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Fly Safe and Level: Customer Examples in Implementing Dual Primary Protection Systems

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INTRODUCTION

In his textbook, *Power System Protection*, Paul Anderson states that reliability in protection systems has always been provided by careful design based on sound judgment of experienced engineers, to which the high availability of our power systems is a testament. He proposes that, for the most part, these systems have not been designed using reliability mathematics or models but are mostly the result of experience and sound judgment [1].

In this paper, the basic concepts of reliability are investigated, and the reliable use of two SEL devices as primary and backup protective relays is promoted. It is not the intent of this paper to discredit the sound judgment and designs that have served the industry well for decades. Rather, the goal is to present concepts and reliability tools to be used to evaluate and improve our designs using quantitative means and to provoke more critical analysis of common assumptions.

Methods to measure manufacturer failure rates, evaluate protection system performance, and estimate the reliability of scheme designs are reviewed. The typical protection system designs of several utilities in North America and the reasons for those design decisions are shared. Applicable NERC and power pool standards and their recommendations regarding reliable designs are documented. Parallels are drawn from other industries concerned with a high degree of reliability. Finally, recommendations are presented to help users undertake their own reliability analysis and scheme improvement.

RELIABILITY IS THE CORE REQUIREMENT OF PROTECTIVE RELAYING

Reliability, as defined by the IEEE, is the ability to perform a function under stated conditions for a period of time. The primary function of protective relays is to maximize service continuity and minimize damage by detecting and operating for in-zone faults and refraining from undesired operations. These general terms are familiar to those of us in the industry.

“At South Texas Project Management Committee meetings, as we discuss budgets, schedules, man-power, unit performance, and the many other usual topics, it is all too easy to lose sight of the fundamental nature of our enterprise,” wrote Mike Hardt in a 1991 letter to the members of the South Texas Project nuclear plant management committee. Attached to his letter was a document titled the “Chernobyl Notebook,” by G. Medvedev, which he recommended each member read cover to cover. The text is a root cause analysis of the worst civilian nuclear accident [2]. Mr. Hardt was reminding the management team that from time to time, attention must be refocused on the basics of designing, operating, and improving safe and reliable power systems.

It is hard to imagine any facet of our society that does not depend upon the safe, reliable, and economical supply of electric power. It is not surprising that the National Academy of Engineering ranked electrification as the most significant engineering accomplishment of the past century, noting its impact on quality of life and economic development. At the heart of the electrical grid are protective relays, installed to maximize service continuity and minimize damage to property and personnel.

Figure 1 The South Texas Nuclear Project and a Bulk Transmission Corridor

The systems that we design must be reliable, meaning they must operate fast, sensitively, and selectively to clear in-zone faults (maintain dependability) while restraining for out-of-zone faults or in the absence of faults (maintain security). Maximum dependability with maximum security is not possible; these two facets of reliability must be balanced appropriately.

Corporate Aviation Comparison

When discussing power system protection scheme designs, it is common to hear concerns regarding possible common-mode mechanical or software failures. Therefore, in traditional designs, greater emphasis is placed on dependability. For example, two different manufacturers' relay trip output contacts are typically wired in parallel to ensure that one may trip regardless of the other relay's health or decision. As Ed Schweitzer says, it is helpful to "get out of our relay kitchen" and look to other engineering disciplines and industries for counsel. In the aviation industry, for example, greater design attention has been placed on the two key areas of improving human error rates and using quantitative reliability design tools.

The practice of using devices from different manufacturers for redundant or backup functions was not common during the era of electromechanical relays. During that era, one was likely to see a panel full of Westinghouse or GE equipment, but not a mixture of both. Loyalties usually followed strict lines of preference based on cost, features, and experience with reliability. It was common to see on a distribution feeder panel distinct overcurrent relays for each phase and a separate ground relay. The promotion of the inherent reliability of this scheme of discrete devices coincided with the introduction of multifunction microprocessor relays, in which previously distinct functions were incorporated. At first glance, one might assume that the electromechanical ground relay provided better backup in the case of a failure of any phase relay. With the digital relay, it was argued, one failure meant the loss of the entire protection scheme. However, the electromechanical phase relays, due to having to be set above load, realistically did not provide backup in the case of a failed ground relay in the traditional scheme. In other words, these schemes did not provide complete redundancy and protection against single failures. In addition, electromechanical relays did not provide any form of self-testing, monitoring, and remote communications of their status.

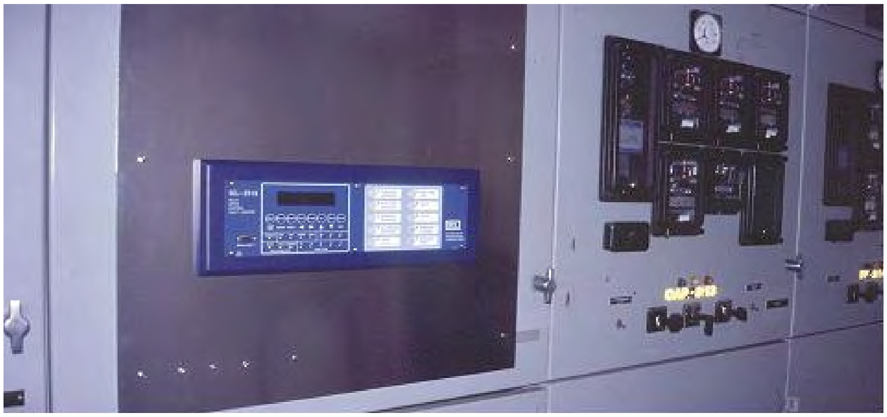


Figure 2 Modern SEL Multifunction Relay and Traditional Electromechanical Design

Seventy to eighty percent of civil and military aviation accidents have implicated human error as the root cause. While accidents attributable to solely mechanical failures have decreased markedly over the past 40 years, those attributable to human error have declined at a much slower rate. Therefore, emphasis is now aimed at reducing the occurrence and consequences of human error through root cause analysis of human error, called human factor analysis. In one study, 100 percent of the human causal factors with air crew-related accidents were accommodated using the framework of human factor analysis and classification [3].

Figure 3 Cessna Citation X Corporate Aircraft

If you were to step on board a corporate jet, such as the Cessna Citation X$^{®}$ shown in Figure 3, you would find a myriad of redundant systems, each built by the same manufacturer, including two Rolls-Royce$^{®}$ jet engines, two Honeywell$^{®}$ flight management systems, radios, air data computers, autopilot systems, etc. Why is it that the aviation industry has no problem using the same manufacturer for redundant power plants, flight management, navigation, and controls? Can you imagine the complexity of flying a plane that had two different engines, or where the control systems were different in the left and right pilot seats? In many power system design discussions, reliance upon one manufacturer alone would not be considered and would be labeled unreliable. However, in aviation design, emphasis is placed on the use of proven high-reliability components, the ability to withstand any single failure, and in some cases, the use of multiprinciple backup (note the attitude gyroscope and altimeter on the dashboard).

Consider one more aviation industry analogy. Southwest Airlines flies one type of aircraft, the Boeing 737. The Boeing 737 is the most popular and reliable commercial jet in the world, with Southwest Airlines owning more than 450 in its fleet alone. Southwest's decision to standardize on the Boeing 737 was a conscious decision that has made a strong impact on the bottom line. With 34 consecutive years of profitability as of January 2007 in what can only be described as a competitive and volatile industry, Southwest is a worthy benchmark.

The interior of a Boeing 737-300 cockpit.

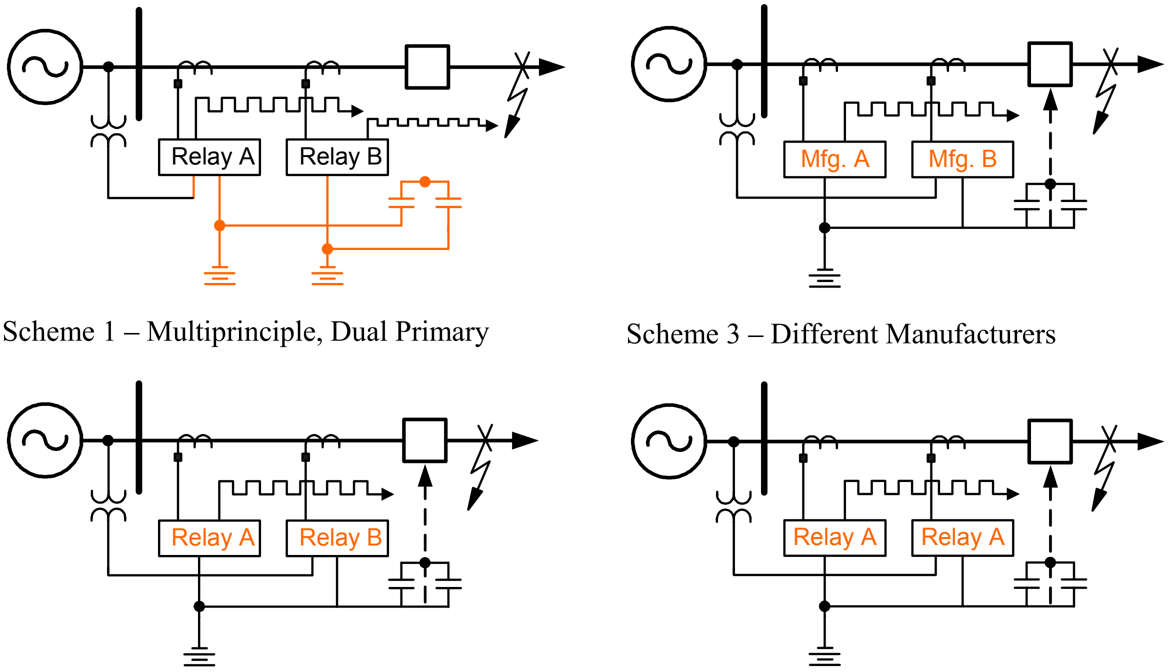
Figure 4 Southwest Airlines Boeing-737 Aircraft

Why does Southwest use one supplier? Training requirements are simplified. Pilots, flight attendants, mechanics, and provisioners concentrate their time and energy on knowing the 737, inside and out. All Southwest pilots are qualified to fly, all flight attendants are qualified to serve in, all maintenance people are qualified to work on, and all provisioning crews are qualified to stock every plane in the fleet. This makes it easy to substitute aircraft, reschedule flight crews, or transfer mechanics quickly and efficiently. The company can reduce its parts inventory and simplify its record-keeping, which also results in savings. Sticking to the 737 series also helps the company negotiate better deals when acquiring new planes. Southwest was the launch customer on Boeing's 737-300, -500, and -700 models. This has enabled the company to buy its fleet of these planes on launch customer terms and to contribute to the design process of new models [4].

One Power Pool, Many Designs

Among the Electric Reliability Council of Texas (ERCOT) utilities, four main protection designs are prevalent. These designs are shown in Figure 5. Interestingly, one utility that uses two different manufacturers for line protection cited the perceived commercial benefits of leveraging one supplier against the other and of maintaining a close relationship with more than one supplier should a problem develop. Many other utility and industrial customers in the state of Texas cite the commercial benefits of sole-sourcing with SEL, such as receiving larger quantity discounts, better reliability, and better commercial and technical support.

The first scheme uses true multiprinciple line protection, with a distance and directional overcurrent relay as primary protection and a line current differential relay as dual primary. At least two major utilities and several industrial systems employ two SEL relays (SEL-421 Protection, Automation, and Control System and SEL-311L Line Current Differential System) in this scheme. SEL is used as primary and dual primary due to commercial, reliability, and service benefits in as many cases as cited performance advantages. The distance schemes are either step-distance or, more commonly, communications-assisted (DCB or POTT via power line carrier or Mirrored Bits® communications and fiber-optic cable). The differential relays use separate communications in many cases, with different routing where possible. At one of the utilities, dual battery systems are installed, one each for primary and redundant systems. Only one set of PTs or CCVTs is commonly installed, yet only the distance and directional relay is dependent on potentials. This scheme design places maximum emphasis on reducing single points of failure through true redundancy. The primary and backup relays use different and complementary algorithms for fault detection. Single points of failure, such as blown PT fuses for the distance relay or loss of channel for the line current differential relay, do not impair the protection system's ability to detect faults and trip at high speed.



Scheme 1 – Multiprinciple, Dual Primary

Scheme 3 – Different Manufacturers

Scheme 2 – Same Manufacturer, Different Models

Scheme 4 – Same Manufacturer, Same Relay

Figure 5 Prevalent Transmission Line Protection Schemes Used by ERCOT Utilities

A second scheme, which is the most commonly used in Texas, uses the same manufacturer for primary and backup, although different models are used (SEL-421 and SEL-311C Advanced Distance Relay With Recloser). In most cases, only the primary relay uses communications, and the backup is step-distance. In at least one case, different algorithms are enabled where available (compensator distance elements in the backup relay versus positive-sequence memory polarized distance elements in the primary relay). The most common reason for this practice is emphasis on observed reliability and service from SEL, coupled with a desire to have primary and backup products sufficiently different to limit susceptibility to common problems (different hardware platforms and designs). Interestingly, one utility that actually experienced a common-mode failure in the 1980s and cited this for years as a reason to use two different manufacturers recently went through a rigorous qualification process and standardized on a dual SEL protection scheme. It should be noted that the observed failure was with two non-SEL solid-state relays, of similar make and model, that were in a failed-off state when a fault occurred, and included no self-testing capability.

A third scheme, used about as often as the multiprinciple design, mandates that a different manufacturer's relay be used for primary and backup. The most common reasons cited for this design decision are fear of a common-mode failure in one manufacturer's products (for example, a design "hole" or rash of failures in common components such as power supplies) and interpretation of the ERCOT Operating Guide recommendations.

Lastly, several utilities have used primary and backup protection using the exact same make and model relay. The most common reason cited for this decision is the goal of reduced human errors through concentration on training, understanding one scheme best, and duplicating engineering efforts and lessons learned.

Why Dual Primary Protection?

True dual primary is implemented in only one of the designs shown. Why use dual primary? Either unit or system can fail or be removed from service by manual means (testing), and the protection system does not lose any performance characteristic (speed, etc.).

Adding redundant relays with independent communications channels decreases unavailability by nearly one-half (47 percent), while adding a redundant channel to a scheme that already employs redundant relays improves unavailability by 31 percent [5].

Designing systems with complete redundancy to maintain survivability in the presence of a single contingency is sound engineering, used in other industries as well. Airline regulations specify that "no single power plant failure or malfunction or probable combination of failures will jeopardize the safe operation of the airplane" [6]. Many may recall the crash of United Flight 232 in Sioux City, South Dakota, in July of 1989, which followed the catastrophic failure of a McDonnell Douglas DC-10's triple redundant hydraulic systems. The failure of the number 2 engine sent spewed fragments, rendering all three hydraulic systems inoperable, all of which had critical components that ran together near the engine casing.

Multifunction Relays Now Include Different Principles of Protection

Today's dual primary systems are more often than before "duplicate" schemes. Historically, dual primary systems tended to consist of two separate relays that used different operating principles. An example of this was the application of distance relays in a communications-assisted scheme together with a phase or current differential scheme. Each primary relay had certain strengths and possible weaknesses that, when used in combination, complemented one another.

Today, digital protective relays can provide multiple operating principles in a single device. For example, a single relay is available that provides time-step distance elements, communications-assisted pilot schemes, directional overcurrent elements, and line-current differential protection; all of this is in a single device (for example, an SEL-311L).

Why Use the Same Manufacturer for Dual Primary?

Human factors are an important consideration in this decision. By limiting the number of relays with which system designers, settings engineers, and maintenance and commissioning technicians must stay familiar, skill levels become greater. When it becomes necessary to divide the available time for setting the relays between two very dissimilar devices, it is not possible to do as thorough a job with both as it would be to devote all the available effort towards one. Additionally, it will be much easier to maintain working knowledge, over time, of a smaller number of unique devices. However, to be fair, when applying identical systems for redundancy, the settings engineer could make a mistake that causes both systems to misoperate. Using two identical or very similar relays can actually increase this hazard, making training and peer review critical.

Benefits of "designing one system and using it twice" include:

- Lower engineering costs
- Common human-machine interfaces (HMIs) for operators
- Common integration architecture
- Easier protection coordination because operating times and sensitivities are the same
- Analysis of data with same skills and tools

- Fewer spares to stock
- Optimized training and maintenance
- Trouble-shooting and monitoring made easier by a side-by-side comparison

Don't Confuse Dual Primary With Primary and Backup!

In Figure 6, remote backup tripping takes place one station away from where the failed primary relay/breaker combination is located. Here we see Breakers 1, 3, and 8 opening to clear the fault. The remote backup clearing action significantly impacts the ability of the power system to continue normal operation, since a total of four lines are taken out of service to clear the fault. In this example, no power transfer is possible across the system shown. Equivalent generation sources at A and B are no longer connected to this part of the system. In the case of local backup, the entire protection system exhibits better selectivity, and the power system continues to transfer power because of it. Remote backup, in the form of time-delayed over-reaching elements, is important for scenarios such as loss of local auxiliary dc battery power.

Consider other protection applications. For example, in the example discussed earlier, one might have used three-phase electromechanical overcurrent relays (50/51P) and a separate, residually connected electromechanical overcurrent relay (50/51N) to protect a distribution feeder circuit. In the case of the single failure of the ground relay, the phase relays may have provided some limited backup protection, but they would not offer complete redundancy due to settings restrictions (phase pickup is set much higher, above load current). Another example is in the protection of a delta-wye power transformer, where a phase current differential relay (87T) is backed up by high-side phase overcurrent and low-side X0 bushing CT ground relays. If the differential relay were to fail, the overcurrent relays would provide backup, limited by their settings, but they would not offer complete redundancy, including similar speed and sensitivity as the primary protection.

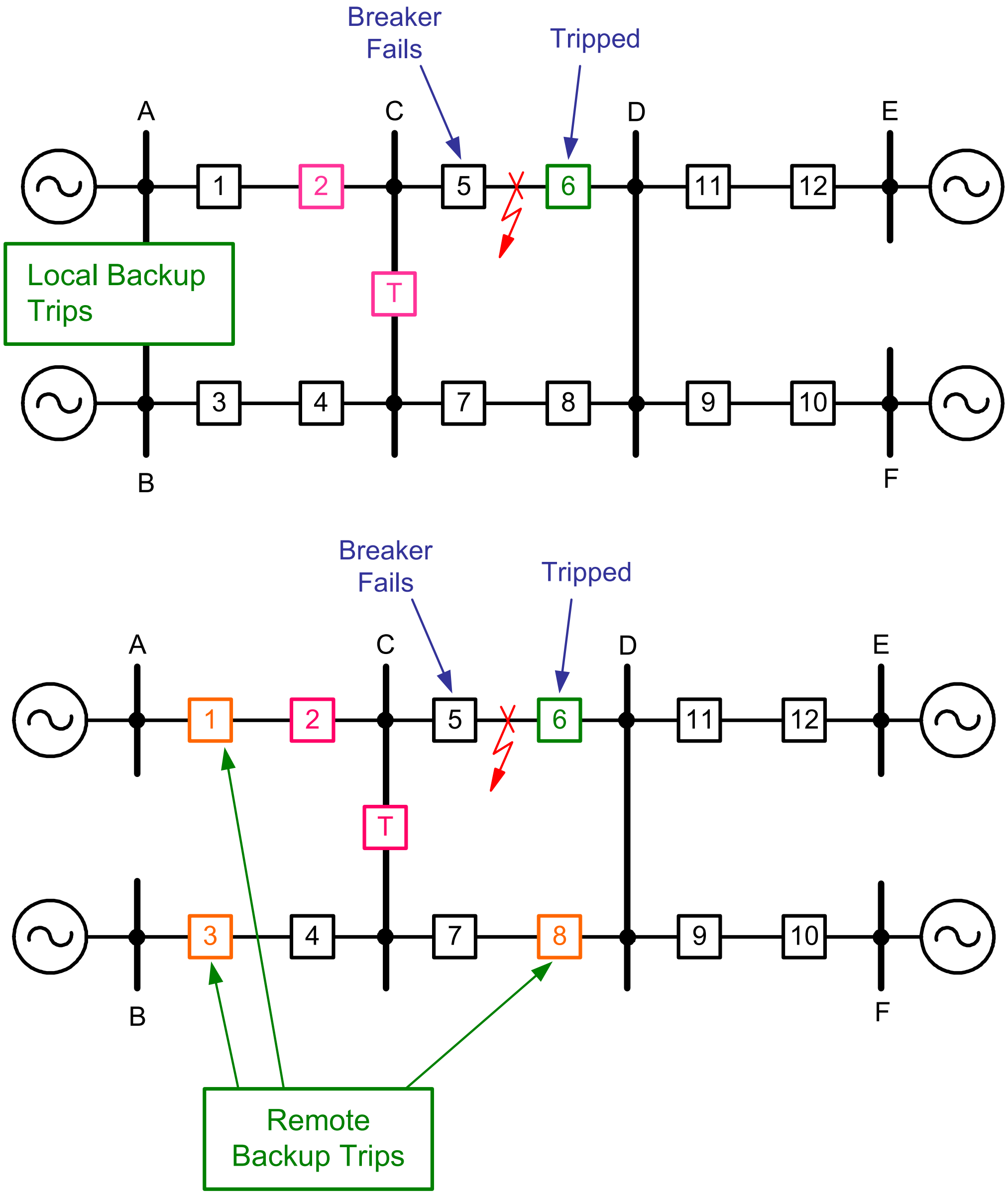


Figure 6 Remote Terminals Provide Backup Protection

More Utilities Using Same Manufacturer for Primary and Backup Protection

Are the practices in Texas inconsistent with those of other utilities? The trending information in market surveys suggests they are not. Newton-Evans Research Company surveyed 64 North American utilities in a 1999 study, 79 utilities in a 2002 study, and 102 utilities in a 2004 study [7]. The use of “different manufacturers with different operating principles” was the most popular approach to scheme redundancy in the mid-1999 survey; use of “the same manufacturer with different operating principles” was the next most popular scheme for each application. By mid-2002, the results had changed somewhat. For transmission and subtransmission applications, use of the same manufacturer with different operating principles had taken over as the most important type of relay scheme redundancy, although not a majority. In the 2004 study, the use of the “same manufacturer with different operating principles" ranked at the top of relay scheme redundancy used for digital relays in transmission and subtransmission applications.

Respondents to the survey in 2004 were also asked to rank leading relay manufacturers in seven categories (technology, price, features, technical service and support, security against hackers, relay setting PC software, and web/internet information availability). SEL was the leader in first place mentions in each of the seven categories. In the 2002 study, 15 categories were listed on the survey (similar to the above with the notable addition of items such as quality and reliability); SEL was the leader in each of the 15 categories included on the survey that year.

Table 1* Most Popular Survey Choice for Scheme Redundancy

Scheme Redundancy Used/Planned for Digital Relaying	Transmission and Subtransmission Lines
1999 – Different manufacturers, different operating principles	Most popular 2nd: Same manufacturer, different principles
2002 – Same manufacturer, different operating principles	Most popular Not a majority
2004 – Same manufacturer, different operating principles	Most popular Majority (53%)

*Source: Newton-Evans Research Company, 1999, 2002, 2004 [7]

REGIONAL RELIABILITY COUNCILS

Reliability councils frequently establish recommendations for the use of protective relay schemes. Websites listed in Table 2 provide more information specific to each council.

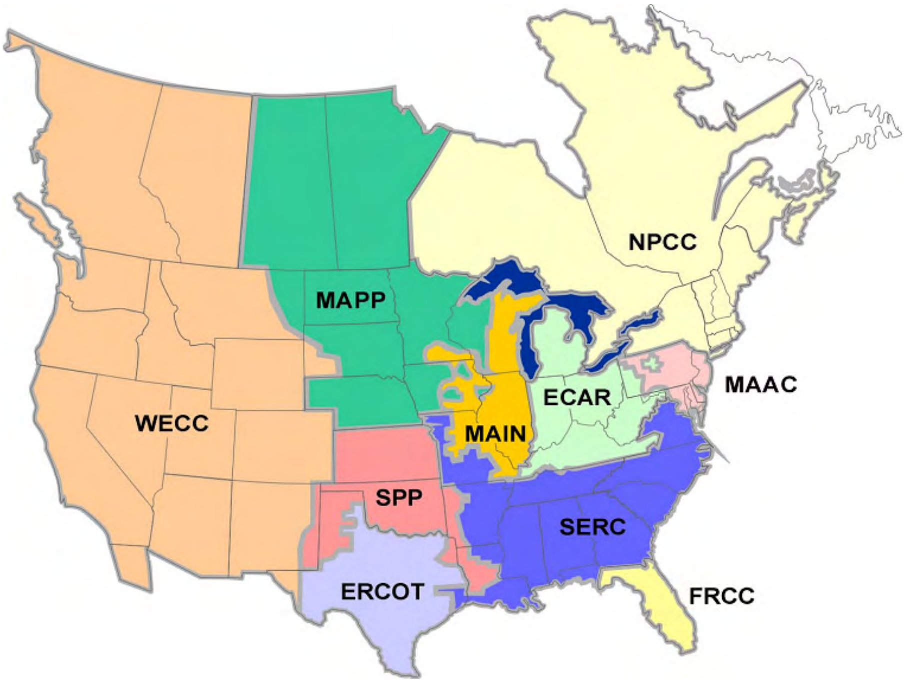


Figure 7 North American Electric Reliability Councils

Table 2 Reliability Council Websites

Reliability Council	Website
NERC, North American Electric Reliability Council	www.nerc.com
ECAR, East Central Area Reliability Coordination Agreement	www.ecar.org
ERCOT, Electric Reliability Council of Texas	www.ercot.com
FRCC, Florida Reliability Coordinating Council	www.frcc.com
MAAC, Mid-Atlantic Area Council	www.maac-rc.org
MAIN, Mid-America Interconnected Network, Inc.	www.maininc.org
MAPP, Mid-Continent Area Power Pool	www.mapp.org
NPCC, Northeast Power Coordinating Council	www.npcc.org
SERC, Southeastern Electric Reliability Council	www.serc1.org
SPP, Southwest Power Pool	www.spp.org
WECC, Western Electricity Coordinating Council	www.wecc.biz

No regional council guidelines prohibit the use of a single manufacturer for dual primary or redundant protection. Several state that the “use of common components,” “areas of common exposure,” and “use of components common to the two protective relay systems” should be kept to a minimum to reduce the possibility of both protective relay systems being disabled by a single contingency (simultaneous failures).

SEL Satisfies ERCOT Dependability and Security Requirements

The Operating Guides for ERCOT are written by the System Protection Working Group, part of the Reliability and Operations Subcommittee of the ERCOT Technical Advisory Committee, which is made up of 19 utility representatives and 3 ERCOT participants. The guide states that the protective relay system is designed to provide reliability. It contains mandates, such as the requirement that redundant protective relay systems use separate ac current inputs and separately fused dc control voltages. It also states that 100 kV and above transmission lines shall be protected by two protective relay systems, independently capable of detecting and isolating all faults.

Section 7 of the ERCOT Operating Guide deals with Disturbance Monitoring and System Protection [8]. Misoperations are defined by this section as a (an):

- Failure to trip for in-zone fault (Type A)
- Slower-than-designed trip for in-zone fault (Type B)
- Unnecessary trip for out-of-zone fault (Type C)
- Unnecessary trip when no fault is present (Type D)
- Employee action related to system design (Type E)
- Failure to reclose (Type F)

With respect to “employee actions,” those that directly result in an undesired trip are not included in this category. An example would be an individual unintentionally causing a misoperation during maintenance testing; this would not be included. However, employee actions as they relate to system design are included. An example would be if a technician unintentionally leaves trip test switches or cut-off switches in an inappropriate position, standard practices or monitoring fail to detect the state of the system, and a subsequent fault occurs, causing a misoperation. This would be included.

It is very important to consider the priorities or weights placed on those misoperation possibilities. Dual manufacturer solutions, where both relays' trip contacts are wired in parallel for fear of common-mode failures, assume an emphasis on dependability and a goal of preventing misoperations of Type A and perhaps B. If we place emphasis on minimizing misoperations of Types C, D, and E, for example, that may lead to selection of relays with higher security or use of common components that lessen human error. Depending on our subjective weighting of design goals, our choice of products, designs, and manufacturers will likely be different. The guide provides guidelines, in most cases, rather than hard and fast requirements.

Two applications are excluded from the redundancy requirement in Sections 7.2.5.1.4 and 7.2.5.1.5. Breaker failure protection and protection of the primary of freestanding, column CTs located on one side of a breaker's interrupting contacts need not be duplicated (redundant).

Section 7.2.5.1.1 clarifies that all elements of the ERCOT system are inclusive of lines, buses, transformers, generators, breakers, capacitor banks, etc.

Some of the specific guidelines of this document include the following:

- Avoid the use of common components.
- Use of two identical protective relay systems is not generally recommended (but not prohibited).
- Protective relay system should be no more complex than required for any given application.
- Components used in the system should be of proven quality.

Note that while the operating criteria recommends that the system design should avoid the use of common components, it does not preclude the use of the same manufacturer for primary and backup. This was confirmed by interviewing members of the working group and observing the actual practice of utilities represented by members of the working group.

Much attention is focused on this one particular section and how it relates to the use of a single manufacturer's relays. There are other important facets to this section, however. In the same section, emphasis is placed on simplicity of design and on using relays of proven quality. Instinctively, we know that installing a less-reliable product in parallel does not improve availability and that increasing complexity of schemes increases the likelihood of human errors.

Other specific guidelines of this document include the following:

- Minimize the possibility of component failure or malfunction due to transients, interference, vibration, shock, and temperature.
- Minimize the possibility of incorrect operations due to personnel error.
- System should take action in the shortest time with due regard to selectivity, dependability, and security.

SEL's dedication to designing and testing relays so that they exceed published specifications speaks to the lengths SEL goes to ensure components have minimum failure exposure due to transients, vibration, shock, and temperature.

Like the airline industry, the regional councils recognize that human factors play a large role in dependability and security issues. Some utilities that use identical make and model products for primary and backup systems cite human factors as their greatest concern when defending their ranking of this recommendation over that of not using common components.

Selectivity, dependability, and security are related to features, reliability, and design of the relays used in a scheme and will be discussed next.

The guidelines for designing reliable schemes in ERCOT are interesting, at times in conflict, and at best leave much room for subjective interpretation by member utilities.

SEL Relay Tripping Time Is FASTEST for ALL Faults at ALL Locations

SEL tests and competitors' curves show that the SEL-421 is the fastest distance relay on the market today. In any application requiring speed with security, the SEL-421 is a great choice.

Operating times shown in Figure 8 are for single line-to-ground faults with zero fault resistance. SEL-421 operating times for other fault types are even faster. Note that for fault locations up to 80 percent of relay reach, the times are still under one cycle. The SEL-421 curve shown in Figure 8 indicates relay speed with the available high-speed output contacts. Use of MIRRORED BITS communications over a fast channel, such as fiber optics, permits very high-speed tripping of both line ends for a fault anywhere on the protected line.

The ERCOT guidelines state that protection should be as fast as possible. Schemes that use different manufacturers' products, or voting schemes, must pay special attention to testing to determine where the weak links are with respect to operating speed and sensitivity, as well as security and dependability.

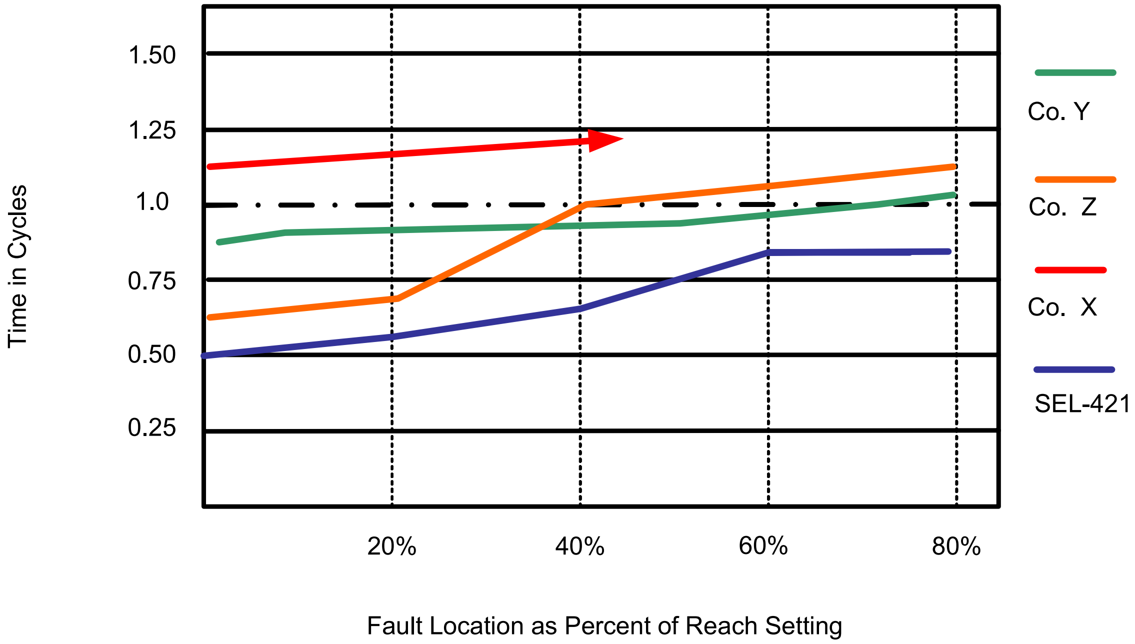


Figure 8 SEL-421-0 Tripping Speed

Similarly, the SEL-311L tripping speed is shown in Figure 9. New dc and second-harmonic restraint, and an additional security timer, slightly delay detection of high-impedance ground faults of the 87L2 (negative-sequence) and 87LG (zero-sequence) differential elements, improving security while retaining sensitivity for these low magnitude faults. The phase current differential elements still typically trip for a bolted, high magnitude fault in less than one cycle.

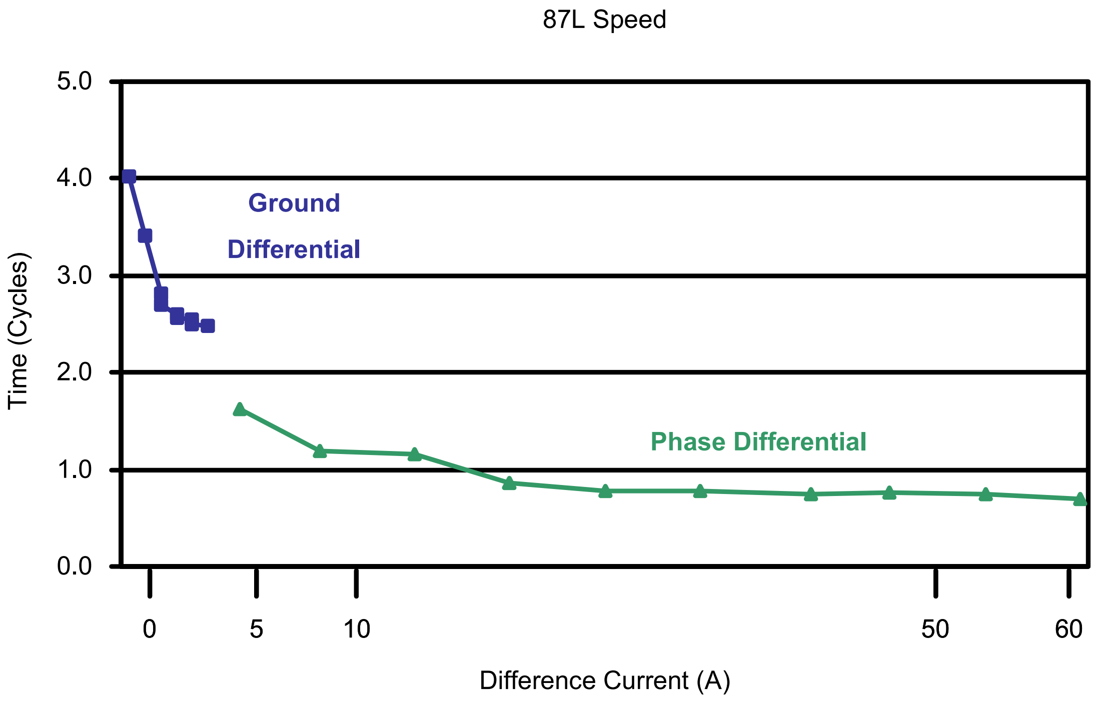


Figure 9 SEL-311L Line Current Differential Tripping Speed

SEL Addresses Power System Dependability Concerns

The operating criteria of reliability councils do not prohibit the use of the same manufacturer for primary and backup, or redundant primary. Still, we find four main reasons cited for designs that mandate the use of different manufacturers' equipment.

- Concern over possible power supply failures
- Common component failure
- Fear of misoperation due to software defect
- Security or dependability priority—should you wire two relays in series

Some utilities worry about the possibility of power supplies failing simultaneously. Others worry about a common component failing, simultaneously, in the two relays. Others are concerned about a common software defect, for example, an error in firmware that affects both relays' ability to operate or sense a fault. Lastly, there are some utility designs that have placed greater emphasis, or at least equal emphasis, on security, that is, the ability to not misoperate during out-of-section faults, normal load, or periods of expected unbalance.

As W. Edward Deming said, "In God we trust, all others bring data." We will try to address each concern with data.

What Is the Risk of Power Supply Failures?

SEL keeps a database that includes root cause analysis for every relay returned for repair. By far, the leading cause of SEL relay returns is "no problem found," that is, a failure mode reported by the customer that SEL cannot repeat in the product hospital or through prolonged testing.

The second leading cause of SEL relay returns, historically, has been power supply failures. SEL looks at product and component failure rates and the pareto of failure causes. When failure rates are elevated, action is taken to correct the root cause of the problem. In the case of power supply failures, SEL embarked on a process a few years ago whereby we would cease reliance on third-party power supply vendors and instead design and manufacture our own SEL power supply, the PS-30. This is a good example of the action SEL takes in root cause analysis and problem resolution, all with the goal of ever-increasing reliability of our products.

Even with the history above, it is important to quantify the likelihood of a power supply failure. Data show that the observed Mean Time Between Failures (MTBF) of the PS-30 is 5000 years. The SEL power supply MTBF is 17 times greater than the product MTBF.

What Is the Risk of Common Component Failure?

What is the risk of common-mode failure? First, consider that relay manufacturers often build their products with the same brand of components, for example, Motorola® microprocessors, Analog Devices integrated circuits, and CCI or other power supplies. So, even using different manufacturers' products does not guarantee the independence of common components; careful inspection of designs should replace assumption.

Several SEL application guides address common-mode failure concerns. These application guides do a great job of detailing hardware and firmware differences between different relay platforms [9-12].

Lastly, simultaneous failure of common components in two SEL relays has never been reported. In the case of one utility in ERCOT, a well-documented event did observe simultaneous failure of two relays (in that case, two brand X solid-state relays, without self-testing capability). Their failure went unobserved until a line fault occurred. SEL relays feature continuous self-testing that detects about 80 percent of potential failures. Comparing analog and digital measurements between dual primary relays raises that percentage to nearly 100 percent. Monitoring alarms and responding quickly is critical and improves unavailability over previous technologies.

What Is the Risk of Misoperation Due to Software Defect?

The risk of misoperation due to an undetected design flaw, or defect in hardware or firmware, is made very unlikely due to the rigorous testing SEL relays endure during design and life tests. Thousands of fault cases are simulated in the lab, months of long-term reliability tests are run, years of life are simulated with a Highly Accelerated Life Test chamber, and designs are based on years of in-field experience and lessons learned.

In addition, if there were a design flaw which made the relay blind to a particular fault, microprocessor-based relays have the distinct advantage of including multiple measuring principles (e.g., distance, directional overcurrent, nondirectional overcurrent, differential) in one relay. It is unlikely that an undetected algorithm problem exists across multiple principles.

Even still, SEL has a demonstrated track record of active root cause analysis, constant product improvement, honest reporting, and proactive customer notification. Perhaps the biggest improvement over the last couple of decades has been the ability to absolutely determine root cause through event report analysis.

Reliability Equals Dependability and Security

Over 1500 MW of load and 4000 MW of generation were shed when Comanche Peak nuclear generating station came offline due to a failure to clear a fault. The root cause was the electromechanical fault detector relays in both the primary and backup trip circuits that were found with corroded, high-impedance across output contacts [13]. The use of a common type of relay in two circuits installed for dependability led to a common-mode failure.

Contrast that with the following two events. In 1995, parts of New Mexico and El Paso experienced significant loss of load during three separate system events. All three events were precipitated by a fault on a frequently faulted line and simultaneous misoperation of a parallel line. Two misoperations were due to component failures in a phase comparison relay, and the third misoperation was due to a power line carrier blocking scheme inadvertently having been left in the disabled position [14]. These incidents led to the development of a so-called trip security system [15]. The trip security scheme, or two-out-of-three voting scheme, was developed specifically to attempt to reduce relay false trip opportunities.

The Western Systems Coordinating Council (WSCC) experienced severe loss of load and islanding during two separate incidents in July of 1996 [16]. Both events were precipitated by a transmission line sagging into a tree, coupled with the simultaneous misoperation of a parallel line. The parallel line tripped due to component failures in an electromechanical ground overcurrent relay and an electromechanical distance relay.

From these events, it should be learned that evaluations of our protection systems should not be solely focused on failure to operate (dependability), but increasingly also focused on the secure operation for out-of-section faults and load.

Relay Only Part of Protection System

A great deal of attention is paid to the protective relay in these scheme designs, and rightly so, as the relay is the center of the decision-making process. However, in spite of our best efforts, design holes have been built into many systems. Several examples are listed here.

Example 1

A single point of failure, the breaker (C-phase SF6 interrupter) fails to interrupt for a distribution fault. See Figure 10. Local breaker failure, although included in the relay, is not enabled. Remote breaker failure (high-side transformer overcurrent) is ineffectual due to insensitive settings, having been set to allow the transformer to carry maximum load plus overload. The fault is luckily cleared after significant delay when the interrupter finally opens on its own, saving the substation from complete destruction.

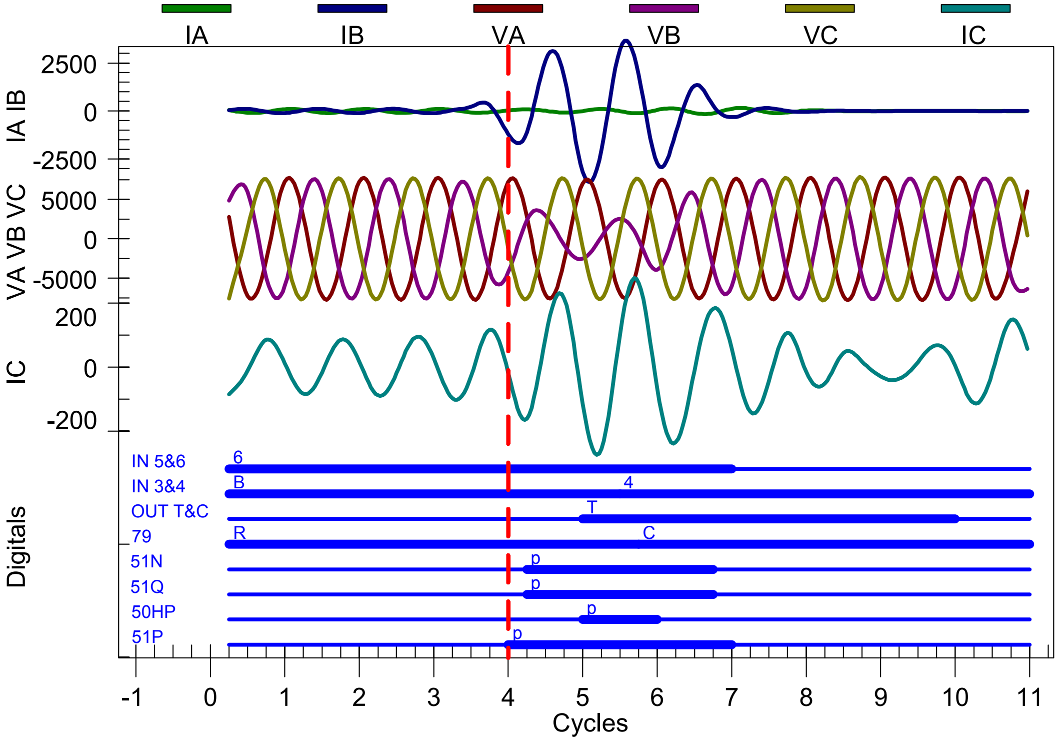


Figure 10 SF6 C-Phase Breaker Interrupter Failure

Example 2

A single point of failure, the dc battery system, fails and remains unmonitored and undetected until a distribution fault occurs. See Figure 11. Remote backup (line relays) are ineffectual due to the transformer impedance, their settings, and infeed. The substation is a total loss.

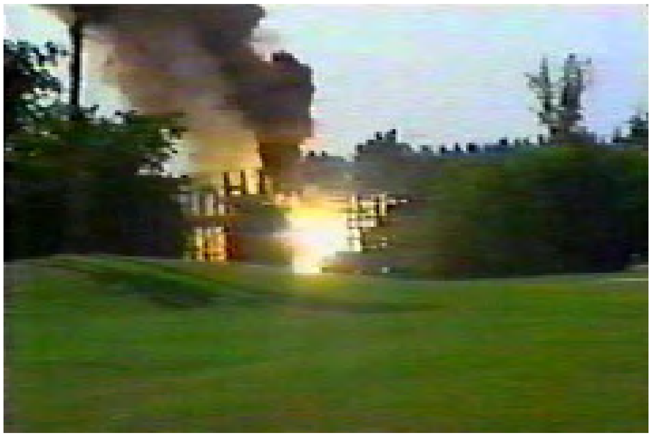


Figure 11 DC Battery Failure Causes Complete Loss of Substation

Example 3

A single point of failure, an electromechanical auxiliary tripping relay, fails to energize trip coil one, trip coil two, and local breaker failure during a 230 kV line fault. See Figure 12. Remote breaker failure backup takes approximately 39 seconds to clear, due to autotransformer impedances and infeed. The fault leads to the loss of 5000 MW of load, a dozen EHV transmission lines, and three nuclear units. No through-fault overcurrent protection was enabled on the large transformers. Within a month, five transformers in the area had caught fire and been destroyed due to suspected transformer age coupled with the through-fault damage.

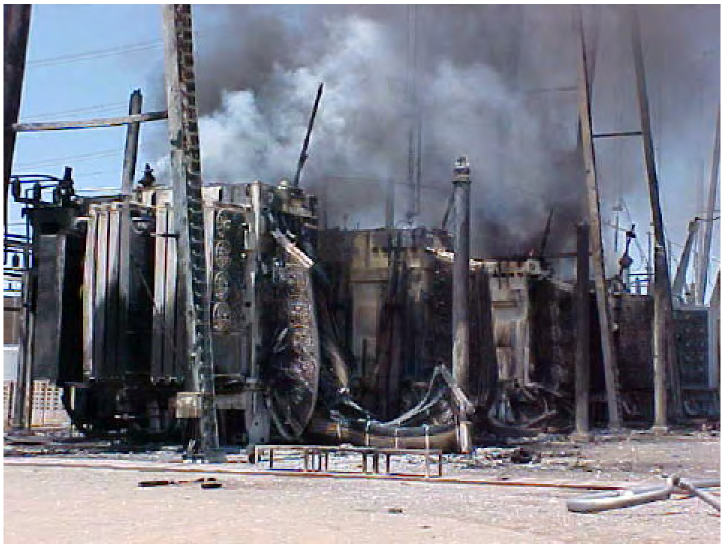


Figure 12 Transformers Destroyed Due to Through-Fault Damage

Example 4

A single point of failure, power line carrier communications, demonstrates three problems in a single event: overly delayed internal tripping due to longer-than-necessary carrier coordination delay setting, a momentary drop-out of the blocking signal (carrier hole), and lack of carrier extension. See Figure 13. The lack of carrier extension causes an undesired operation for an out-of-section fault.

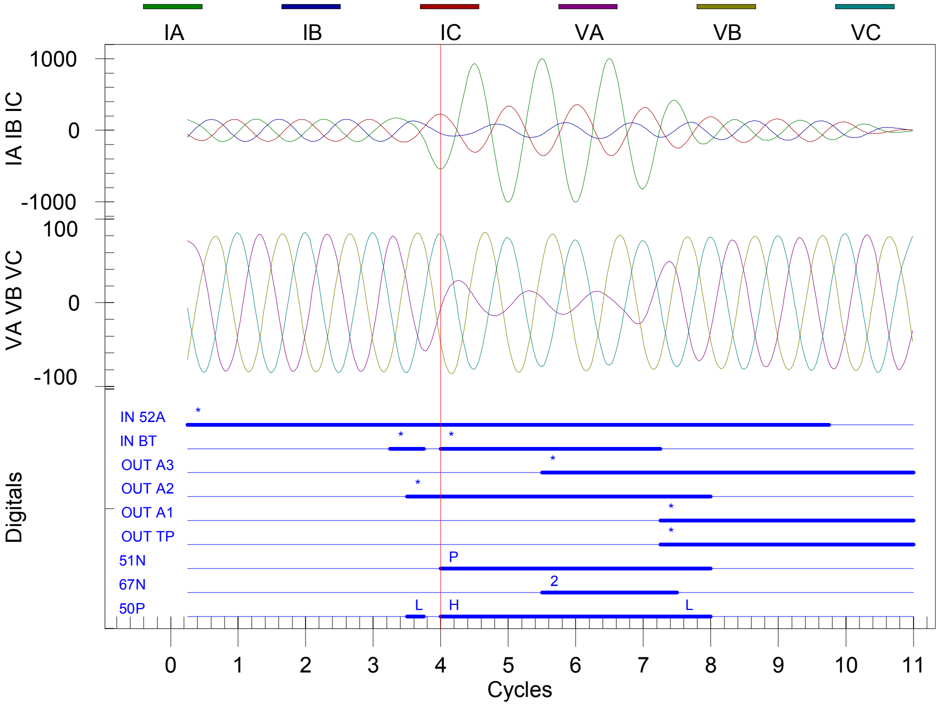


Figure 13 PLC Communications Problems

Example 5

A poorly rated CT in industrial switchgear saturates for transformer inrush current downstream, causing the operation of the ground overcurrent element and total loss of plant load. See Figure 14.

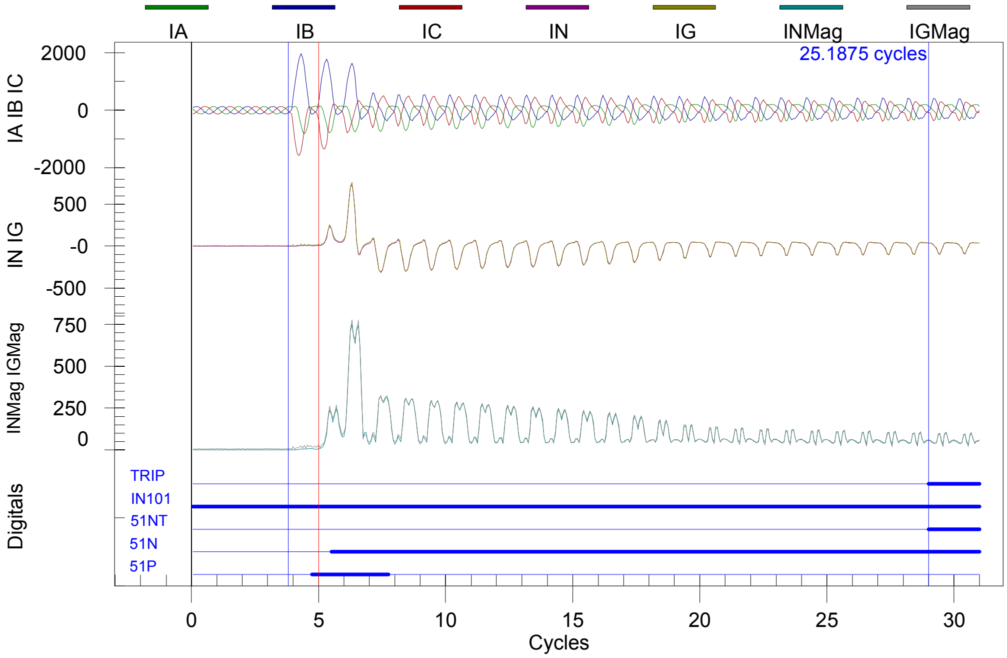


Figure 14 ANSI Accuracy Class C35 CT Saturation Causes Relay Misoperation

Example 6

A loose PT fuse falls into an adjacent phase, confusing distance relays into believing a fault has occurred. Both primary and backup systems misoperate. See Figure 15. A conspiring low-set fault detector, set below load current, helps to cause this misoperation.

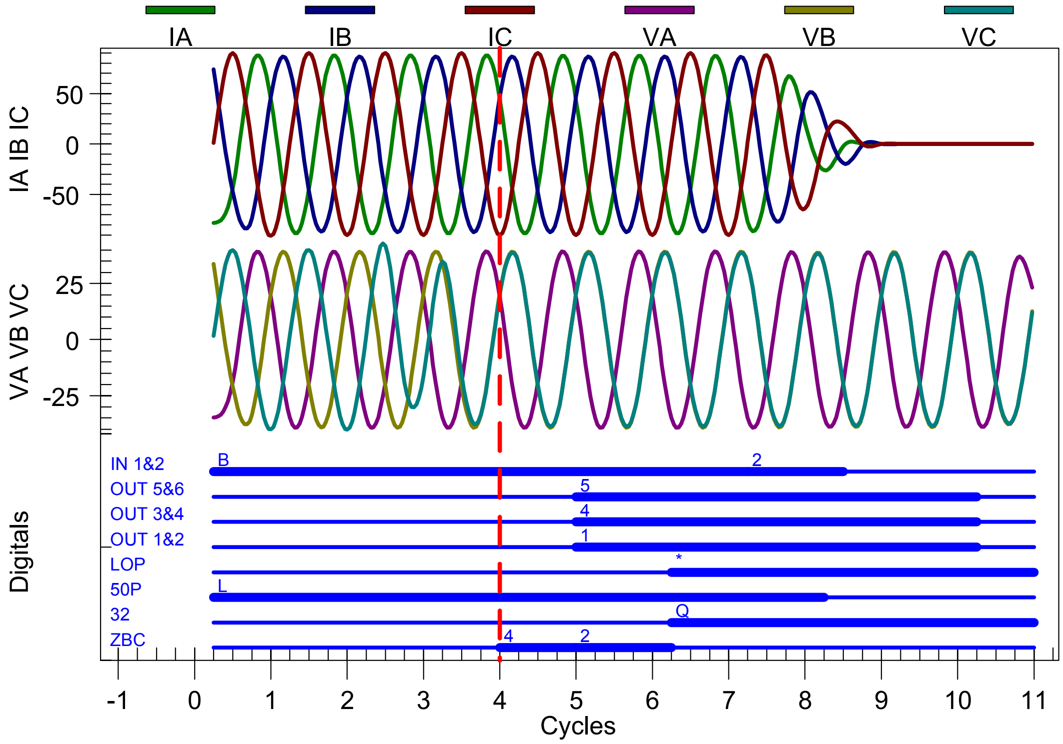
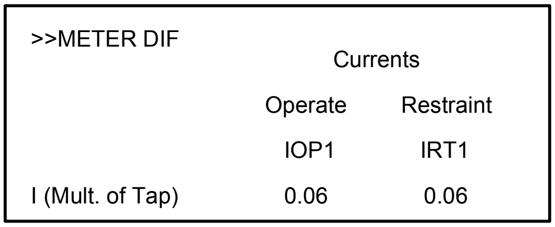


Figure 15 Loose PT Fuse

Example 7

In a transformer differential application, an engineer incorrectly set the transformer phase shift and CT connection compensation settings, creating a standing differential current measured by the relay during normal through-load conditions. See Figure 16. The settings mistake goes unchecked by technicians during commissioning of the station. During an external system fault, the relay operates, dumping all load from the substation.



```
>>METER DIF
                              Currents
                        Operate       Restraint
                         IOP1           IRT1
I (Mult. of Tap)         0.06           0.06
```

Figure 16 Incorrect 87T Compensation Settings

Example 8

Lastly, the C-phase CT in a transformer differential application is connected on an unintended tap position, sending a different and lower secondary current magnitude to the relay than intended, and from other phases. See Figure 17. This creates a standing difference quantity that is measured by the relay. The settings mistake goes unchecked by technicians during commissioning of the station. During an external system fault, the relay operates, shedding all load from the substation.

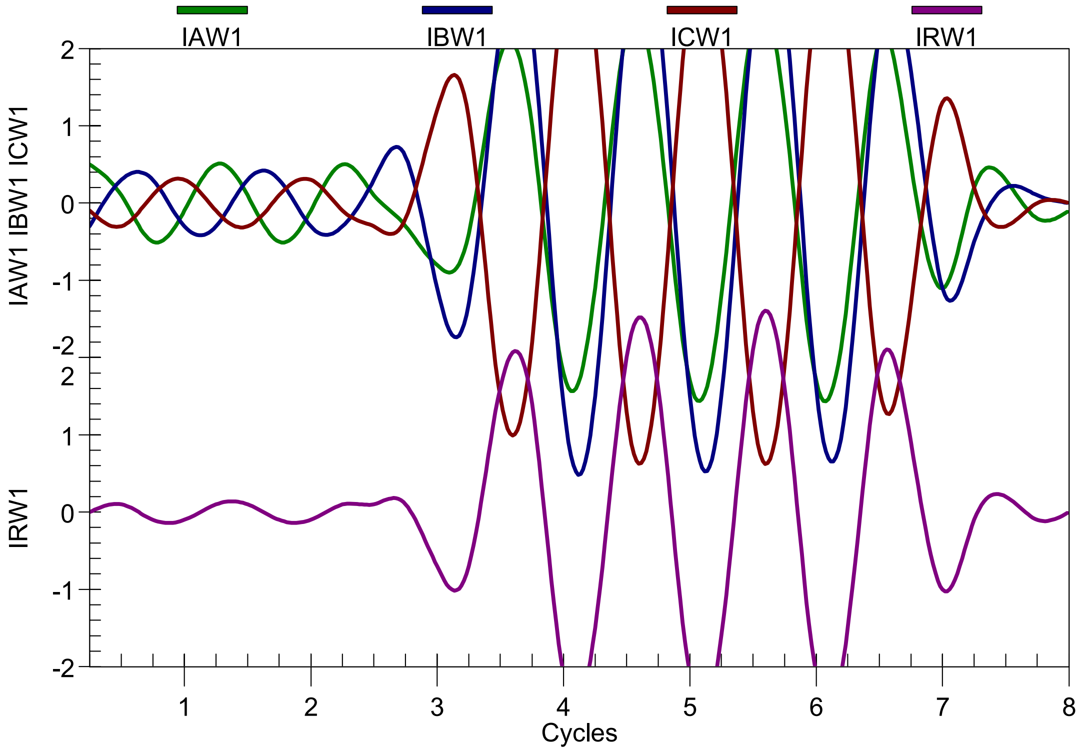


Figure 17 Incorrect CT Tap Wired

Using dual primary relays is good engineering practice. However, stopping there and not analyzing the entire protection system, relays plus all other components, invites misoperations. The relays are critical but are only one part of the entire protection system design that must be analyzed using quantitative reliability measures.

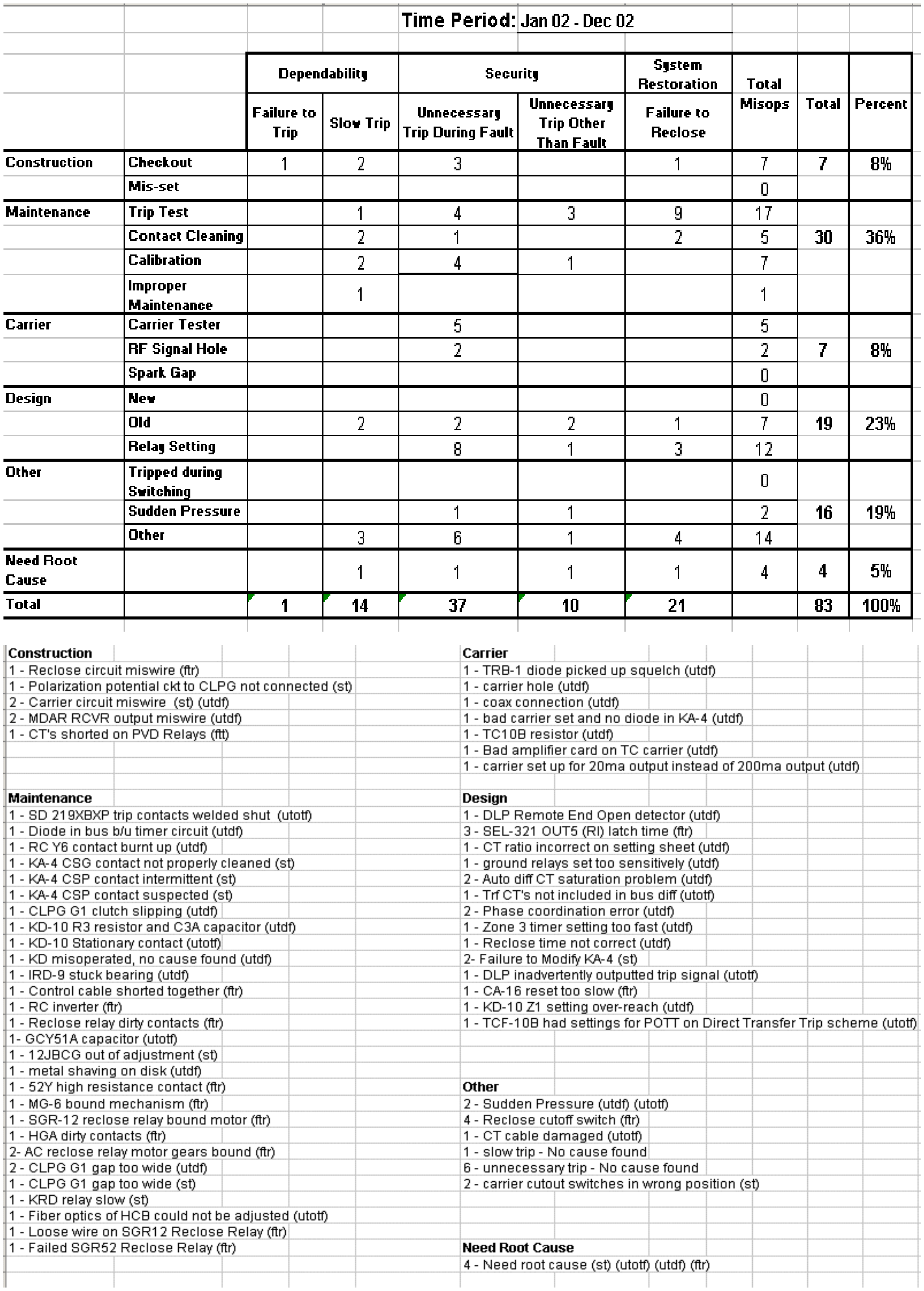
How Good Is Good Enough?

In 1996, a utility introduced their internal measures for protection performance [17]. Relay operations were categorized as successful, successful trip/unsuccessful reclose, unsuccessful operation, failure, unnecessary, and no conclusion. Overall effectiveness, dependability, and unnecessary events were then calculated.

IEEE/PSRC Working Group I3 produced a Performance Measuring Methodology, on which the utility's data were based. It provides a simple approach to analyzing the performance of the protection system. Another utility's results are shown. Their goal is 92 percent correct operations (out of 100 percent of the operations). See Figure 18 and Figure 19.

Note: Percent misoperations is equal to the (number of misoperations • 100) / (total # of events + k), where k is the number of misoperations for any common event minus one.

Ron Schwartz, Senior Vice President at SEL, likes to say "what gets measured, gets done." It is highly recommended that each and every operation be analyzed. If defined as a misoperation, root cause must be determined, so that solutions can be verified and implemented to improve reliability of the protection system.



Time Period: Jan 02 - Dec 02

		Dependability		Security		System Restoration	Total Misops	Total	Percent
		Failure to Trip	Slow Trip	Unnecessary Trip During Fault	Unnecessary Trip Other Than Fault	Failure to Reclose			
Construction	**Checkout**	1	2	3		1	7	**7**	**8%**
	Mis-set						0		
Maintenance	**Trip Test**		1	4	3	9	17	**30**	**36%**
	Contact Cleaning		2	1		2	5		
	Calibration		2	4	1		7		
	Improper Maintenance		1				1		
Carrier	**Carrier Tester**			5			5	**7**	**8%**
	RF Signal Hole			2			2		
	Spark Gap						0		
Design	**New**						0	**19**	**23%**
	Old		2	2	2	1	7		
	Relay Setting			8	1	3	12		
Other	**Tripped during Switching**						0	**16**	**19%**
	Sudden Pressure			1	1		2		
	Other		3	6	1	4	14		
Need Root Cause			1	1	1	1	4	**4**	**5%**
Total		**1**	**14**	**37**	**10**	**21**		**83**	**100%**

Construction
1 - Reclose circuit miswire (ftr)
1 - Polarization potential ckt to CLPG not connected (st)
2 - Carrier circuit miswire (st) (utdf)
2 - MDAR RCVR output miswire (utdf)
1 - CT's shorted on PVD Relays (ftt)

Maintenance
1 - SD 219XBXP trip contacts welded shut (utotf)
1 - Diode in bus b/u timer circuit (utdf)
1 - RC Y6 contact burnt up (utdf)
1 - KA-4 CSG contact not properly cleaned (st)
1 - KA-4 CSP contact intermittent (st)
1 - KA-4 CSP contact suspected (st)
1 - CLPG G1 clutch slipping (utdf)
1 - KD-10 R3 resistor and C3A capacitor (utdf)
1 - KD-10 Stationary contact (utotf)
1 - KD misoperated, no cause found (utdf)
1 - IRD-9 stuck bearing (utdf)
1 - Control cable shorted together (ftr)
1 - RC inverter (ftr)
1 - Reclose relay dirty contacts (ftr)
1- GCY51A capacitor (utotf)
1 - 12JBCG out of adjustment (st)
1 - metal shaving on disk (utdf)
1 - 52Y high resistance contact (ftr)
1 - MG-6 bound mechanism (ftr)
1 - SGR-12 reclose relay bound motor (ftr)
1 - HGA dirty contacts (ftr)
2- AC reclose relay motor gears bound (ftr)
2 - CLPG G1 gap too wide (utdf)
1 - CLPG G1 gap too wide (st)
1 - KRD relay slow (st)
1 - Fiber optics of HCB could not be adjusted (utotf)
1 - Loose wire on SGR12 Reclose Relay (ftr)
1 - Failed SGR52 Reclose Relay (ftr)

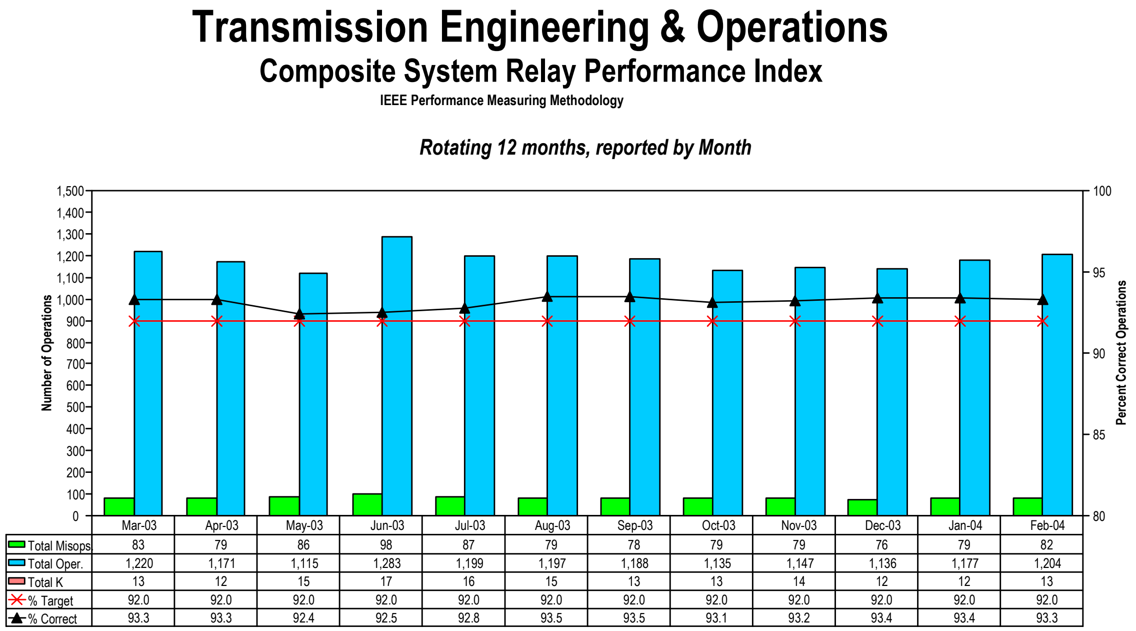
Carrier
1 - TRB-1 diode picked up squelch (utdf)
1 - carrier hole (utdf)
1 - coax connection (utdf)
1 - bad carrier set and no diode in KA-4 (utdf)
1 - TC10B resistor (utdf)
1 - Bad amplifier card on TC carrier (utdf)
1 - carrier set up for 20ma output instead of 200ma output (utdf)

Design
1 - DLP Remote End Open detector (utdf)
3 - SEL-321 OUT5 (RI) latch time (ftr)
1 - CT ratio incorrect on setting sheet (utdf)
1 - ground relays set too sensitively (utdf)
2 - Auto diff CT saturation problem (utdf)
1 - Trf CT's not included in bus diff (utotf)
2 - Phase coordination error (utdf)
1 - Zone 3 timer setting too fast (utdf)
1 - Reclose time not correct (utdf)
2- Failure to Modify KA-4 (st)
1 - DLP inadvertently outputted trip signal (utotf)
1 - CA-16 reset too slow (ftr)
1 - KD-10 Z1 setting over-reach (utdf)
1 - TCF-10B had settings for POTT on Direct Transfer Trip scheme (utotf)

Other
2 - Sudden Pressure (utdf) (utotf)
4 - Reclose cutoff switch (ftr)
1 - CT cable damaged (utotf)
1 - slow trip - No cause found
6 - unnecessary trip - No cause found
2 - carrier cutout switches in wrong position (st)

Need Root Cause
4 - Need root cause (st) (utotf) (utdf) (ftr)

Figure 18 Categorization of Operations and Root Cause Pareto Chart at One Utility



	Mar-03	Apr-03	May-03	Jun-03	Jul-03	Aug-03	Sep-03	Oct-03	Nov-03	Dec-03	Jan-04	Feb-04
🟩 Total Misops	83	79	86	98	87	79	78	79	79	76	79	82
🟦 Total Oper.	1,220	1,171	1,115	1,283	1,199	1,197	1,188	1,135	1,147	1,136	1,177	1,204
🟥 Total K	13	12	15	17	16	15	13	13	14	12	12	13
✕ % Target	92.0	92.0	92.0	92.0	92.0	92.0	92.0	92.0	92.0	92.0	92.0	92.0
▲ % Correct	93.3	93.3	92.4	92.5	92.8	93.5	93.5	93.1	93.2	93.4	93.4	93.3

Figure 19 Performance Statistics of the Overall Protection System from Another Utility

ANALYSIS OF RELAY FAULT DATA TO IMPROVE SERVICE RELIABILITY

Eighteen months of data from every operation on one utility's power system were analyzed for root cause [18]. This involved studying 1425 total events. Of the total, 66 were incorrect operations (security problems) and 13 were failures to operate (dependability problems). See Figure 20.

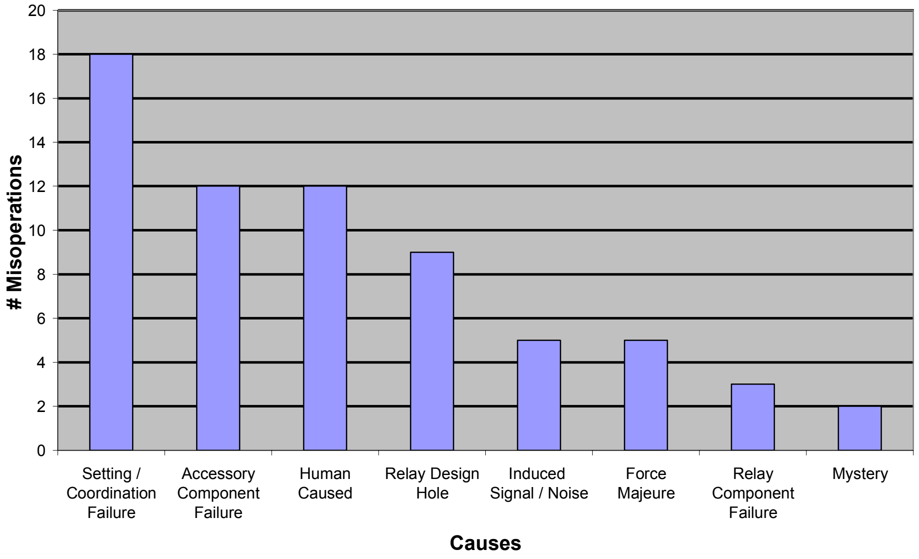


Figure 20 Root Causes of Misoperations

Of all failures to trip, there were none attributed to relay design holes. See Figure 21. In fact, only one event in over 1400 was attributed to relay component failure at all, a failure to trip. And this was due to a component failure in a 55-year-old electromechanical pilot wire relay with no automatic self-testing.

The conclusions of the paper state that false trips outnumber failure to trips by a factor of *five to one*. Despite this, the emphasis at many utilities remains firmly on dependability and using different manufacturers' relays connected in parallel in trip circuits. These data suggest that these efforts may be misplaced, if in fact the goal is to achieve the highest reliability possible.

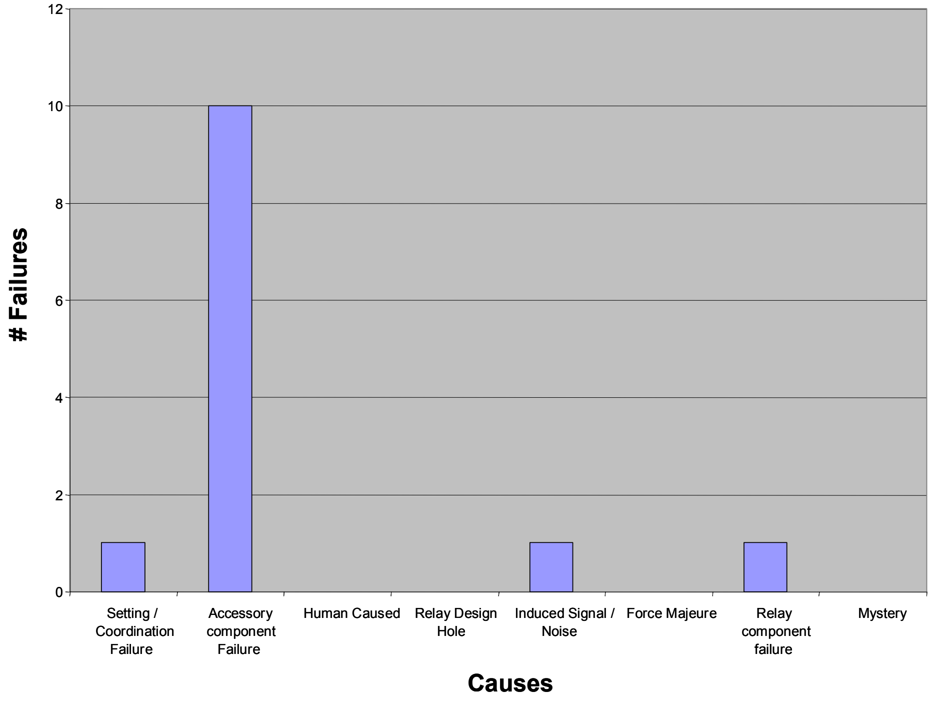


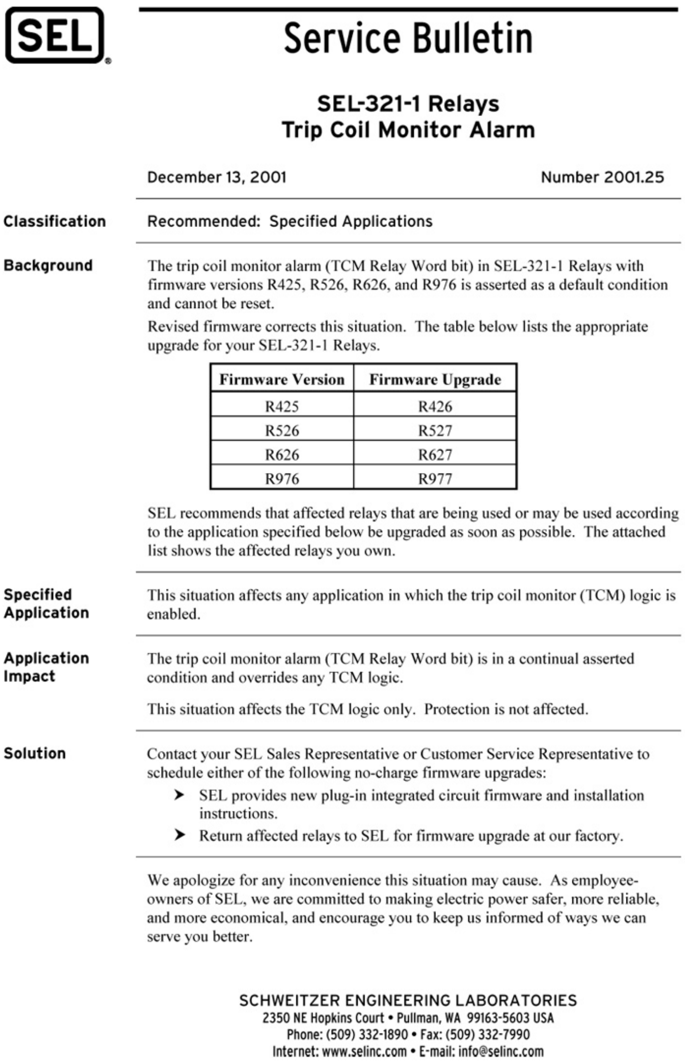
Figure 21 Root Causes of Failures

REVIEW OF FAILURE RATE AND MTBF

Assume the following important measures of failure rates and reliability:

- A utility has a population of 300 devices in service January 1.
- At the end of one year, total service years = 300 devices • 1 year = 300 years.
- Three device failures occur in that same year.
- The device failure rate = 3/300 = 0.01 failures/year = 1% failure rate.
- The device MTBF = 300/3 = 100 years.

A more conservative estimate than MTBF is the Mean Time Between Removals (MTBR), which includes all "no problems found" returns as real failures (that is, failures reported by a customer, but not repeatable by SEL, are assumed to be real), as well as firmware failures. An even more stringent measure used by SEL is the Maintenance Indicator (MI), which further adds Service Bulletin-related maintenance activities to documented failures, despite the fact that many of these activities are proactive, done before an actual failure in the field has occurred. An example Service Bulletin is shown in Figure 22.



SEL

Service Bulletin

SEL-321-1 Relays
Trip Coil Monitor Alarm

December 13, 2001 Number 2001.25

Classification Recommended: Specified Applications

Background The trip coil monitor alarm (TCM Relay Word bit) in SEL-321-1 Relays with firmware versions R425, R526, R626, and R976 is asserted as a default condition and cannot be reset.

Revised firmware corrects this situation. The table below lists the appropriate upgrade for your SEL-321-1 Relays.

Firmware Version	Firmware Upgrade
R425	R426
R526	R527
R626	R627
R976	R977

SEL recommends that affected relays that are being used or may be used according to the application specified below be upgraded as soon as possible. The attached list shows the affected relays you own.

Specified Application This situation affects any application in which the trip coil monitor (TCM) logic is enabled.

Application Impact The trip coil monitor alarm (TCM Relay Word bit) is in a continual asserted condition and overrides any TCM logic.

This situation affects the TCM logic only. Protection is not affected.

Solution Contact your SEL Sales Representative or Customer Service Representative to schedule either of the following no-charge firmware upgrades:

- SEL provides new plug-in integrated circuit firmware and installation instructions.
- Return affected relays to SEL for firmware upgrade at our factory.

We apologize for any inconvenience this situation may cause. As employee-owners of SEL, we are committed to making electric power safer, more reliable, and more economical, and encourage you to keep us informed of ways we can serve you better.

SCHWEITZER ENGINEERING LABORATORIES
2350 NE Hopkins Court • Pullman, WA 99163-5603 USA
Phone: (509) 332-1890 • Fax: (509) 332-7990
Internet: www.selinc.com • E-mail: info@selinc.com

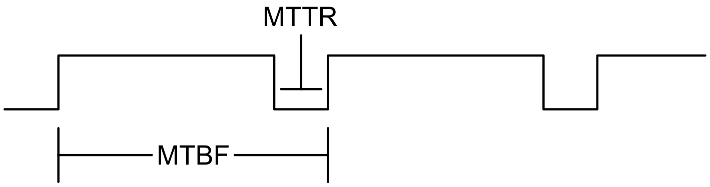
Figure 22 SEL Service Bulletins Notify Customers of Product Improvements

It is important to note that SEL records the date when a particular serial number relay is sold and tracks products by end user, sale date, and serial number. From that, a good approximation of the relays in service in a given year can be developed. We know the installed base of SEL relays. SEL records all reported failures and repairs failed products at one factory location in Pullman, Washington. From these data, we calculate our observed MTBF, MTBR, Initial Quality (IQ), and MI. To the best of our knowledge, SEL is the only relay manufacturer that records and discloses observed reliability data.

These data are critical to SEL. They are used daily in root cause analysis and the improvement of designs and manufacturing of products. To our customers, however, these data provide important input to reliability-based design tools such as fault tree analysis.

FAILURE, REPAIR, AND UNAVAILABILITY

Assume that relay self-tests detect a problem within seconds, but it takes two days to repair the failure once detected. If the alarm contact is monitored, then the relay will be back in service in two days, and the unavailability of the protection system is then the actual failure rate of the system times Mean Time to Repair (MTTR), or 0.01 failures/year times 2 days = 0.02 days/year. See Figure 23. The MTTR is the sum of the mean time to detect plus the mean time to repair or replace.



Failure Rate $\lambda = \dfrac{1}{\text{MTBF}}$

Unavailability $q = \dfrac{\text{MTTR}}{\text{MTBF}} = \lambda \bullet \text{MTTR}$

Figure 23 Definition of Protection System Unavailability

Suppose the alarm contact is not monitored continuously, and failures are only discovered during misoperation or maintenance testing, done once every two years. This was common in the electromechanical relay era. Assume that we repair problems the same day we find them. If a maintenance test detects the failure, then on average the relay was down for 1 year (MTTR = 1 year). The unavailability, then, is the failure rate times the MTTR, or 0.01 failures/year times 365 days = 3.65 days/year. This is 183 times worse—automatic self-testing and remote monitoring of self-testing pays off!

Unavailability is only part of the analysis, however. We can further estimate the likelihood or probability that a fault will occur during the time when protection is unavailable. Assuming 100 faults per year, for example, and multiplying times the unavailability produces the number of missed faults possible in a given year. For example, 100 faults per year times an unavailability of 2 percent yields two missed faults per year. See Figure 24.

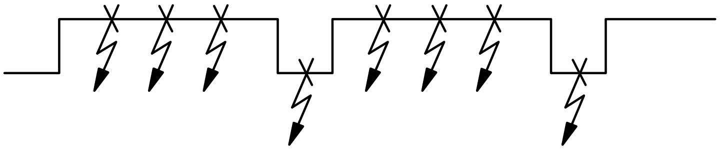


Figure 24 Probability That a Fault Occurs During Protection System Unavailability

Using dual SEL relays improves service availability for many reasons, including the following SEL processes:

- Ongoing reliability tests
- Highly Accelerated Life Tests
- Weekly analysis of data for elevated failure rates
- Customer notification of known problems through Service Bulletins

QUANTIFYING ATTRIBUTES OF SYSTEMS USING FAULT TREE ANALYSIS

First used by H. A. Watson of Bell Laboratories to analyze the Minuteman Launch Control System, fault tree analysis is a reliability-based, quantitative design tool that helps model system elements and determine factors that influence failure and overall reliability [19]. The aviation and nuclear industries use this design methodology.

Reliability can be quantified by comparing unavailability for devices and systems. The unavailability for systems is determined by combining the unavailability of system devices. The unavailability, q, is calculated using MTTR and MTBF.

Fault trees can be tailored to study different failure modes of interest, that is, either failure to trip (dependability) or undesired trip (security). They are practical, graphical, and easy to use [5].

Small fault trees, which are easy to analyze manually, are very useful. The process can help compare complex systems, quantifying attributes of each system. This produces useful results, even with approximate failure rate data. The end result is product selection, system design, and applied resources with greater impact.

By concentrating on those components that produce the largest impact on system unavailabilities/failure rates, we can find practical improvements:

- Add redundancy
- Eliminate dependencies
- Reduce MTTR—monitor alarms
- Reduce MTTR—improve repair times
- Increase MTBF—use devices with lower failure rates
- Modify schemes based on fault tree results, event analysis, and lessons learned

Increasing MTBF by using higher reliability products and eliminating human errors through duplication of common settings, wiring, and procedures is accomplished through the use of dual primary SEL relays.

Fault Tree With Redundant Relays

The first step in constructing a fault tree is to pick the top event (see Figure 25). Use OR gates to combine events that can singly cause upper events (SUM unavailabilities). Use AND gates to combine events that must happen together to cause upper events (MULTIPLY unavailabilities).

Break down the system into events for which you can obtain or estimate reliability data. Remember, even if approximate data are used, the main benefit of comparing scheme designs is still easily achieved and very useful results are attained. Review fault trees for common causes of failure or to identify the weakest link in a design.

Interesting studies using fault tree analysis include determining the relative advantage to adding relays and connecting them in different methods, such as:

- Single relay
- Two relays with trip contacts in parallel
- Two relays with trip contacts in series
- Two-out-of-three voting scheme

What is the relative advantage of different schemes on dependability (failure to trip as the top event)? What is the relative advantage of different schemes on security (inadvertent tripping for an out-of-section fault or load)? What is the relative advantage of adding independent relays and communications channels? What is the effect on failure rate of humans when different manufacturers' relays are introduced? These are interesting angles to consider when designing schemes, and fault tree analysis is a useful tool in making decisions based on data and sound analysis, rather than gut feel.

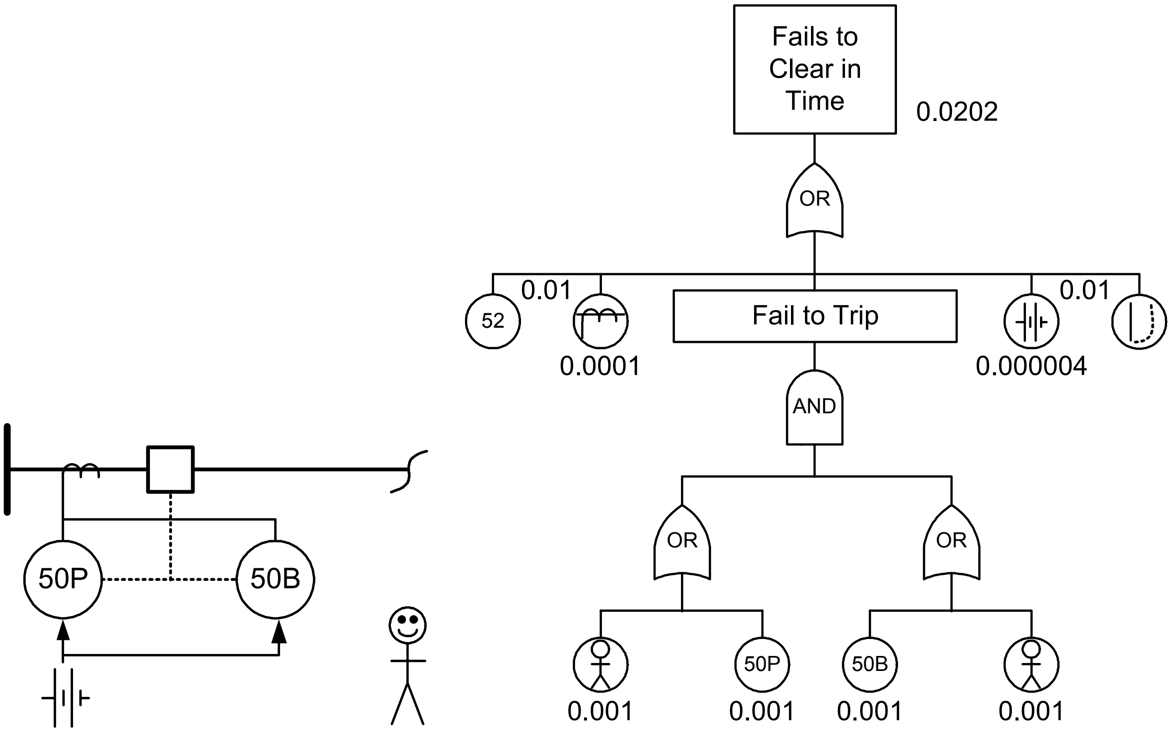


Figure 25 Fault Tree With Redundant Relays

USE SEL RELAYS TO INCREASE DEPENDABILITY

These are some of the advantages of SEL relays which increase the dependability and availability of protection schemes:

- Low initial cost, meaning affordable redundancy
- Low failure rates (higher MTBF)
- SEL worldwide, ten-year product warranty
- SEL has never charged for service
- SEL does not charge when “no trouble found”
- 72-hour turnaround: receipt to shipment
- Urgent? Fastest possible, verbal commitment on repairs
- Technical support that is unmatched in the industry

SEL OFFERS UNSURPASSED TECHNICAL TRAINING AND SUPPORT

At technical seminars, such as the annual WPRC Technical Seminar, SEL introduces new products and technology. SEL participates in and supports all major industry conferences.

Featured short courses and training workshops are well advertised and offered locally and often.

SEL University bridges the gaps between academia and industry by offering computer-based courses, power system and integration fundamentals courses, and hands-on application and product classes.

Field application engineers assist with selection, application, training, setting, interpretation of data, and all aspects of customer technical service. SEL sales representatives, customer service representatives, and factory personnel respond quickly. Simply put, SEL strives continuously to provide the best technical training and support in the industry.

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SEL System Solutions Address Power System Problems
2004
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Calendar of Events
2004 Training Workshops in the Southwest
SEL SCHWEITZER ENGINEERING LABORATORIES Online
Technical Service Centers
SEL
I-44
RELAY CONFERENCE
FEATURED
Topic-of-the-Month
TRAINING

Figure 26 SEL Offers Unmatched Technical Support

Conclusions

1. Same-manufacturer redundancy and sole-sourcing are used in other reliability-conscious industries.
2. There are a wide variety of control schemes employed by utilities.
3. The use of SEL for dual primary is not prohibited.
4. Reliability council design guidelines are valuable but in many cases leave much room for subjective interpretation.
5. Dependability and fear of common-mode failures are only two of the topics in operating guide criteria—others include overall reliability, speed, simplicity, and security.
6. Dual primary schemes (but not necessarily dual manufacturer) offer enhanced reliability.
7. Surveys prove that the dual primary, same manufacturer solution is gaining momentum.
8. Common platform and power supply concerns are best addressed with data rather than gut feel.
9. Quantitative root cause analysis of events and performance analysis are invaluable to improving overall system performance.
10. Fault tree analysis provides a practical means to evaluate complete system designs.
11. Observed reliability data are useful in design tools and operations improvements.
12. SEL offers industry-best technical support, training, quality, and reliability.

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BIOGRAPHY

David Costello graduated from Texas A&M University in 1991 with a BSEE. He worked as a system protection engineer at Central Power and Light and Central and Southwest Services in Texas and Oklahoma. He has served on the System Protection Task Force for ERCOT. In 1996, David joined Schweitzer Engineering Laboratories, Inc. where he has served as a field application engineer and regional service manager. He presently holds the title of senior application engineer and works in Boerne, Texas. He is a senior member of IEEE and a member of the planning committee for the Conference for Protective Relay Engineers at Texas A&M University.

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