

Assessing the Effectiveness of Self-Tests and Other Monitoring Means in Protective Relays

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INTRODUCTION

Microprocessor-based protective relays perform self-tests to determine that the relay subsystems are functioning properly. An earlier paper by these authors [1] showed that reliance on relay self-testing features safely allows the utility to increase the traditional routine maintenance interval for those relays.

This paper further defines digital relay self-test effectiveness. Digital relay monitoring methods are presented which extend the relay self-test capabilities. Statistical models quantify the benefits of relay self-tests and illustrate the usefulness of the additional monitoring features. The results suggest a new model for routine digital protective relay monitoring and maintenance:

- Monitor digital relay self-test alarm contacts.
- Monitor digital relay loss-of-signal alarms, when available.
- Analyze event reports as soon as possible following each event.
- Use relay output control functions to verify output contacts, if faults are infrequent.
- Compare relay meter readings to other meters to verify calibration of both devices.

WHY TEST PROTECTIVE RELAYS?

The goal of protective relay testing is to maximize the availability of protection and minimize risk of relay misoperation. With this in mind, we must define adequate testing and monitoring practices for digital protective relays.

DIGITAL RELAY SELF-TESTS

Digital relays use a microprocessor, an ac signal data acquisition system, memory components containing the relay algorithms, contact inputs to control the relay, and contact outputs to control other equipment. The algorithms and settings contained in the relay memory define the protection characteristics.

Digital relays usually include automatic self-test functions. These self-tests verify correct operation of critical relay components. If a self-test detects an abnormal condition, the relay can close an output contact, send a message, or provide some other indication of the failure. The relay disables trip and control functions on detection of certain self-test failures.

Since self-tests are executed often in the digital relay, they detect component failures soon after they occur. As a minimum, digital relay self-tests include tests of memory chips, a/d converter, power supply, and microprocessor.

It is convenient to consider digital relays in three sections:

- 1) Analog Input Section
- 2) Contact Input/Output Circuitry
- 3) Processing Section

The analog input section consists of the signal connections, isolation transformers, low-pass filters, one or more multiplexers, and an analog-digital converter. Automatic self-tests partially monitor the analog input section. Since the analog input portion is not fully self-tested, maintenance practices should verify the analog input components.

The contact input/output circuitry is another part of the digital relay that allows only partial automatic testing. It is possible to design output hardware that is fully redundant and verifiable through self-tests. However, the existing hardware is reliable, so the additional cost of more complex hardware is not justified. Routine verification of the output contacts and optoisolator inputs is appropriate when the equipment does not operate regularly in response to faults.

The digital processing section, typically a microprocessor, is the interface between the analog input section and the contact input/output section. Self-tests monitor the processor and associated memory components. Since the analog and contact input/output sections cannot function without the processing section, normal use also verifies the relay processing section.

Self-test effectiveness defines the portion of all relay failures that can be detected by the relay self-test functions. Field data shows that a practical value of self-test effectiveness is 80%. While it would be possible to devise relay hardware and software that could detect nearly all relay failures, it is likely that such a relay would be too expensive to use. Therefore, it is important for relay vendors to devise reliable hardware, and incorporate simple tests that detect as many failures as possible. In order to benefit from relay self-test operation, the utility should monitor the self-test alarm contact outputs of all digital relays.

ADDITIONAL RELAY MONITORING FEATURES

Utilities should use these additional monitoring functions to detect failures in the analog input section and contact output section, augmenting the relay self-testing capabilities.

Many relay maintenance features are executable by remote command and often could replace routine maintenance altogether. Relays that do not regularly operate for faults may require more thorough routine checks.

Loss of Relaying Voltage or Current Features Act as Self-Tests

Many digital distance relays include features that detect the removal of ac voltage or ac current. The loss of voltage (LOV) element and the loss of current (LOI) element are two such features. Most relays use the presence of certain phase or sequence currents and voltages to differentiate genuine fault conditions from blown fuse or open current transformer secondary conditions. In addition to verifying the security of the signal wiring, these monitoring features also detect certain types of analog input failures that could occur inside the relay.

For instance, if an instrument voltage transformer in a relay fails, the relay can detect and indicate an LOV condition. The utility can monitor the LOV signal, compare it to similar signals from other relays connected to the signal source, determine the point of failure, and repair it before a misoperation occurs. The LOV feature is a self-test applied to the relay and to some equipment outside the relay.

Metering

Digital relay metering features give the user a convenient means of verifying the presence and accuracy of the relay analog inputs. When relay signal sources and input channels are operating correctly, the relay meter quantities should match the outputs of other meters measuring those signals.

The advantage of a meter test is that the relay remains in service and capable of clearing faults while the test is in progress. A meter test could be executed on a nearly continuous basis without reducing relay availability.

The meter test practice is sound if the digital relay uses the same measuring circuitry for both metering and relaying. If the relay uses separate circuitry for its metering functions, the metering data checks only those components common to both the metering and relaying circuitry. In this instance, some additional check must be made to verify the relay element measurements.

Relay Event Data Analysis Detects Problems

Event reports generated by the digital relay in response to a fault often contain:

- Prefault and fault current and voltage measurements.
- Indication of the relay contact input and output states through the event.
- Relay setting and element operation information.

Event report analysis is a valuable maintenance tool. The event report concisely shows that the relay is measuring ac signals and receiving dc contact input signals. When the relay closes output contacts, it is shown in the event report.

Analysis of digital relay fault data is preferable to routine relay maintenance because an actual fault is a true test of the instrument rather than a simulated test. Power system responses to the relay control signals should be discernable from information in the event report. A brief review of the event report can indicate failures in the external connections or internal components of the analog input section or contact input/output section. Many times, improvements in the protection scheme can be discovered by reviewing the contents of event reports [2]. The ability of the relay to store and deliver the event report further verifies the relay processing section.

Exercising Output Contacts

Many digital relays provide a feature that allows the user to control the relay output contacts. This check verifies the output contact and the integrity of the external wiring. A trip command feature provides a convenient means of tripping the circuit breaker without requiring a test set.

If the relay routinely operates correctly for faults, the actual contact operations are adequate verification of the relay input/output functions.

DIGITAL RELAY MAINTENANCE PRACTICES

Routine testing was the primary method of detecting protective relay failures. The only other way of determining that a relay failed was to observe a misoperation. Routine testing was scheduled based on utility experience with the devices in question and the resources available to perform the tests. Tests tended to be thorough, but complex and time consuming.

Digital relay routine testing practices should verify relay functions that cannot be fully verified by the relay self-testing. Figure 1 shows how all relay failures can be detected using a regime consisting of:

- Self-test alarm monitoring
- Loss of signal (LOV, LOI) monitoring
- Review of relay event reports
- Periodic checks of relay inputs and outputs
- Periodic calibration check by comparison

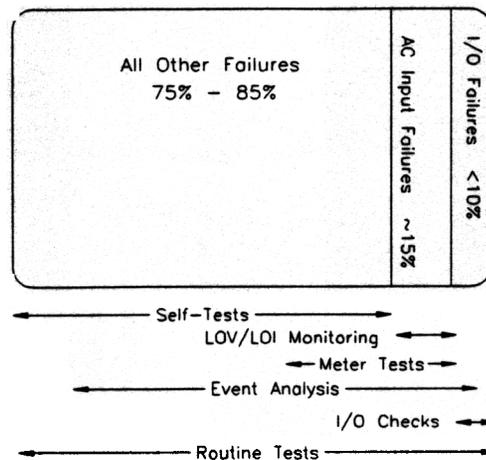


Figure 1: Digital Relay Self-Testing and Monitoring Functions Entirely Replace Traditional Routine Tests

Relay self-testing and event data analysis detect the majority of relay failures. Monitoring LOV and LOI functions, executing meter tests and Input/Output checks verify the balance of relay functions. Taken together, this regime replaces complex routine tests. These simple tests can be performed quickly, minimizing the need for complex test equipment.

PROBABILITY APPLIED TO RELAY TESTING METHODS

Having defined the necessary tests and monitoring methods, it is now necessary to optimize the testing interval. Several papers [1,3,4] describe probabilistic methods of determining the optimum test interval for protective relays. Two probability measurements of interest are Abnormal Unavailability and Protection Unavailability.

The model assumes that when a fault occurs while the relay is out of service, a larger portion of the power system is isolated than was actually necessary to remove the fault. Abnormal Unavailability is the unavailability of the power system that occurs as a direct result of the relay misoperation.

The Protection Unavailability is the probability that the relay will be out of service. The relay could be out of service because of a failure, testing, or repairs.

The purpose of the statistical analysis is to define practices that minimize the unavailability of the relay and protected power system.

Reference [1] introduced a nine-state model defined by the operating condition of the relay and the protected component. The model accounts for relay self-testing, but does not account for other monitoring means. Figure 2 shows a ten-state model that accounts for self-testing and models routine relay verification through other simple checks. The circles represent the model states. The arrows represent the transition paths between the states.

The probability model is divided into four quadrants representing the condition of the relay (Protection) and the line (Component). State 1 represents a normal operating condition where the line is energized (Component UP) and the relay is operating properly (Protection UP). When a line fault occurs, the Component makes the transition to a down state, represented by State 2. In State 2, the line is faulted and the relay signals the circuit breaker to trip. Circuit breaker operation takes the model system to State 6, where the line is isolated. The line is repaired and re-energized, taking the model back to State 1.

States 5, 3, 9, and 10 represent conditions where the relay is out of service and unavailable to trip if a fault occurs. In State 5, the relay is out of service for routine testing. In States 3, 9, and 10, the relay is out of service due to a relay failure. State 9 represents the relay under repair. The model enters State 9 from State 1 when a relay self-test detects a failure. The model system enters State 9 from State 3 when a routine test detects a relay failure. The model enters State 9 from State 10 when a meter check detects a failure.

The model enters State 3 from State 1 when a relay failure occurs that is not detected by the relay self-test function and could not be detected by meter checks.

Represent relays with varying degrees of self-test effectiveness by adjusting ST (see definitions that follow). The overall relay failure rate (F_p) is multiplied by ST, to indicate the portion of failures detected by self-tests or loss of signal (LOV/LOI) functions.

The effectiveness of meter checks is adjusted using ME. Multiply F_p by ME to indicate the portion of failures detected by meter tests. Failures not detected by either self-tests or meter tests are only detected by routine testing or by observing a misoperation.

The model enters State 4 if a fault occurs while the relay is out of service, or if a common-cause failure of the relay and power system occurs. If a fault occurs while the relay is out of service, remote backup protection operates to isolate the fault. When the remote protection operates, a larger portion of the power system is taken out of service than would have been if the failed relay had operated properly. This is represented in State 4 and State 8 by the isolation of C and X, where X is the additional equipment removed from service by the backup relay trip operation.

Repair Rates:

- R_c Protected component repairs per hour
- R_t Relay routine inspections per hour
- R_r Relay repairs per hour

Switching Rates:

- S_n Normal tripping operations per hour (reciprocal of normal fault clearing time)
- S_b Backup tripping operations per hour (reciprocal of backup fault clearing time)
- S_m Manual isolation operations per hour

Inspection Rates:

- I_{pm} Protection routine inspection interval, hours
- Θ_{pm} Protection routine inspection rate ($1/I_{pm}$)
- I_{me} Protection meter inspection interval, hours
- Θ_{me} Protection meter inspection rate ($1/I_{me}$)

Unless otherwise noted, the model uses the following transition rates:

- $F_p = 0.01$ relay failures per year (MTBF = 100 years)
- $R_r = 0.5$ relay repairs per hour
- $R_t = 2.0$ relay routine tests per hour
- $R_c = 0.5$ component repairs per hour
- $F_{cc} = 1.0$ common-cause failure per million hours
- $S_n = 43200$ operations per hour (reciprocal of 5-cycle fault clearing time)
- $S_b = 10800$ operations per hour (reciprocal of 20-cycle backup fault clearing time)
- $S_m = 0.5$ operations per hour (2 hours to isolate component after backup operation)

RESULTS CALCULATED USING THE NEW STATISTICAL MODEL

From the model, we can calculate the Abnormal Unavailability and Protection Unavailability of relays with or without self-tests and with or without meter tests, simply by adjusting the transition rates that define the model.

Figure 3 shows the Abnormal Unavailability versus routine test interval for a system using a relay that does not have self-testing, signal monitoring, or metering features. The plot is for a relay protecting a line that is faulted twice per year. The optimum routine test interval is the point where Abnormal Unavailability is lowest: approximately 700 hours or 1 month. When the test interval is shorter, the relay is often out of service due to testing. In this area, the relay is being tested too much and is likely to miss any fault that occurs. When the test interval is longer, the relay becomes more likely to be out of service because of an undetected problem: the relay is being tested too little.

The model results indicate, to achieve the highest reliability, the relay test interval should be much shorter than the interval between faults. They also suggest that, if possible, the relay should be left in service while the tests are performed. This is precisely what automatic self-tests and meter checks do for digital relays.

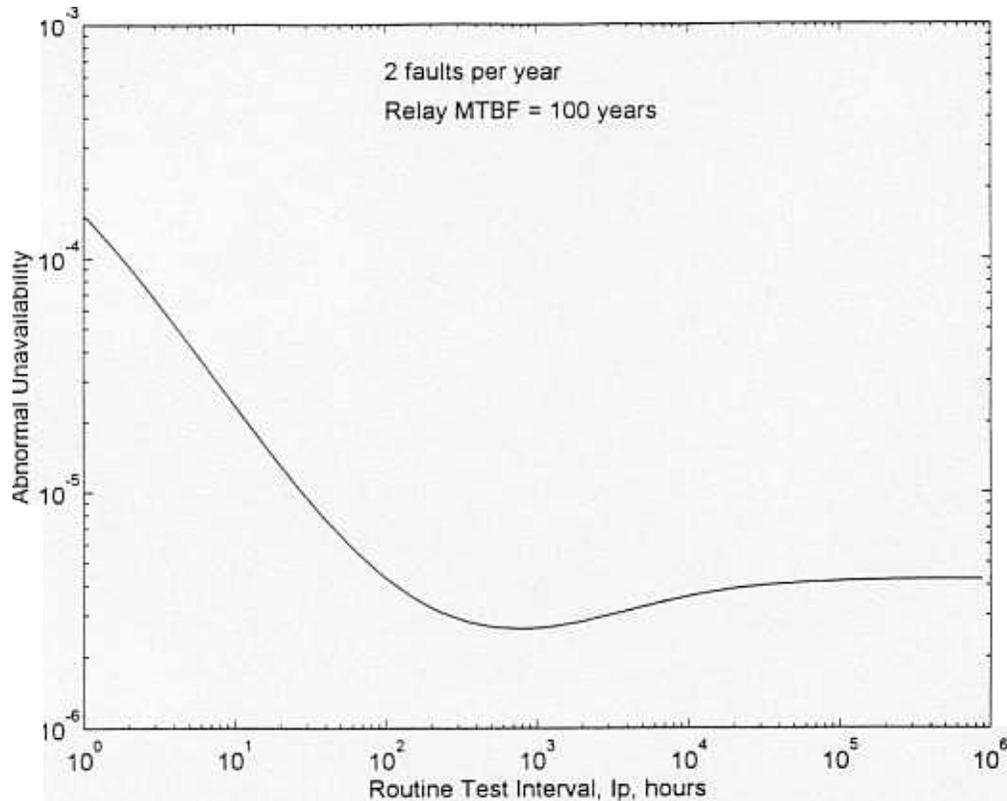


Figure 3: Optimum Test Interval for a Relay Without Self-Tests

Figure 4 compares relays with and without self-tests on the basis of Protection Unavailability. Figure 4 shows traces representing four types of relay self-tests. When $ST = 0\%$, the relay is not equipped with self-testing. When $ST = 50\%$, the relay self-tests detect half of all relay failures immediately. When $ST = 90\%$ and 99% , the relay self-tests detect 90% and 99% of relay failures, respectively. In this example, meter tests are not used, therefore failures not detected by self-tests are only detected when the relay is routine tested or when a misoperation occurs.

Figure 4 shows that a relay without self-tests ($ST = 0\%$) is ten times as likely as a digital relay with 90% self-tests to be out of service due to a relay failure when the routine test interval is 10^5 hours (approximately 11 years). The non-self-testing relay is 100 times as likely as the relay with 99% self-tests to be out of service. In addition, the relay featuring 99% self-tests shows a decreasing Protection Unavailability as the test interval increases. This relay is less likely to miss a fault if the test interval is longer. This yields a surprising result: to improve availability, test such a relay less frequently. Figure 5 shows the Abnormal Unavailability of the same four systems.

Figures 4 and 5 illustrate one further important point: as relay self-test effectiveness increases, reliance on other testing types can be safely reduced.

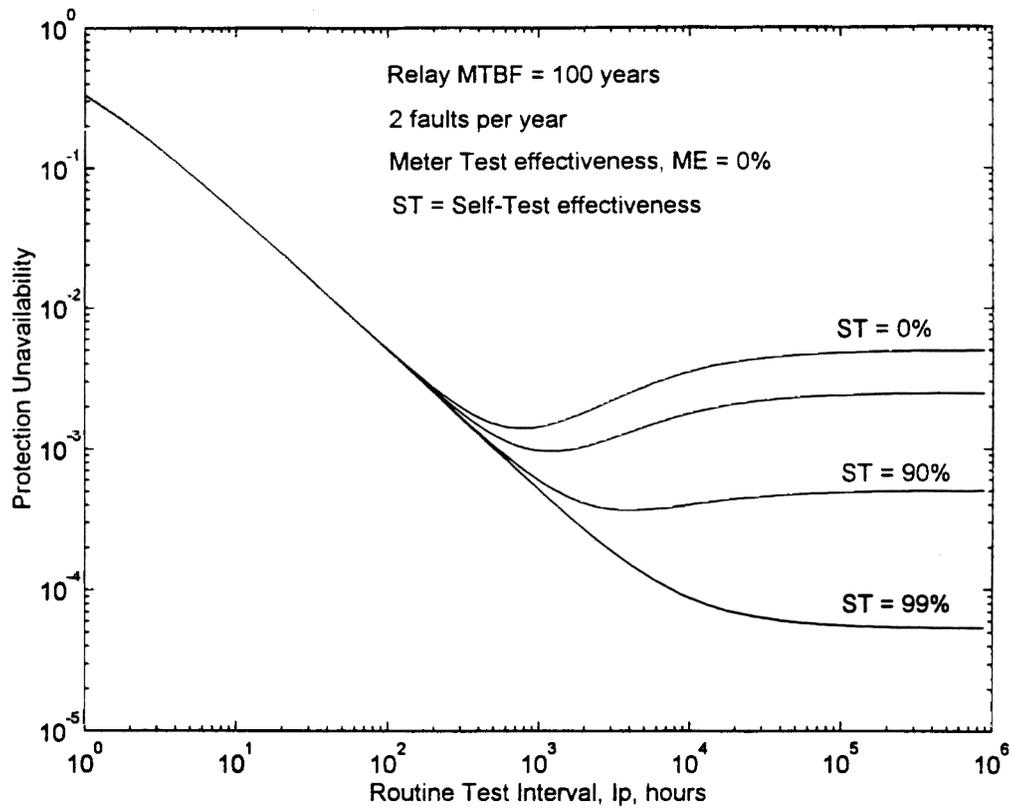


Figure 4: Value of Relay Self-Tests

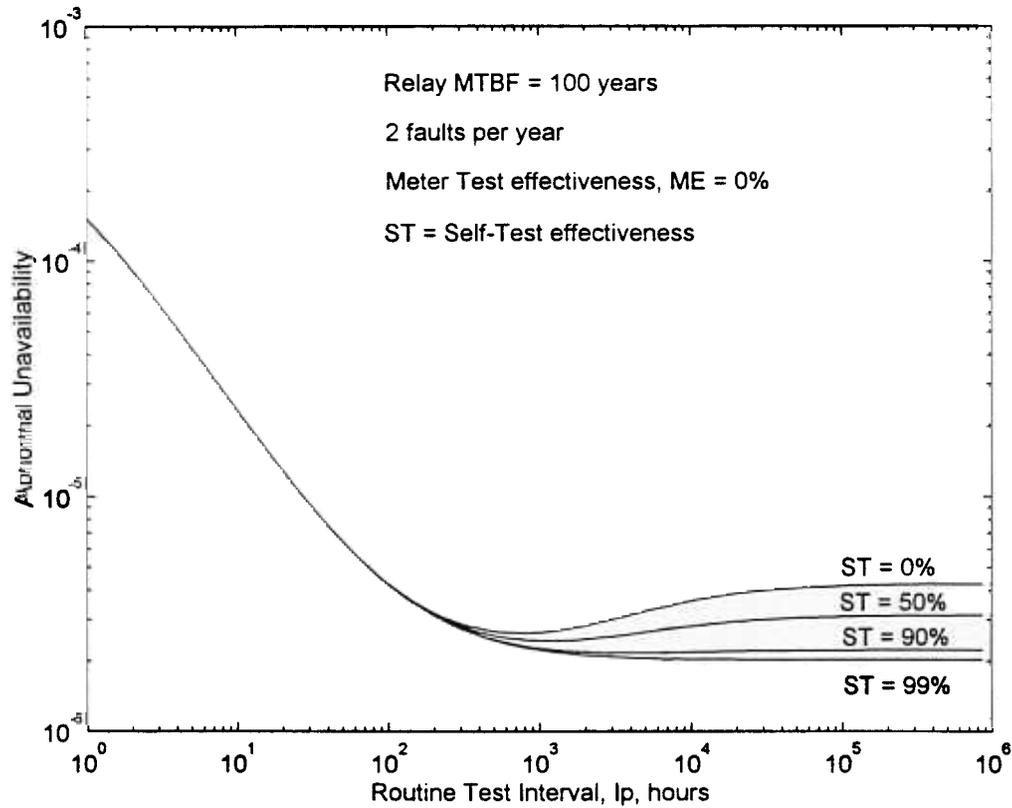


Figure 5: Value of Relay Self-Tests

When examining self-test effectiveness for a particular model or brand of relay, it is necessary to consider the additional monitoring methods described earlier. The first method illustrated is the periodic meter test.

Figure 6 shows the effect of periodically reviewing the relay meter function output to determine that the relay analog input section is operating correctly. To simplify the illustration, the routine maintenance interval is fixed at five years. Contact I/O checks would be performed at this interval. A self-test effectiveness of 80% is selected, based on actual field performance of one type of digital protective relay.

When $ME = 0\%$, the meter function does not detect relay failures, so the meter test interval has no impact on system Abnormal Unavailability. When $ME = 20\%$, meter tests detect 20% of relay failures.

When meter test effectiveness is 20%, the optimum meter test interval is about 500 hours, or three weeks. This is about 8 times as frequently as faults occur. While adding meter tests does provide some benefit to the system availability, we see from Figure 6 that the incremental benefit of adding meter tests is not nearly as great as the benefit of monitoring relay self-test alarms.

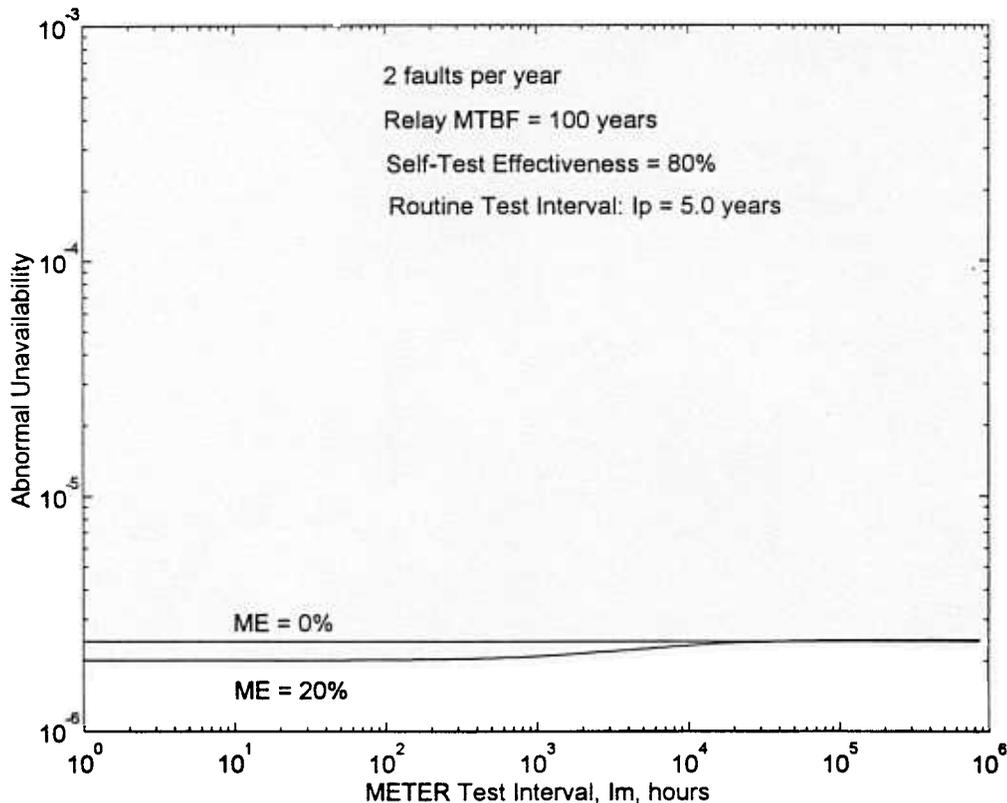


Figure 6: Benefit of Performing Meter Tests

Figure 7 shows the value of using ac signal monitoring functions, such as LOV and LOI, to augment the relay self-tests. If we assume that the LOV and LOI functions detect 10% of failures immediately, we can add 10% to the self-test effectiveness index when LOV and LOI monitoring is added.

This is legitimate because the ac signal monitoring functions detect certain types of failures as quickly as the relay self-tests.

In Figure 7, the trace marked "No Monitoring" assumes that the utility monitors the relay alarm contact, but does not monitor the condition of the ac signals using LOV or LOI functions. The self-test effectiveness is 80% and 18% of failures are detected by periodic execution of the meter function. The trace marked "Monitoring" assumes that the utility monitors the self-test alarm and uses available ac signal monitoring functions to detect a total of 90% of relay failures immediately. Meter tests detect 8% of failures. In both cases, the remaining 2% of failures are detected by contact input/output tests performed on a five-year interval.

Figure 7 shows that meter tests decrease the Abnormal Unavailability when executed frequently. However, the value of adding the meter tests is small.

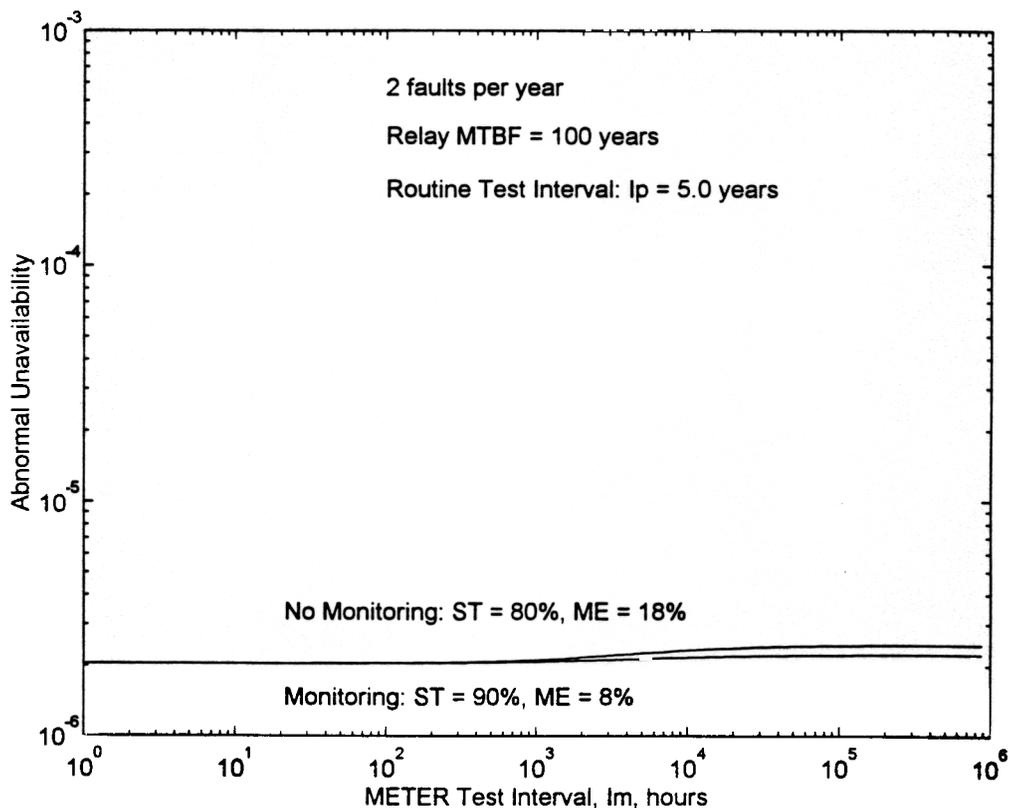


Figure 7: Using AC Signal Monitoring as a Self-Test

Figure 8 shows a plot Protection Unavailability versus routine test interval for three relays. Relay 1 has no self-testing. Relay 2 has self-tests with 80% effectiveness. Relay 3 has self-tests with 80% self-test effectiveness, augmented by monitoring of available LOV/LOI functions that detect another 18% of relay failures.

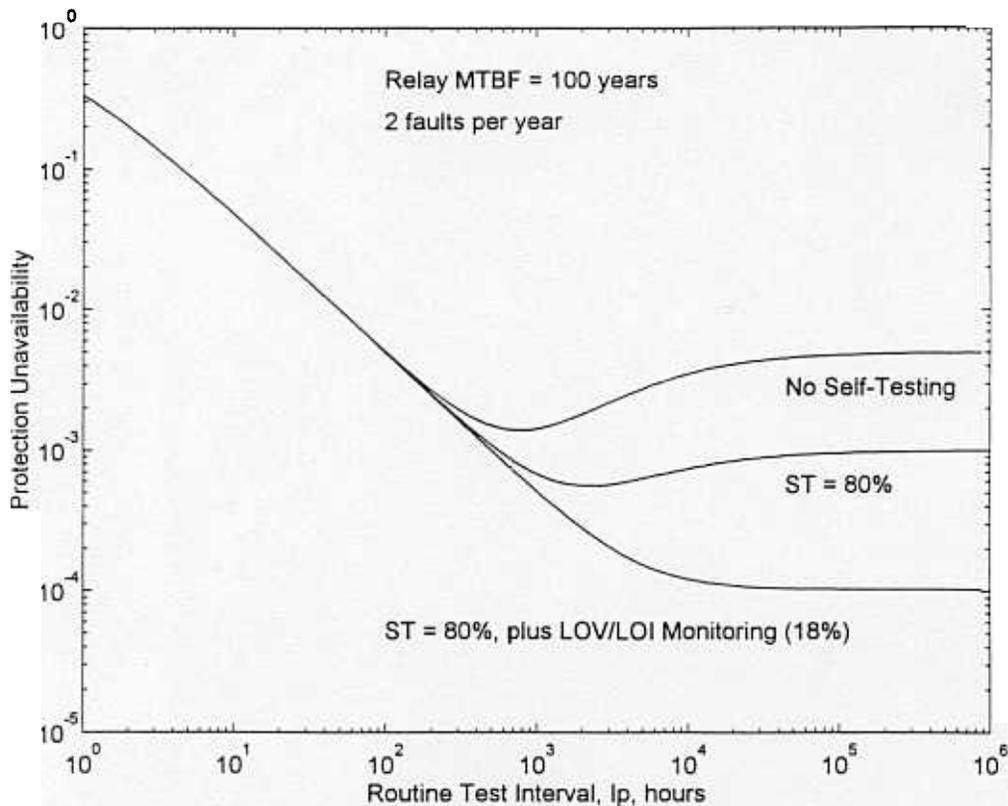


Figure 8: Compare the Benefits of Adding Self-Tests and Loss-of-Signal Monitoring

CONCLUSIONS

The features of digital relays reduce routine tests to a very short list: meter checks and input/output tests. Relay characteristic and timing checks are not a necessary part of routine maintenance tests for digital relays.

Monitor the relay self-test alarm contact. Even if self-test effectiveness is low, there is significant improvement in the relay and power system availability when relay failures are detected and quickly repaired, as shown in Figure 8.

Monitor AC signal functions that detect the loss of relaying voltage and current, if available. When used, these functions extend the capabilities of the relay self-tests.

Perform meter checks on an infrequent basis. The value of meter checks is to verify relay calibration.

Verify contact input/output operation by reviewing relay event reports, or through tests executed when the line is out of service for other reasons. This minimizes the impact of the test on the relay availability.

Use the digital relay reporting functions as maintenance tools. Event report analysis should supplement or replace routine maintenance checks of relays with self-tests. Event report analysis increases a tester's understanding of the digital relay and of the power system.

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BIOGRAPHIES

Edmund O. Schweitzer, III is President of Schweitzer Engineering Laboratories, Inc., Pullman, Washington, U.S.A., a company that designs and manufactures microprocessor-based protective relays for electric power systems. He is also an Adjunct Professor at Washington State University. He received his BSEE at Purdue University in 1968 and MSEE at Purdue University in 1971. He earned his PhD at Washington State University in 1977. He has authored or co-authored over 30 technical papers. He is a member of Eta Kappa Nu and Tau Beta Pi.

Daqing Hou received BS and MS degrees in Electrical Engineering at the Northeast University, China, 1981 and 1984, respectively. He received his PhD in Electrical and Computer Engineering at Washington State University in 1991. Since 1990, he has been with Schweitzer Engineering Laboratories, Inc., Pullman, Washington, U.S.A., where he is currently a research engineer. His work includes system modeling, simulation, and signal processing for power system digital protective relays. His research interests include multivariable linear systems, system identification, and signal processing. Hou is a member of the IEEE and has authored or co-authored several technical papers.

John J. Kumm received his BSEE degree at the University of Idaho in 1989. Since 1989, he has been with Schweitzer Engineering Laboratories, Inc., Pullman, Washington, U.S.A., where he is currently an application engineer. His work includes product support and specification. He is a member of IEEE Power Engineering Society.

APPENDIX A

Calculate the probability that the model will reside in a given state using a Markov Transition Matrix or using the flow graph method [4]. We used a PC-based matrix calculation software, MatLab™, to perform the matrix calculations. All the transition rates must first be converted to operations per hour. The Markov Transition Matrix is assembled from the transition rates and manipulated as shown in the equations below. The resulting vector, P, includes the probability of the system residing in any of the ten states.

Markov Transition Matrix for the ten-state system shown in Figure 2 is:

$$T = \begin{bmatrix} a_{11} & F_c & F_{pp} & F_{cc} & \ominus_{pm} & 0 & 0 & 0 & F_{st} & F_{me} \\ 0 & a_{22} & 0 & 0 & 0 & S_n & 0 & 0 & 0 & 0 \\ 0 & 0 & a_{33} & F_c & 0 & 0 & 0 & 0 & \ominus_{pm} & 0 \\ 0 & 0 & 0 & a_{44} & 0 & 0 & 0 & S_b & 0 & 0 \\ R_t & 0 & 0 & F_c & a_{55} & 0 & 0 & 0 & 0 & 0 \\ R_c & 0 & 0 & 0 & 0 & a_{66} & F_p & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & R_r & a_{77} & 0 & R_c & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & S_m & a_{88} & 0 & 0 \\ R_r & 0 & 0 & F_c & 0 & 0 & 0 & 0 & a_{99} & 0 \\ 0 & 0 & 0 & F_c & 0 & 0 & 0 & 0 & \ominus_{me} & a_{00} \end{bmatrix}$$

$$a_{11} = 1 - (F_c + F_{cc} + F_{st} + F_{pp} + \ominus_{pm} + F_{me})$$

$$a_{22} = 1 - S_n$$

$$a_{33} = 1 - (\ominus_{pm} + F_c)$$

$$a_{44} = 1 - S_b$$

$$a_{55} = 1 - (R_t + F_c)$$

$$a_{66} = 1 - (R_c + F_p)$$

$$a_{77} = 1 - (R_r + R_c)$$

$$a_{88} = 1 - S_m$$

$$a_{99} = 1 - (R_r + F_c)$$

$$a_{00} = 1 - (\ominus_{me} + F_c)$$

$$P^T = [P_1 \ P_2 \ P_3 \ P_4 \ P_5 \ P_6 \ P_7 \ P_8 \ P_9 \ P_{10}]$$

$$P^T \cdot T = P^T \text{ or } P^T \cdot [T - I] = 0$$

where I = Identity Matrix

$$\text{and } \sum_i P_i = 1$$

$$\text{Abnormal Unavailability, AbUn} = P_4 + P_8$$

$$\text{Protection Unavailability, ProtUn} = P_3 + P_5 + P_9 + P_{10}$$

