operating these assets at higher ratings while maintaining safe limits. By operating the assets with confidence at these higher ratings, a delay or cancellation of major capital additions and substation rebuilds can be realized. As [the utility's] protective and

> control infrastructure ages and becomes obsolete, this integrated solution becomes the most attractive and cost effective approach for replacement programs. [7]

More recently, technical enhancement concerns were illustrated by the Western Area Power Administration (WAPA) publication *Customer Circuit*. In the publication, Calae Runge, an information technology specialist for policy and planning, states “We have to get everyone to realize what technology is, and how much is out there” [8].

Reference [8] also describes how, like most utilities, WAPA’s technical inventory includes everything from PCs and tablets to programmable microprocessor-based relays. To meet Federal Information Technology Acquisition Reform Act requirements and other mandates, WAPA is consolidating reporting for all their technology. They report how much they spend and how they can support multiple functional requirements with IT and protection system digital equipment.

Reference [8] explains, “The telecommunication equipment and relays installed at many WAPA substations have a technology component that allows them to communicate with other systems.” Chris Meyers, supervisory electrical engineer, is quoted as stating, “Anything with a microprocessor is subject to reporting… We now have to take supply chain risk into account for our purchases and have IT sign off on relays” [8].

In concert, WAPA recently updated their Electric Power Training Center (EPTC) and its miniature power system to make it better reflect the P&C in their transmission system and support training related to operations of the bulk electric system. The outdated EPTC equipment represented former substation P&C designs that are being phased out by WAPA. The new system also permits the evaluation of new cybersecurity issues [9].

In a WAPA news release [9], Joseph Liberatore, electrical engineer, describes “the removal of older technology to showcase variants of WAPA’s Digital Control System standard” and how “an automation controller has been added to further expose students to modern substation configurations.” The new ECS design, based on microprocessor relays, supports staging and testing WAPA’s current standard and possible future designs [9].

III. Rapid Pace of Change of Technology

Technology adoption is affecting the world, and statistics that show how fast technology is growing include:

- It is predicted that there will be 50 billion devices worldwide that are connected to the Internet of Things (IoT) by 2030 [10].
- Tech startups number over 1.35 million [11].

Technology adoption is affecting employees’ private and work lives, as illustrated below.

- Internet growth: As of March 2021, over 5 billion people use the internet, which constitutes 65.6 percent of the global population [12].
- Artificial intelligence (AI) growth: By 2025, the AI market across the globe is expected to reach $89.8 million [13].
- IoT growth
  - The IoT’s revenue opportunity is estimated to be $3 trillion by 2025 [14].
  - Global technology spending on the IoT is predicted to reach a compound annual growth rate (CAGR) of 13.6 percent between the 2017 to 2022 prediction period [15].
  - By 2023, it is forecast that there will be 3.5 billion cellular IoT connections. A 30 percent CAGR is predicted between 2017 and 2023 [16].
  - It was expected that the adoption of IoT services and devices in 2019 would reach an inflection point of 18 to 20 percent [15].
- Cybersecurity concerns
  - In January 2019, 1,170,983,728 user records were leaked [17].
  - A 2018 report found that Microsoft Office applications were the most common group of malicious file extensions, at 38 percent [18].
  - A report determined that 48 percent of data breaches are caused by malicious or criminal attacks [19].
  - Every second, 56 data records are compromised worldwide [20].
  - Over 6 billion records were stolen in the United States between 2013 and 2020. That means 64 percent of the records stolen worldwide occurred in the United States [20].
- Solar power predictions
  - By 2040, renewable energy is estimated to increase by 400 percent [21].
  - A solar project was installed every 100 seconds throughout the United States in 2018 [22].
  - In the last 10 years, adoption of solar energy has grown around 50 percent [23].
  - In 2019, the U.S. added 5,637 MW of utility-scale solar generating capacity, which increased by 77.8 percent the following year [24].
  - The Energy Information Administration forecasts an increase of 21.5 GW of utility-scale solar generating capacity and 7.6 GW of wind capacity in 2022. This increase in solar capacity will outpace the 15.5 GW addition of solar capacity in 2021 [25].

All this technology adoption may lead to a truncated substation service life in order to adopt new technology to improve the ECS and attract and retain technical staff to design, install, and service the newer technology.

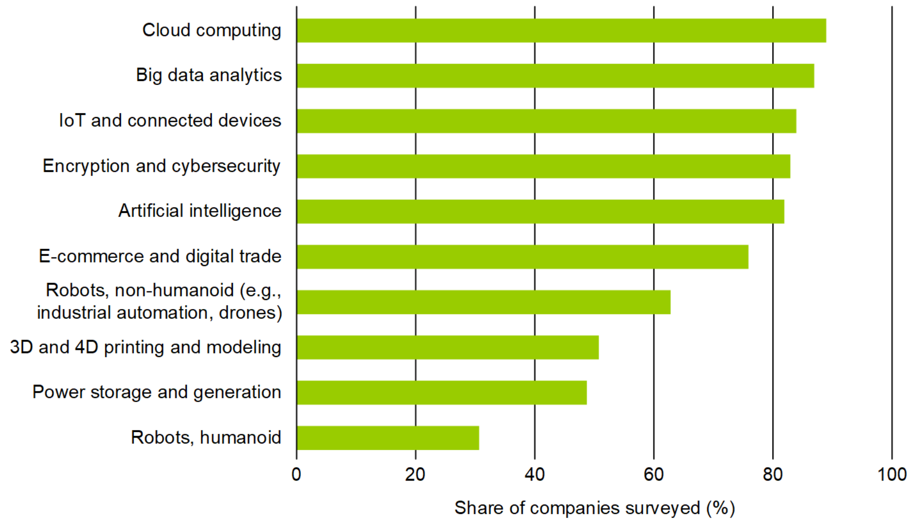

Fig. 3. Technologies that will likely be adopted by companies by 2025, according to the companies surveyed [26].

IV. P&C Skills Changes and Shortage

The interests and skill sets of individuals available to work on P&C and substation designs change constantly, which is not the case for much of the available global workforce. In addition to new technologies likely to be adopted, as shown in Fig. 3, the World Economic Forum's "The Future of Jobs Report 2020" states that certain roles are appearing in particular industries, such as renewable energy engineers within the energy sector. "The nature of these roles reflects the trajectory towards areas of innovation and growth across multiple industries" [26].

This means that necessary skills are no longer hard (measurable and teachable abilities) and soft (attentive, good listener, ability to get along with others) but rather they are either durable or perishable [27]. Perishable skills (diminishing in value due to association with aging and obsolete methods) must be replaced when they have no remaining business value, while durable skills (creativity, critical thinking, and collaboration) remain useful for long periods of time. Even with the use of digital communications in substation designs, the skills to understand and hardwire instrumentation and control (I&C) to the primary equipment are durable, not perishable. Skills to understand and apply first principles of protection signal transfer via digital methods are durable. However, as the best-known methods (BKMs) change with technology, the skills associated with specific methods, tools, and suppliers are perishable. For example, the need to decode Modbus Plus protocol, install a terminating resistor at the end of the IRIG-B coaxial cable run, and analyze serial data with an oscilloscope has perished.

Present BKMs may also perish, but many durable skills that the present workforce requires are not related to a specific technology but rather a base layer of understanding and mindsets. "These skills aren't just 'ways of thinking'; they are tangible, teachable and measurable. They include skills like design thinking, project management practices, effective communication, and leading others" [27].

The technical lifespan based on rapid change, shorter than a reliability lifespan, does not maximize the product purchase and installation investment but may reflect the desire to add functions, increase accuracy, include new technology like traveling wave, arc flash, Arc Sense™ technology, or energy packets with better communication options, faster processing, higher-resolution displays, and easier testing and commissioning.

Digitization is affecting people and the skills shortage that industries face today. Updating designs and training by adding durable skills empowers employees to be more satisfied and make dynamic, longer-term contributions to an organization.

V. Device and System Design Lifespans

The IEEE Std 525 *Guide for the Design and Installation of Cable Systems* in Substations stresses dependable electrical safety and service throughout a substation's design life. It defines the design life of a substation as "the time during which satisfactory substation performance can be expected for a specific set of service conditions, based on component selection and applications" [1]. Satisfactory performance, as the driving force to determine design life, differs both from utility to utility and from time to time.

A. *Satisfactory and Unsatisfactory Performance Due to New Requirements*

For example, a P&C design lifespan may end when desired features in programmable relays change as the utility innovates with existing features and as new features become available in the relays. For utilities with a mission unchanged by new technology or service requests, stable and unchanging substation applications are best-served by long design lifespans based on appropriately high-quality devices. This provides business continuity by using static designs, well-known programmable devices and software tools, and well-understood technical requirements for field service teams.

The ISO 22300 *Security and Resilience – Vocabulary* standard defines business continuity as "the capability of an organization to continue the delivery of products or services at acceptable predefined levels following a disruption" [28]. A disruption can include the retirement of a champion utility ECS design employee who did not share their knowledge with other employees, unforeseen requirements to add renewables, or new legislation forcing a utility to make drastic changes to substations. Business continuity, in this case, means that the performance of the substation design remains satisfactory, substation service life remains unchanged because the utility anticipated such changes, and the relay design remains adequate for business as usual.

The ISO 22316 *Security and Resilience – Organizational Resilience – Principles and Attributes* standard defines organizational resilience as "the ability of an organization to absorb and adapt in a changing environment to enable it to deliver its objectives and to survive and prosper" [29]. The Internet Technology Information Library is a set of best practice processes for delivering IT services to a utility organization, and therefore its customers [30]. IT departments often define resilience as the ability of an organization to anticipate, prepare for, respond to, and adapt to both incremental changes and sudden disruptions from an external perspective. In both cases, business resilience means that when a disruption occurs that causes the substation performance to no longer be satisfactory, the design must change to support the new service requirements. For example, in a standalone design, using programmable relays that also have features within them to migrate to a networked design offers business resilience. Even though the substation design performance is enhanced with systemic communications, the utility uses the same relays, software, and field service technologies. The P&C and field technical staff are resilient and nimble, executing new designs or additions to existing products as the P&C evolves to meet changing customer demands and needs.

In the event that the relays presently in use are not capable of meeting the new design changes, the P&C design is not resilient and may need to be enhanced or replaced.

Another concept of business resilience, related to business continuity, is the ability of the P&C system to enhance the utility's ability to react to other challenges. For example, relays that satisfy substation performance and do not include internet commerce secrecy technology, like Transport Layer Security (TLS) cryptographic technology, may help the utility to fend off internet-enabled attacks that exploit vulnerabilities in such technologies. A system design based on privacy rather than secrecy also provides better performance by avoiding frequent field updates to relay firmware and associated supply chain risks, as TLS secrecy methods change.

B. Satisfactory and Unsatisfactory Performance Due to Poor Quality

The paper "Durability and Reliability, Alternative Approaches to Assessment of Component Performance Over Time" explains the idea that reliability in constructed buildings or systems is often called durability [5]. Reliability is quality over time, or the probability that a device will function as intended without failure for a specific period of time. Durability is long-term reliability, or the ability of a device to perform reliably when needed over a long period of time. For programmable electronic devices this means both hardware and software must function reliably and, specifically for microprocessor relays, this means they must work continuously, 24 hours a day, 7 days a week.

Product reliability represents product quality and is a performance indicator used to assess the required durability of each programmable electronic device within a system. With respect to the IEEE 525 "specific set of service conditions, based on component selection" [1], it is important to understand the need for similar durability and reliability of all of the programmable electronic devices in a system.

Reliability, related to product success or failure in service, is sufficient if the suppliers of relays and other programmable devices provide adequate product reliability.

> Manufacturers of mechanical and electrical components investigate their product's reliability, and even demonstrate expected failure rates. They recognise the need to supply data in order to allow the assessment of confidence for life cycle cost estimates [5].

Durability is a qualitative comparison of a product's ability to avoid operational failure in service and does not consider the service lifetime period. Reliability is quantitative and based on the probability that a product will operate as intended for a definable period of time without failure. The failure rate, which is the inverse of MTBF, often changes over the lifespan of devices as they remain in service and may increase with product age, and the only reliable metric is an observed in-service failure rate [31]. Programmable electronic device failures typically follow a bathtub curve, as illustrated in Fig. 4.

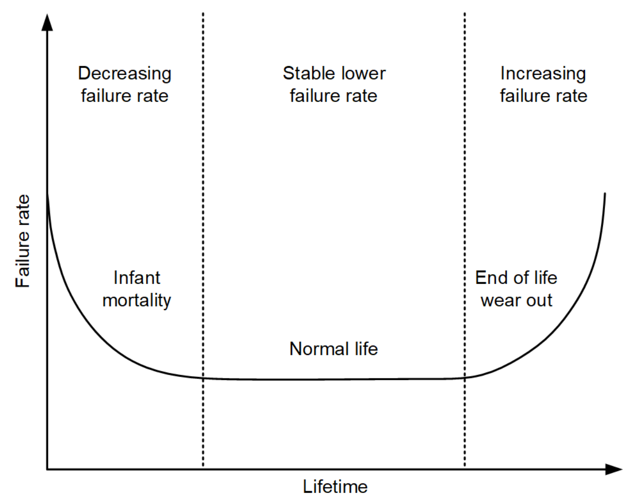

Fig. 4. Representative illustration of change in failure rate over time for programmable electronic devices [31].

During the substation service life, utilities will observe that different device types and suppliers have different in-service failure rates. Based on design and manufacture, some devices will have prolonged normal-useful-life durations with stable, low failure rates. Others may exhibit shorter normal-useful-life spans and experience end-of-life wear-out failure rate earlier than other products. This asymmetric performance-based failure rate lifespan complicates substation service life evaluation based on unsatisfactory performance due to poor quality. Utilities are often forced to consider the least reliable system component as the lowest common denominator. Also, time-based maintenance strategies, required by some reliability compliance organizations, are evolving into time-based system component replacement schedules.

C. Satisfactory and Unsatisfactory Performance Due to Technical Obsolescence

Similar to the perishable nature of skills, which is based on perishable technology that becomes obsolete as best practices change, some technology is perishable by design. TLS is a cryptographic protocol used to provide secrecy for internet-based commerce, buying, and selling, among anonymous people over public networks. The secrecy cannot be made strong enough to last forever because it can only be as strong as the available processing power in the typical home computer that needs to use it, and no stronger. Therefore, it is perishable by nature and becomes degraded as newer, more powerful processors become available and used in the home. Vulnerabilities in cryptographic protocols used by the general public are quickly exploited and weaponized. Also, secrecy methods that are perishable become ineffective and obsolete as more powerful processors become readily available, and they must therefore be replaced [32]. The technical obsolescence lifespan of these internet secrecy methods influences the technical lifespan of the substation designs that use them. Designs or relay firmware need to be updated, which requires the removal of each affected device from service for repair. It is interesting to note that substation designs do not require, and work better without, the features enabled by internet cryptography, including anonymous users, the use of public networks, or secrecy instead of privacy. Rapid and unnecessary technical obsolescence prevents the utility from maximizing the initial product purchase and installation investment in exchange for the use of IT and internet-based cryptography.

D. Sustained Reliability Service Life

Sustainable lifespan uses a product's useful life as the duration for which the probability of failure is sufficiently low. This allows the utility to maximize the initial product purchase and installation investment. Even though it is not deliberate, early field failure of poor-quality products may risk the inability to clear a fault and leave the grid compromised. Suppliers of devices with short sustainable lifespans may also prematurely obsolete devices and choose not to provide repair, upgradeability, and interoperability with other devices. This may make spare parts expensive and create high costs of repair. If a product is of high quality, it not only lengthens the useful life of the product but also increases the availability of the same device during its service life and lengthens the time that the device and system provide satisfactory substation performance.

The cost of an ECS dramatically increases if a protective relay fails after 3 years rather than performing for its useful life of 30 years. This early failure also has nondirect economic losses for consumers, such as reduced safety and performance; increased labor to observe service bulletins, research failures in service, and make claims; and more frequent receiving, installing, and testing of replacements.

Reliability lifespan is also the device safety lifespan. This means that the useful lifespan is the duration of time that it is safe to rely on a device based on the probability of failure. The paper "The Useful Life of Microprocessor-Based Relays: A Data-Driven Approach" illustrates that relays are capable of reliably performing within specification throughout, and well beyond, their expected service life of 20 years. Field data demonstrate that high-quality manufacturing processes using high-quality materials yield microprocessor-based relays with a long useful life [33]. The IEC 61508 *Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems* standard describes methods applicable to evaluate the entire safety life cycle of systems based on programmable electronic devices, from cradle to grave. IEC 61508 promotes device and design evaluation based on risk analysis to plan ways to provide the required risk reduction. Products with lower quality, and subsequent low MTBF, have a shorter safe life [34].

Further, documenting a product's reliability and safety lifespan based on the observed MTBF creates a better understanding of the importance of consuming sustainably and responsibly. Considering product reliability systematically in technical standardization and requirements offers distinct advantages. First, minimum reliability and MTBF as product acceptance criteria extend the lifespan of products and systems by design without limiting innovation. This requirement may act as a deterrent against premature obsolescence and incorrect use of products, such as field installation of devices not tested for it, which may lead to early failures. Second, standardized interfaces within systems allow for better options for field upgrades and repairs of system components.

E. Least-Reliable-Component Service Life

Least reliable lifespan uses the product useful life of the poorest quality device in a system as a proxy for the useful life of the entire system. Although other programmable devices may be much more reliable, the system may be considered at risk based on the probability of failure regarding the shortened useful life of the weakest link. This prevents the utility from maximizing the initial product purchase and installation investment. However, the added expense of premature replacement may prevent an in-service failure and does not rely on asset managers to understand and evaluate redundancy and other design compensations. When choosing programmable electronic devices, ECS and P&C designers need to ask, and be informed about from suppliers, how long devices and designs should last, if used and maintained properly. They should also learn about product ruggedness, such as temperature ratings, and reparability of goods, as well as availability and cost of spare parts. Without such information, designers cannot choose similarly long-lasting and reparable goods to include in a system.

F. Time-Based System Service Life

As mentioned, reliability compliance organizations that require time-based system component maintenance schedules may also define a time-based service life without consideration of a specific design or device MTBF. Utilities that have low-availability devices mixed with high-availability devices, as standalone or interconnected in a system, may rely on a time-based replacement schedule. Similarly, utilities with early generations of standalone microprocessor-based relays from different suppliers that have exceeded their reliability service life, have some with higher failure rates or malfunctions and others that do not but have been in service for their design service life [31]. This method prevents the utility from maximizing the initial product purchase and installation investment in exchange for the simpler time-based replacement strategy.

G. *Expanding the Service Life of Service Conditions*

"New features and communication protocols are being implemented into [relays and other programmable electronic devices] to support the grid modernization initiatives and provide solutions for integration of new generation sources (wind, solar, energy storage, etc.)" [31]. Based on this, even if the substation system continues to provide acceptable performance for the initial design, new requirements may change that. If the existing relays are not capable of performing new substation design requirements with acceptable performance, their service life is concluded, and another service life begins with the new design. This does not mean that in-service systems are inadequate or need to be replaced, but rather, that moving forward, the new design with updated requirements may be used. In fact, some utilities maintain two or three substation designs with different active requirements and choose among them based on the system being built or upgraded. This method prevents the utility from maximizing the initial product purchase and installation investment in exchange for the expanded functionality.

H. *Changing the Service Life of Workforce Service Conditions*

Existing workforce skill and stability degrades as people age out and retire. As mentioned, digitization of substation systems via Ethernet, computers, and software-based applications requires new skills. Efforts to prolong the service life of a technical design may become self-defeating since skill sets of future technicians and engineers are likely to be drastically different in just a few years' time. The pool of candidates for a new workforce has these new skills, and likely not the previous generation of workers' interest in, and awareness of, physical wiring for I&C. Therefore, not only will technology change the design, but the design will also need to change in order to be exciting and attractive to potential new hires. Again, this service life calculation method prevents the utility from maximizing the initial product purchase and installation investment in exchange for the newer design and related technical service methods.

I. *Business Lifespan*

From a business planning perspective, the lifespan of a design informs the utility how to depreciate the asset, plan operations and maintenance (O&M) expenses for its business service life, and then plan capital expenses for its replacement. As mentioned previously, the business service life may be a subset of the system's actual time in service, may encourage replacement while designs are still satisfying required substation design performance, and may be much shorter than the reliability-based service life.

VI. Deciding to Replace In-Service Devices and Designs

Digital P&C devices should be designed for an expected durability lifespan of 25 to 30 years and for field upgradeability when the technical system design service lifespan is shorter. Therefore, the time duration that field firmware upgrades are available must be the same across the entire fleet so that devices do not become unable to receive field upgrades and become incompatible with other devices. Also, P&C devices need to be built to fail infrequently but be repaired or replaced quickly if they do fail. This is referred to as plug-and-play, and it enables faster replacements when needed.

Designs need to support short mean time to detect failure based on internal diagnostic self-announcement of alarms and short mean repair times, as mentioned in IEC 61850 and IEC 60870 *Telecontrol Equipment and Systems*. If a repair cannot be carried out successfully in the field, durability and reliability is improved when manufacturers and suppliers provide diagnostic and repair support. Record-keeping in microprocessor devices dramatically improves troubleshooting and diagnostics over EM counterparts.

The decisions made regarding when and why to replace products should be left to the utility and not dictated by premature field failures. Even though it is essential to maintain safety by replacing field failures, high failure rates and low durability metrics should not be the primary reasons that end users choose to replace devices. Enhancement strategies are best designed to improve business performance, and the utility is best served when relay reliability service life is longer than any other service life duration.

The logic of frequent changes in IoT, the cloud, and the edge based on IEC 62443-4, *Security for Industrial Automation and Control Systems,* and frequent secrecy and key-exchange methods in cybersecurity drive some suppliers to design something, manufacture it at the lowest possible cost, sell it at the highest possible margin, and move on. However, in the mission-critical work of infrastructure defense, durability drives longer useful life, and the intended and unintended consequences of changes must be well-understood [32].

VII. P&C Design and Field Service Processes' Lifespan

Best practice to monitor in-service designs for durability after a system technical design life is ended depends on the component durability lifespans and may include either upgrade or, potentially, replacement of the system. For example, one manufacturer might support devices for extended periods of time, and another manufacturer might plan product lifespan to last for only 10 years. At the end of that period, that manufacturer may stop issuing new features, security updates, and technical support. Lack of technical and warranty support may prompt replacement while continued technical and warranty support will support upgrade and longer service life of the original system.

In order to support system lifespan decision-making, manufacturers should both communicate new feature field upgrade availability, and detect service or security issues and communicate them via service bulletins. Some manufacturers do not communicate, but regardless of how utilities learn about issues, in order to respond promptly, utilities must know exactly which devices they have, where those devices are, and how to plan for upgrade or replacement.

Perhaps a company chooses to keep devices from a specific manufacturer for much longer than they would keep devices from another manufacturer with less reliable devices, but it is understood that there are risks associated with using unsupported and potentially vulnerable devices and software from a manufacturer. In order to know the best path, develop a best practice for monitoring old devices in service regardless of their intended lifespans including:

- Implementing active and accurate inventory monitoring.
- Tracking risks and preparing to adapt.
- Choosing devices to upgrade and to obsolete.
- Planning upgrades to coincide with feature need and maintenance cycles.
- Planning replacements of obsolete devices proactively and responsibly.
- Creating a decommissioning procedure checklist.

VIII. Planning CAPEX for a P&C Design Upgrade

Substation designs using enhanced microprocessor relay features can significantly reduce future O&M costs. Standardization of equipment, panel layout, communication needs, and power needs can reduce complexity, training, and the number of spare parts. Developing a program for replacing depreciated equipment can keep P&C systems up-to-date with technology designed for the newest challenges. When required, setting up a full-time replacement program, in addition to a design enhancement program, can reduce multiple upgrade challenges. These are some considerations:

1. Designated resources are used to implement the upgrade projects, making use of experience gained on each upgrade.
2. Lessons learned early in the program mean the same problem is not repeatedly experienced, reducing costs.
3. Necessary tools and testing processes can be tailored to fit the upgrade program equipment and move from station to station.
4. Completed upgrade projects have the same look and feel, increasing the familiarity for workers.
5. The most up-to-date firmware and security applications can be applied.
6. Full useful life can be used and depreciated on schedule.
7. Capital budgeting can be set with relative certainty based on previous project history.
8. Liability can be reduced with faster protection, communication, and remote access by implementing safety enhancements like arc-flash detection, downed conductor identification, and incipient fault detection.

Regulated utilities are controlled by a governing body that monitors the costs to deliver electricity and the price that utilities can charge customers. The utility is expected to earn a reasonable profit that provides a return to its investors in exchange for their capital investment in the utility.

Below is the basic formula used by the regulatory commission.

Revenue requirement = expenses + (rate base • cost of capital)

Revenue requirement is the money needed to cover costs, including a fair return to investors. The calculated revenue requirement is compared to the revenue at existing rates to decide if a base rate increase or decrease is needed.

OPEX includes operating and maintenance costs, depreciation and amortization on assets, income, and general tax expenses.

Rate base, representing investor-supplied capital, is made up of plants in service (net of depreciation to date) and working capital, less deferred income tax, and other miscellaneous adjustments.

CAPEX includes the cost of debt, or the average interest rate paid on outstanding debt. It also includes the cost of equity – the return an investor expects to receive when they buy stock. That return includes dividends and growth in stock value.

Typically, utilities do not earn a return on OPEX. The intent is to provide no incentives to drive up OPEX costs, thereby keeping prices low for the consumers.

To attract investors, CAPEX must include a reasonable return on investment, and it must be a justifiable investment to improve safety, reduce OPEX, improve reliability, or meet other requirements as stipulated by the regulating authority.

Relay replacements impact both CAPEX and OPEX through either capital expenditures or maintenance costs.

Utilities that operate protective relays until failure absorb the cost of these replacements in OPEX. These costs are multiplied by impacting customer power sales, reduced customer satisfaction, higher emergency repair costs, and reduced reliability. Many utilities' rate base includes evaluation criteria that monitor impacts on customer service. As shown in the System Average Interruption Duration Index (SAIDI) graph in Fig. 5, there are many causes that can affect customer outages. Other common measurements of system reliability include System Average Interruption Frequency Index (SAIFI), Customer Average Interruption Duration Index, and Customer Average Interruption Frequency Index. Replacing relays before they fail can have a positive impact on these reliability numbers.

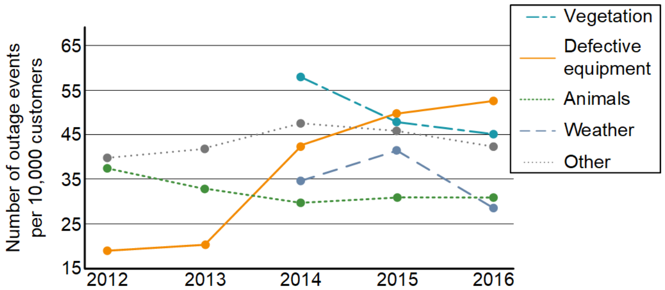

Fig. 5. Example SAIDI graph [35].

By updating the protective relays on a system as new as 5 years old, utilities can still meet the criteria for CAPEX based on recent relay improvements and required security and functional improvements. Properly documenting reduced maintenance costs (reduced testing) and improved customer indices such as SAIDI and SAIFI can provide support for rate case adjustments.

IX. Utility Perspectives on Planning CAPEX for P&C Design Upgrade

A. Dominion Energy (Author Perspective)

At Dominion Energy, power system P&C have continuously improved since the distribution grid was connected. From the early days of fuses to EM protective devices to digital relays, each step has seen an improvement in protection, reliability, and safety. The next steps in the power system evolution include a P&C system approach rather than discrete relays acting independently. These systems are not the final step but a beginning of new levels of innovation.

With respect to service life, Dominion recognizes that the useful life of their in-service microprocessor relays is far from over. They have built a laboratory to test new firmware and logic designs and have a robust field service process. However, at Dominion and elsewhere, skilled engineers are aging out and retiring, and it takes three years to train relay technicians in-house.

Today, when Dominion interviews entry-level engineers and technicians, they hear that new candidates do not want to learn or spend time on traditional analog hardwiring and physical electrical wiring operational technology (OT). New technologists are looking for exciting careers working on digital OT, modern high-speed communications, and digitization of I&C and P&C. Dominion collaborated with other utilities to create new DSS designs and learned about the utilities' new data communications and protection standards, specifically how they reorganized staff and created new divisions, like substation network communications, to match the new technologies. Dominion needs to carefully design their digital transformation because each new standard and each new installation needs to be in service for 40 years. At the same time, Dominion employees want to create careers and showcase the new P&C as a glamorous and cool career. They will need to create processes that support the new workforce diversity. The utility needs to and wants to go digital with a digital transformation of their P&C and DSSs.

Dominion is not dissatisfied with their installed base of microprocessor relays because the prolonged useful life means few field failures and satisfactory service conditions. What prompted employees at Dominion to pursue an enhancement strategy and DSSs is not dissatisfaction with the previous design, but excitement about the opportunities that a newer digital design brings. They think that their margin for innovation is in Dominion's capital expansion and investment in DSS. Dominion is focusing new relay designs on new substations and greenfield installations. In fact, the growth in new Dominion substations and DSS, year over year, represents an increase of 50 percent. Dominion feels that digital modularity is the key to increase cost and resource efficiency and effectivity. They are planning to leverage fiber optic connections among distributed programmable electronic devices. The utility can create innovation by better leveraging the multifunction nature of the devices. Over time, this will create a smaller O&M need with smaller enclosures, fewer personnel, and better data acquisition. Certain Dominion employees are part of a digital evolution that is carefully and thoroughly adopting digital technologies that in turn enable digital revolution or enable the employees to create solutions previously not considered.

The Dominion grid transformation plan, focused on modernizing the distribution grid, has been approved and includes DSS enhancements using IEC 61850. Dominion plans to share their results and promote the benefits of DSS to innovate new advanced solutions.

A justification for the digital transformation at Dominion is the increased reliability of the power system via the increased access to information about the primary equipment from the interconnected microprocessor relays.

In the future, there could be a lot of change in their power generation and future customer requirements. DSS deployment and relay enhancement will make them nimble and flexible in creating new solutions rapidly and prepare them to leverage the skill sets of new recruits from area schools.

B. Commonwealth Edison Company (Author Perspective)

A 2021 news release from ComEd said the company is increasing the price of electricity distribution charges by $51 million to continue providing better reliability of the electric grid while confronting more regular, extreme storms. This will raise a customer's average monthly bill by 20 cents [36].

In that news release, ComEd also stated that they believe that the power grid needs to be able to withstand extreme storms and to be dependable as they add more renewable energy to it because of the impacts to the grid and to customers. California and Texas both experienced recent grid failures due to severe weather. After a long-lasting thunderstorm as well as 13 tornadoes last August, ComEd was able to restore power to over 500,000 customers in the span of a day. If the company had not made smart grid investments, two times as many interruptions would have occurred because of the thunderstorm. Instead of restoring power in 24 hours, it would have taken ComEd two weeks [36].

ComEd has four active digital smart substation design standards that they deploy in stations based on the substation design applications and requirements.

The four digital smart substation versions for ComEd are listed as follows:

- A (Basic) – Includes microprocessor relays, serial SCADA and engineering access communications, and MIRRORED BITS communications. Time synchronization via IRIG-B with hardwire (HW) connections between physical contacts for tripping.
- B (Generation 1) – Includes microprocessor relays, Internet Protocol (IP) station bus SCADA and engineering access communications, MIRRORED BITS communications, and limited GOOSE. Time synchronization via Precision Time Protocol (PTP) with HW tripping.
- C (Generation 2) – Includes microprocessor relays, IP station bus SCADA and engineering access communications, and GOOSE. Time synchronization via PTP with GOOSE tripping.
- D (Generation 3) – Includes microprocessor relays, IP station bus SCADA and engineering access communications, and GOOSE. Time synchronization via PTP with GOOSE tripping. Also, this design includes digital process bus with IEC 61850 Sampled Values and time-domain messaging for power system analog values.

The utility chooses between these four design standards at new substations and those undergoing a wholesale retrofit where they need to reduce the size of the ECS and increase functionality. Their installed base of microprocessor relays is serving them well, and their high reliability allows ComEd to leave the relays in service as they focus their resources on other enhancement plans.

ComEd explains that there is a small cost increase due to the additional Ethernet communications equipment. However, the increased benefits of supervising all protection signal and SCADA communications justify the additional cost. ComEd also uses information available within the relays and collected by the system to (1) automate situational awareness and (2) reduce predictive maintenance and replace it with performance-based maintenance. They are nearing the point where coordinating data collection with the present grid state and measurements during operations is enabled by thorough software-based asset management. This virtually eliminates periodic maintenance and dramatically reduces field maintenance practices.

ComEd presently tests all wiring and DC circuits, injects test currents and voltages into every relay, and tests trip circuit and instrument transformers every three years in traditionally wired systems. They now use new digital systems to supervise these measurements while the system is in service and during operations. The only scheduled testing is a simple trip-and-close test during off hours on the three-year cycle. The more comprehensive field wiring testing is pushed out to every ten years, and maintenance of supervised signals may be even further reduced.

SCADA operation benefits from signal supervision as well by providing increased confidence to the operators that communications are functional and the operational values in the SCADA display are accurate.

It may be statistically unlikely, but power system problems, including the August 14, 2003, Northeast blackout, have been caused, or made worse, by undetected failures in data acquisition systems.

> At 3:05 p.m., when the first power-line failure occurred at FirstEnergy, system operators did not receive alarm notifications because of the malfunctioning [alarm and event processing routine] AEPR software. That software continued to malfunction until 3:42 p.m., when the lights at FirstEnergy's control facility flickered and alerted engineers to the larger problem. It was only then that an operator noticed the problem with the AEPR software [37].

At ComEd, personnel safety is improved, and the SCADA operations are better informed with the vast amount of new information about both the power system and P&C system. With that, it becomes important to monitor, detect, alarm, and automatically correct communications issues.

Presently, based on useful life and safety service life, ComEd still plans a 20-year service life for their four present design standards.

X. CONCLUSION

It is a challenge to identify when an asset has reached the end of its useful life, especially for programmable electronic devices used for protection, metering, and control. As mentioned, the IEEE defines the design life of a substation as "the time during which satisfactory substation performance can be expected for a specific set of service conditions, based on component selection and applications" [1]. Design life is influenced by satisfaction with its performance. The type of performance that is most relevant and important changes over time and among utilities.

The end of the useful life, described as when the device is not satisfying functional performance, is no longer useful due to failures, or no longer meets present functional requirements, is dramatically different among suppliers. Unfortunately, utilities often must use the useful lifespan of the least robust device as a proxy for the useful life of a fleet of programmable electronic devices to schedule replacement prior to field failure. There may be financial benefits to replacing an entire group of similar devices periodically, regardless of the performance of each individual device. This is sometimes extended to a system of dissimilar devices (fault recorders, RTUs, meters, and relays) all installed at the same time as part of a system. In these cases, the useful life of each individual device, though important, is not as important when considering replacement as financial, operational, and compliance benefits.

There are many considerations beyond useful life performance and failure rates for justifying a replacement or a replacement program. The changes to the grid and the demands of the new applications can drive a relay or system from satisfactory performance to unsatisfactory performance because of a lack of security, communication, safety, or functionality and include:

- Satisfactory and unsatisfactory functional device performance, leading to end of relay useful life. Although electronics do have a physical useful life, when used within purpose-built relays well within operational margins upon circuit boards designed to reduce stress, they may not experience high rates of failure even after 20 years in service. Not all microprocessor relays meet this standard. Observance of repair and failure rates inform a utility about functional performance.
- Unsatisfactory functional device performance, leading to end of design useful life. Programmable electronic devices, installed with microprocessor-based relays, are reaching the end of their useful life prior to the relays, and the performance of the fleet is unsatisfactory. This leads to a design service life determined by the least reliable device and the replacement of devices at the end of their useful life and relays before the end their of useful life as part of a reliability upgrade program.
- Unsatisfactory supplier performance, leading to end of device useful life based on unsatisfactory manufacturer support or replacement equipment availability. Influenced by the way devices are designed and manufactured, the normal useful life of poorly made devices may be unpredictable and short, while well-made devices may have prolonged useful lifespans with low and stable failure rates. Supplier obsolescence of devices within a P&C design standard also renders the design performance unsatisfactory.
- Unsatisfactory time-in-service performance, leading to end of design useful life. A time-in-service-based service life may be driven by reliability compliance requirements regardless of individual device useful life or MTBF.
- Unsatisfactory performance of new expanded service conditions. The service life of a design may end when new demands require design changes that the existing design cannot meet. Even when existing devices have not reached the end of their useful life or the end of their original design life, they may not satisfy the new design requirements.
- Unsatisfactory performance of design serviceability due to differences between required skill sets and those available in the new workforce. As employees age and individuals retire, the remaining workforce skill and stability may degrade. In addition to loss of personnel familiar with existing methods and equipment, utilities must manage the recruitment and training of people to support new substation digitization skills based on software, computers, and Ethernet. Years of experience in maintaining, setting, commissioning, and troubleshooting is walking out the door as the industry is witnessing the rapid retirement of many seasoned engineers and field personnel. As this experience is leaving, new design requirements must be implemented not only to achieve the new information demands, but to be maintainable for the new generation workforce. These designs must balance the complexity to meet those new demands with simplicity of design.
- Unsatisfactory performance of design based on depreciation and capitalization. Asset depreciation and O&M expense planning influence the business service life of devices and systems which, in turn, trigger capital expense planning for asset replacement when appropriate.
- Unsatisfactory performance of design based on technical obsolescence. The technical obsolescence lifespan of perishable methods, such as frequently changing TLS versions, influences the technical lifespan of the substation designs that use these methods. When these features are used as intended, and become obsolete prematurely, the existing design must be updated in the field. Updated cryptography algorithms require updated device firmware. Firmware upgrades require that each device be removed from service for repair followed by systemic testing of interdependent functions and communications. Once the relay firmware is updated, it may not communicate to other devices until they too are updated, which creates a systemic enhancement requirement.

Optimizing power system performance requires diligence in factoring in relevant changes that affect the overall operating requirements. Simply replacing relays one-for-one may not produce the best results for reliability or help achieve any of the multiple demands placed on the system from operations, maintenance, or compliance standpoints. It may not even give a return on investment from a business management standpoint.

Implementing system upgrades on a planned and scheduled basis can reduce maintenance costs, improve operations, and raise customer satisfaction through lower costs and improved reliability. The utility must find the balance between service life and useful life to meet the changing service conditions, and justification of these planned replacement programs can be based on one, some, or all the factors discussed in this paper.

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XII. Biographies

Matt Gardner is director of system protection with Dominion Energy's power delivery group. In this role, Matt oversees the company's system protection organization, including both engineering and field operations responsibilities. His organization also includes Dominion Energy's transmission & distribution protection and control standards, data engineering and analytics, and operations engineering studies groups. Since joining Dominion in 2008, Matt has held various roles in planning, operations, and engineering. Outside of Dominion Energy, Matt has a range of experiences spanning industry, academic, and regulatory domains. As an IEEE Senior Member, Matt stays deeply involved in industry groups, such as the IEEE Power and Energy Society, CIGRE, EPRI, and the North American Transmission Forum, to name a few. Matt also has a passion for the development of future generations of technical talent in the industry and is actively involved with a broad number of academic institutions and consortia, including Virginia Tech. Matt received his PhD degree in Electrical Engineering from Virginia Tech where he was a Bradley Fellow. He also holds BS and MS degrees in Electrical Engineering from Virginia Tech. Matt is a licensed Professional Engineer in the Commonwealth of Virginia.

John Bettler has a BSEE from Iowa State and an MSEE from Illinois Institute of Technology (IIT). John has worked at Commonwealth Edison Company (ComEd), a power company in the Chicago area, for 29 years. He has experience as a field engineer and protection engineer. Currently, he is the principal engineer for ComEd's relay section. His team's purview includes 4 kV and 12 kV feeders up to 765 kV transmission lines and all transmission and distribution equipment in between (e.g., transformers, buses, caps, and inductors). John's team also reviews interconnections, independent power producers, and distribution generation projects. John is also adjunct faculty at IIT and University of Wisconsin-Madison teaching power and protection classes. He is a PE in Illinois.

David Dolezilek is a principal engineer at Schweitzer Engineering Laboratories, Inc. (SEL) and has three decades of experience in electric power protection, automation, communication, and control. He develops and implements innovative solutions to intricate power system challenges and teaches numerous topics as adjunct faculty. David is a patented inventor and continues to research and apply first principles of mission-critical technologies. He has authored over 80 technical papers, many based on the practical use of IEC 61850 engineering processes, and has taught digital transformation of energy control systems in over 50 countries. David is a founding member of the Distributed Network Protocol (DNP3) Technical Committee (IEEE 1815), and as a founding member of UCA2, he helped to migrate that work to become the IEC 61850 communications standard. As such, he is a founding member of both IEC 61850 Technical Committee 57 and IEC 62351 for security. He is a Senior Member of IEEE, the IEEE Reliability Society, and several CIGRE working groups.

Jonathan Sykes received his BSEE from the University of Arizona in 1982. After graduation, he worked at the Salt River Project for 27 years and provided oversight for protection and control as a senior principal engineer. From 2009 to 2019, Jonathan was the senior manager at the Pacific Gas and Electric Company, providing leadership for the protection, compliance, and test organizations. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2019 as the manager of SEL Engineering Services, Inc. (SEL ES) for the Phoenix and Albuquerque offices and now is the director of SEL ES sales. He is an IEEE Fellow for his work on implementing leading-edge techniques for remedial action schemes and quantifying upgrade and modernization strategies for P&C equipment. As a distinguished speaker for IEEE, he has given keynote presentations throughout the world and has published numerous technical papers and magazine articles. He has been a longtime contributor to the IEEE Power & Energy Society (PES) Power System Relaying and Control Committee, and in 2019, his peers elected him as the secretary of the IEEE PES executive board. He is a registered professional engineer and past chairman of the NERC System Protection and Control Subcommittee.

Mark Zeller received his BS from the University of Idaho. He has broad experience in industrial power system maintenance, operations, and protection. He worked for over 15 years in the paper industry, working in engineering and maintenance with responsibility for power system protection and engineering. Prior to joining Schweitzer Engineering Laboratories, Inc. (SEL) in 2003, he was employed by Fluor to provide engineering and consulting services. Since joining SEL, Mark has held positions in research and development, marketing, business development, and sales and customer service. Mark has authored numerous technical papers and has several patents with SEL. He is a Senior Member of IEEE and is presently serving as the regional sales and service director for the Northwest region.

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