Predicting the Optimum Routine Test Interval for Protective Relays

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PREDICTING THE OPTIMUM ROUTINE TEST INTERVAL FOR PROTECTIVE RELAYS

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Abstract: This paper discusses the goals of routine maintenance testing for protective relays. The paper advances a Markov Probability model that predicts the optimum test interval for protective relays with and without self-testing capabilities. The model uses known system transition rates and relay failure rates. The probability model shows that the optimum test interval for a relay with self-tests is quite long.

INTRODUCTION

This paper statistically illustrates the differences in optimum test intervals between traditional relay designs and new relay designs. The paper introduces a new statistical model that is applicable to protective relays with and without automatic self-test functions.

When a relay fails, the failure can prevent operation for a fault, cause the relay to false trip, or alter the relay operating characteristics. This paper focuses on those relay failures that would prevent the relay from tripping in the event of a fault.

For this discussion, we will refer to two different types of protective relays. Relays which include self-testing, alarms, and event reporting we refer to as digital relays. Those which do not include these features are referred to as traditional relays.

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 test intervals for the various types of protective relaying equipment.

Traditional relays do not provide self-tests or status monitoring; therefore, routine testing is required to verify proper operation. If a problem exists in a traditional relay, the problem may go undetected until routine maintenance is performed or the relay fails to operate for a fault. The reliability of the traditional relay is, therefore, largely dependent on the frequency of routine maintenance.

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Digital relay failures can also cause relay misoperations and prevent operation for faults. However, relay characteristics are typically not affected by failures. Failures tend to be significant enough to either generate a self-test failure indication or cause the user to recognize the problem during normal operation of the relay.

DIGITAL RELAY SELF-TEST AND REPORTING FUNCTIONS

As a minimum, digital relay self-tests include tests of memory chips, a/d converter, power supply, and storage of relay settings. These periodic self-tests monitor the status of the digital relay and close an alarm contact when a failure is detected. Additionally, the digital relay may disable trip and control functions upon detection of certain self-test failures. Since the relay self-tests are executed often in the digital relay, component failures are usually discovered when the failure occurs.

Because the digital relay provides an indication when a problem occurs, the possibility that a failed digital relay could remain in service for a significant amount of time is reduced. If the utility monitors relay self-test alarm contacts, a failed relay can generally be repaired or replaced within hours or days of a failure.

Digital relavs provide event reporting and metering features which supplement routine maintenance. Event reports typically provide a record of each relay operation with the same resolution as the sample rate of the digital relay. If testing personnel devote a small percentage of their time to analyzing these fault records, they can find relay problems displayed in the event report data. Analysis of actual fault data is a true test of the instrument rather than a simulated test. Careful analysis of relay event reports and meter information indicates problems which could otherwise go undetected by digital relay self-tests.

Event reports can also indicate problems external to the digital relay. Transformers, trip circuits, communication equipment, auxiliary input/output devices are examples of external equipment which may be indirectly monitored using the event report.

ROUTINE MAINTENANCE TESTING

The goal of routine maintenance is to verify that the protective relay will not operate unnecessarily and will operate when required. Routine testing of protective relays has been the primary method of detecting failures in traditional relays. The only other way of determining that a traditional relay has failed is to observe a misoperation.

Typically, routine maintenance is performed periodically with a specified interval between tests. A common belief is that a shorter test interval increases overall system reliability.

SELECTING THE OPTIMUM TEST INTERVAL

Several IEEE papers [1,2] describe probabilistic methods of determining the optimum test interval for traditional relays. Anderson and Agarwal [1] propose a calculation method that produces several probability measures. Two measurements of interest are Abnormal Unavailability and Protection or Relay Unavailability. These will be discussed in some detail below.

The model shown in [1] makes the following assumptions regarding the relays modelled:

1) An inspection or fault must occur in order to detect a relay failure.

2) A relay must be taken out of service to be inspected.

3) The time required to test a relay is equal to the time required to repair or replace a failed relay.

4) Inspection of the protection always detects failures and does not cause failures.

5) Repair always restores the protection to good as new.

Assumptions 1 and 2 make the model primarily applicable to traditional relays, those relays without self-tests. Assumption 3 simplifies the model calculations without detracting appreciably from the results.

The eight-state model proposed in [1] does not account for relay self-testing. Figure 1 shows a nine-state model that accounts for self-testing. The model is divided into four quadrants representing the condition of the relay (Protection) and the line (Component).

State 1 represents the 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, but the relay is operating properly and signals the circuit breaker to trip. The normal switching transition takes the model system to State 6 where the line is isolated. The line is then repaired and reenergized, taking the model system back to State 1.

States 5, 3, and 9 represent conditions where the relay is out of service and unavailable to trip should a fault occur. In State 5, the relay is out of service being inspected. In States 3 and 9 the relay is out of service due to a relay failure. State 9 represents the relay under repair. The model system enters State 9 from State 1 when a relay failure is detected by the relay self-test function. The model system enters State 9 from State 3 when a relay failure is detected by a routine maintenance test. The model system enters State 3 from State 1 when a relay failure occurs that is not detected by the relay self-test function.

The effectiveness of self-testing can be varied in the model. The overall relay failure rate, Fp, is multiplied by a per unit factor, ST, to indicate the portion of all relay failures that are detected by self-test operation. The remainder of failures can only be detected by routine test or by observing a misoperation. Digital relays with varying degrees of self-test effectiveness can be represented in the model by adjusting the value of ST.

The model system enters State 4 if a fault occurs while the relay is out of service, or if a common-cause failure of the relay and system occurs. The model assumes that if a fault occurs while the relay is out of service, remote backup protection must operate 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 removed had the failed relay operated properly. This is represented in State 4 and State 8 by the isolation of C and X, where X is the additional equipment that was removed from service by the backup operation.

The two interesting probability measures obtained from analysis of this system are Relay Unavailability and the Abnormal Unavailability. The Relay Unavailability is the probability that the relay will be out of service while the system is energized. This is represented by the sum of the probabilities of residing in States 3, 5, and 9. The Abnormal Unavailability reflects the result of a fault occurring while the relay is out of service. Abnormal Unavailability is the sum of the probabilities of residing in States 4 and 8.

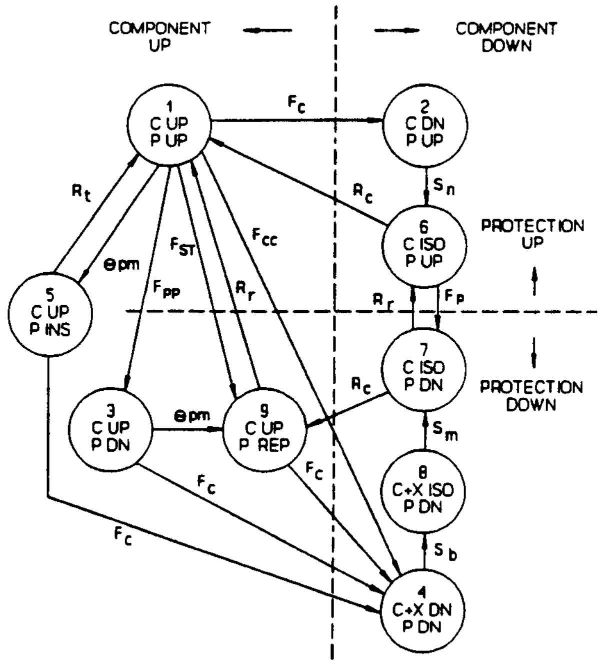

Figure 1: Markov Model of a Protection/Component System That Accounts For Relay Self-Testing

From the model, we can calculate the Abnormal Unavailability and Relay Unavailability of relays with or without self-tests by adjusting the transition rates that define the model. The transition rates are defined below.

Failure Rates:

- F_p Relay Failures (reciprocal of relay Mean Time Between Failures, MTBF)
- ST Self-test Effectiveness Index (per unit)
- F_{st} Relay Failures detected by self-test (Fp·ST), failures per year
- F_{pp} Relay Failures not detected by self-test (Fp·[1-ST]), failures per year
- F_c Component Failures, faults per year
- F_{cc} Common-cause failures of the relay and component, failures per year

Repair Rates:

- R_c Protected Component repairs per hour
- R_t Relay 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 Rate:

- I_{pm} Protection Inspection interval
- θ_{pm} Protection Inspection rate (1/Ipm)

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

- R_r = 0.5 relay repairs per hour
- R_t = 1.0 relay routine test 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 = 21600 operations per hour (reciprocal of 10 cycle fault clearing time)
- S_m = 0.5 operations per hour (2 hours to isolate component after backup operation)

The probability of the system residing in a given state can be calculated using a Markov Transition Matrix or using the flow graph method [2]. 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 includes the probability of the system residing in any of the nine states.

Markov Transition Matrix for the nine state system shown in Figure 1 is:

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

where:

$$a_{11} = 1 - (F_e + F_{cc} + F_{st} + F_{pp} + \theta_{pm})$$

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

$$a_{33} = 1 - (\theta_{pm} + F_e)$$

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

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

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

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

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

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

Let $\bar{P}$ be a probability vector of the nine Markov Model States,

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

Then we have:

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

where I is a nine by nine identity matrix. Finally, we need the following equation to overcome the singularity of [T-I],

$$\sum_i P_i = 1$$

We can then define the two probabilities of interest Abnormal Unavailability, $AbUn = P_4 + P_8$, and Relay Unavailability, $RelUn = P_3 + P_5 + P_9$.

STATISTICAL MODEL RESULTS

Figure 2 shows the Abnormal Unavailability versus routine test interval for a system using a traditional relay that does not have self-testing. The plot is for a relay with a Mean Time Between Failures (MTBF) of 50 years monitoring 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 one 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 with the relay: 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 do for digital relays: test often and test without disturbing the protection.

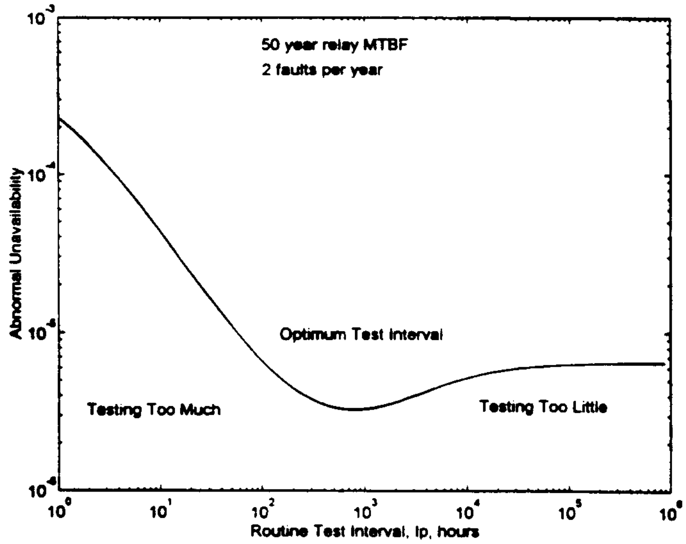

Figure 2: Selecting the Optimum Test Interval

Figures 3 and 4 show the sensitivity of the Abnormal Unavailability for a traditional relay to the number of faults per year and to the relay MTBF, respectively. Figure 3 shows traces for systems responding to one and ten faults per year. We see that the number of faults per year has the largest effect on the Abnormal Unavailability when the test interval is extremely low. The optimum test interval is not appreciably influenced by the number of faults per year.

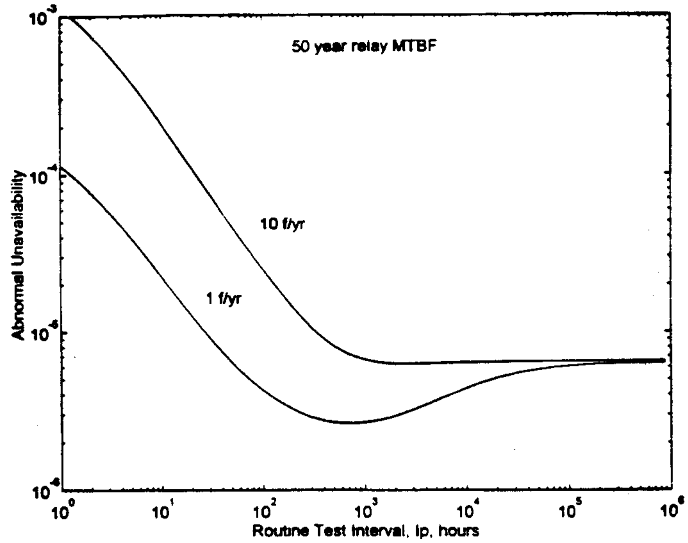

Figure 3: Sensitivity to Faults per Year, Relay Without Self-Tests

Figure 4 shows that MTBF has the greatest effect on Abnormal Unavailability when the routine test interval is long. This is reasonable. With a low MTBF and a long test interval, the relay is more likely to have experienced an undetected failure when a fault occurs.

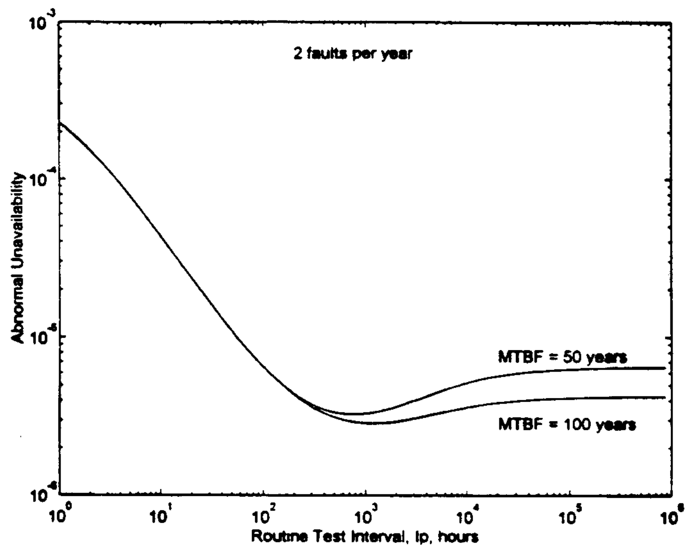

Figure 4: Sensitivity to MTBF, Relay Without Self-Tests

Figure 5 compares relays with and without self-tests on the basis of Relay Unavailability. Figure 5 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 relays failures immediately. When ST = 90% and 99%, the relay self-tests detect 90% and 99% of relay failures, respectively.

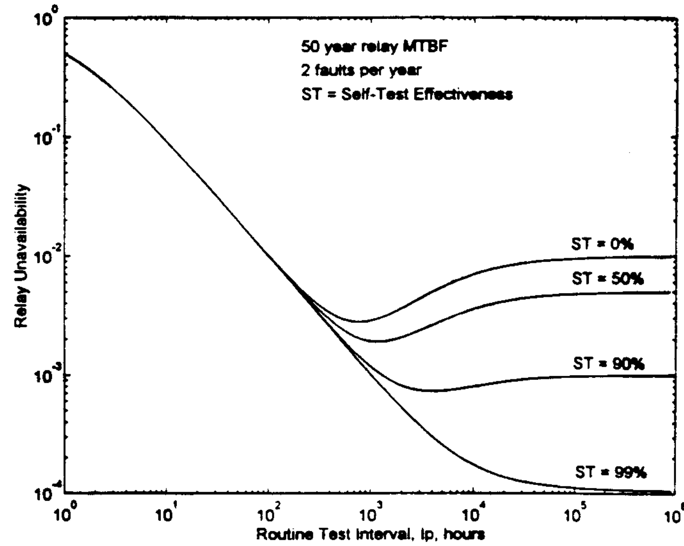

Figure 5: Effect of Self-Tests on Relay Unavailability

Figure 5 shows that a traditional relay (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 traditional 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 6 shows the Abnormal Unavailability of the four systems.

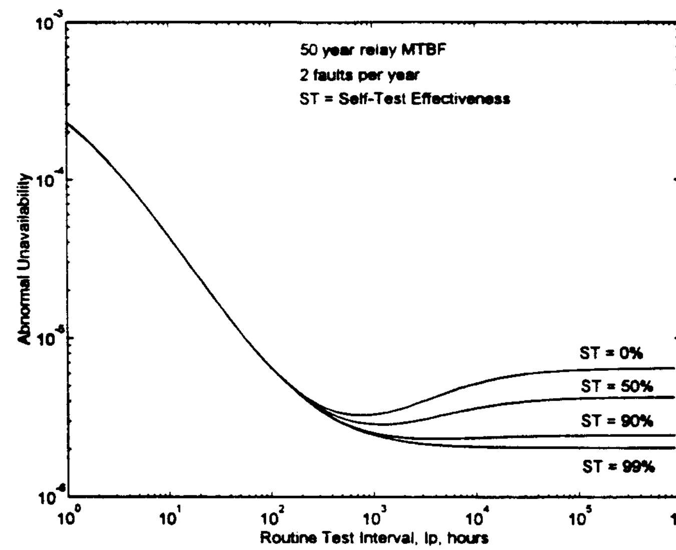

Figure 6: Effect of Relay Self-Tests on Power System Unavailability

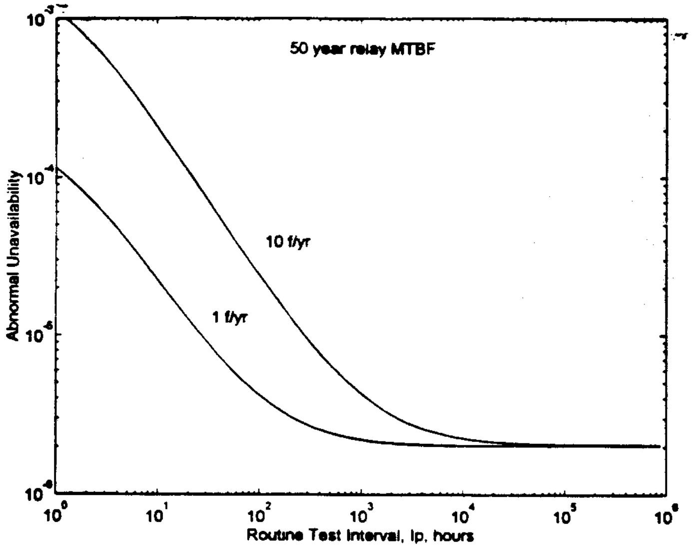

Figure 7: Sensitivity to Faults per Year, Relay with Self-Tests

Figure 7 shows that, for a relay with self-tests, Abnormal Unavailability is not appreciably affected by the frequency of faults, for long routine maintenance intervals. The plot shows performance for one and ten faults per year.

Figure 8 shows another surprising result. The plot shows Abnormal Unavailability for two systems using relays with self-tests. One relay has an MTBF of 10 years, the other has an MTBF of 100 years. The plot shows that the system with the low MTBF relay has only a slightly higher Abnormal Unavailability. The benefit of a long MTBF is that reliable relays do not need to be repaired or replaced as often as relays with a short MTBF. This saves maintenance time and money. Thus, a long MTBF is valuable in saving money on repairs, but is not very important to availability.

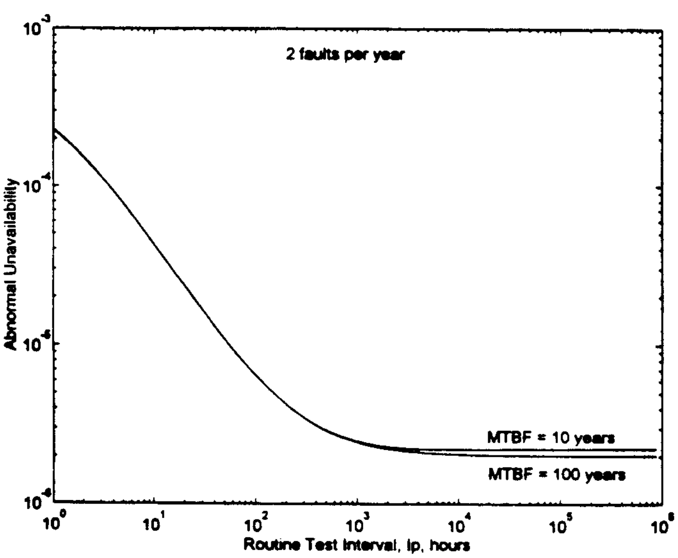

Figure 8: Sensitivity to MTBF, Relay with Self-Tests

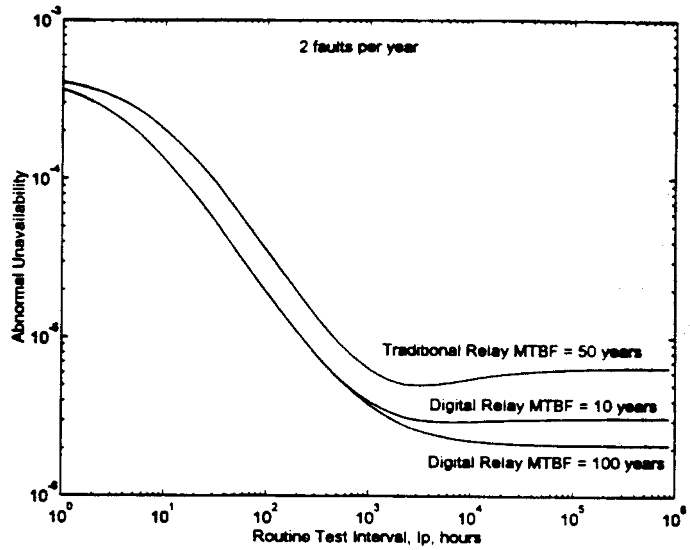

Figure 9: Comparison of Digital and Traditional Relay Terminals

Figure 9 compares Abnormal Unavailability for a power system protected by traditional relays to a power system protected by digital relays. For this plot, the two digital relays have MTBF of 10 and 100 years, self-test effectiveness of 95%, and a test time of four hours. The traditional relay has no self-tests, an MTBF of 50 years, and a test time of eight hours. This chart shows that a traditional relay terminal tested once every four months is not as reliable as a digital relay terminal tested every 40 years.

CONCLUSION

The features of digital relays reduce routine tests to a very short list: meter checks and input/output tests. Routine characteristic and timing checks are not necessary for digital relays. Probability analysis shows that relays with self-tests do not need to be routine tested as often as relays without self-tests. If the relay is measuring properly, and no self-test has failed, there is no reason to test the relay further.

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.

Because self-tests quickly indicate the vast majority of relay failures, the MTBF of a digital relay does not have a large impact on the power system Abnormal Unavailability. When a relay is equipped with self-tests, the benefit of a high MTBF is that fewer relays need replacement or repair. A high MTBF saves maintenance time and money. Relay self-testing saves routine testing time.

When a relay is not equipped with self-tests, a high MTBF and a short test interval are both essential to minimize system Abnormal Unavailability.

Reducing the complexity and frequency of digital relay routine tests saves labor. The labor resources can be applied to more frequent and complete tests of traditional relays. The result will be higher overall reliability and availability from all relays, both digital and traditional.

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BIOGRAPHIES

Edmund O. Schweitzer, III (M '74, SM '89, F '91) is President of Schweitzer Engineering Laboratories, Inc., Pullman, Washington, U.S.A., a company that designs and manufacturers 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.

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