A Novel Routine Test Schedule for Protective Systems Using an Extended Component-Based Reliability Model

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ABSTRACT

This paper presents a novel approach for evaluating the reliability of protective systems taking into account its components reliability. In this paper, a previously proposed extended model is used for Directional Overcurrent scheme. In the extended model, the impacts of individual protective components are taken into account. An optimum routine test schedule is determined for each protective component as a separate unit. A comparison is made to show that the proposed approach has excellence over conventional routine test inspections. Impacts of factors such as circuit breaker inadvertent opening, required time for performing routine test inspections, human mistakes and self-checking and monitoring effectiveness is analyzed using the model. Redundancy in some parts of the protective system is examined. Permanent and transient faults on the protected zone, operation of backup protection and Common-Cause failures are also recognized in the model.

KEY WORDS
Reliability, Protective System, Routine Test, Redundancy

1. Introduction

Protection system is a vital part of any electric power system and plays an incredible role in maintaining high degree of service reliability required in the present day power systems. Protective relaying suffers from two types of failures; failure to operate and unwanted operation. Protection system failures can have significant effect on the continuity of electricity supply to customers, making its reliability evaluation a priceless task. In those situations where protection system does not perform its intended operation, catastrophic failures can occur, leading to significant amount of customer interruptions and in some cases isolation of the power system. A well-designed protection system responds to the predefined abnormal conditions in an expected time delay without causing other backup systems to react and probably disconnect healthy neighbor components from the circuit. Protection system reliability has two main aspects; dependability and security. Dependability is the probability that a protection system operates when required; security is the probability that the system remains quiescent in those situations where no reaction is required. These capabilities are usually in opposite direction to each other, making the design and reinforcement planning a difficult task. Arun G. Phadke, et al [1] explored hidden failures in protection systems and investigated the modes in which the protection system may fail to operate correctly and the consequences of these failure modes. Kumm, et al [2] statistically illustrated the differences in optimum test intervals of traditional and new relay designs. Anderson, et al [3] introduced an improved Markov model for redundant protective system. The result demonstrated that redundant protective system could improve overall system reliability. Kangvansaichol, et al [4] estimated the optimal routine test interval and compared the abnormal unavailability for several configurations of pilot protection schemes using Markov model and Event Tree method. Billinton, Fotuhi-Firuzabad and Sidhu presented a Markov model to examine routine test and self-checking and monitoring facilities [5]. A. Abbarin and Fotuhi-Firuzabad extended the previous Markov model and examined redundancy and protective components effects [6]. In this paper, a novel routine test schedule is presented which exactly determines the frequency of performing routine test on each protective component to maximize protection system availability and to avoid unnecessary expenditure. The impacts of factors such as breaker inadvertent opening, required time for performing routine test, human mistakes and self-checking and monitoring functionalities are also simulated.

2. Hidden Failures

Most of the times, relay operations are correct and satisfactory. But, mal-operation following sudden changes in the system conditions might lead to substantial electric service interruptions and system separation. While the probability of this category of faults is low, the consequences can be very dangerous and harmful. Hidden failure is defined as a permanent defect that will cause a relay or a relay system to incorrectly and inappropriately remove a circuit element(s) as a direct consequence of another switching event [7]. Hidden failure remains unrevealed until another system event such as a switching event, under-voltage, overload or short circuit happens and usually leads to increase of insecurity. A hidden failure is a defect from which any of the protection system elements may suffer and it is applicable to potential transformers (PT), current transformers (CT), cables, lugs and connectors, all kind of relays, communication channels, etc.[3]. Hidden failures are generally classified into hardware failures, outdated settings and human errors. According to North American Reliability Council (NERC) reports, hidden failures are known to be the key contributors in wide-area disturbances and sequence of events; therefore presenting a methodology for identifying these defects before leading to major consequences is of a great value. A method for detecting hidden failures is to carryout routine test maintenance or adding self-checking and monitoring functions to the relay logic during the design stage. In this way, routine tests or preventive maintenances are accomplished with a special time interval in order to increase protective system availability.

3. Protective System Reliability Modeling

In this paper the general and detailed reliability modeling described in [5] and [6] respectively, is used for enhancing the reliability of Directional Protective scheme shown in figure 1. The general five state reliability model shown in figure 2 together with the more detailed, 23-state Markov model of a protection/component system shown in figure 3 which is introduced in [6] and expanded to the 65-state Markov model, is used to examine different reliability aspects of a None-pilot Directional Overcurrent protective system of a transmission line. The general reliability model can be regarded as basis for modeling different relaying schemes. In the detailed reliability model of figure 3, abbreviations used are as follows:

UP: Operational state; Dn: failed state;
Du: Unrevealed failure of protection system;
iso: Isolation of the line or neighbor components;
Sc: The relay is removed from service for self-checking
Rt: One of the protection system components is removed from service for routine test inspection.
The detailed discussion about each state, transition rates, various definitions and terms such as "abnormal unavailability" as well as different aspects of 65-state Markov model which is shown as a 23-state model in figure 3, is found in [6].

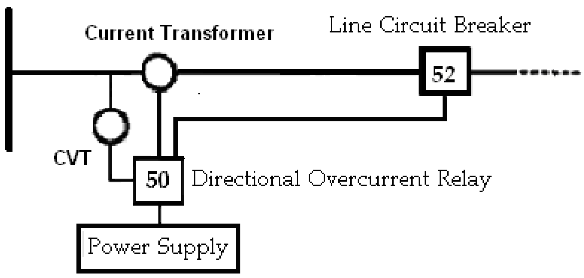

Fig.1: Overcurrent System Protection of a Transmission Line

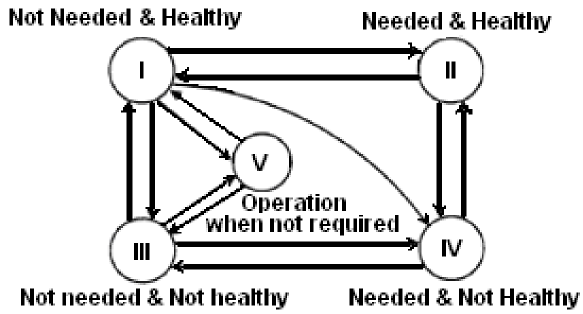

Fig.2: General Reliability Model of Protective System

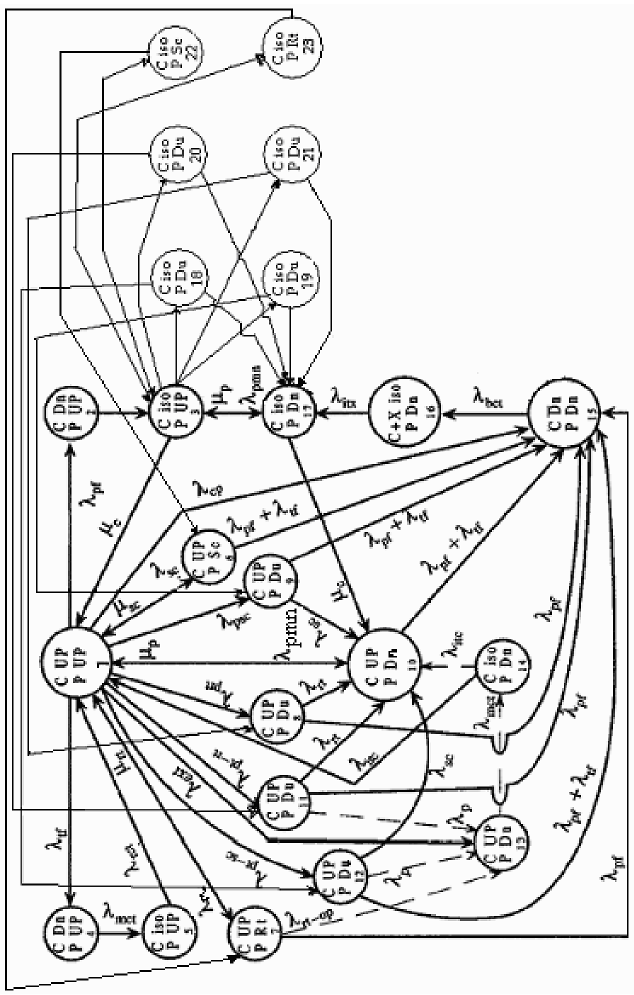

Fig.3: Detailed Reliability Model of Protective System

4. Optimum Routine Test Schedule

A commonly used method for protection system reliability enhancement is to carry out routine test inspections with specified time intervals. Considerable work has concentrated on this area. Here a novel routine test schedule is presented by which the optimum test intervals of each protective component are determined. Simulation are conducted based on directional over current scheme comprising of components such as Power Supply Unit (PSU), Current Transformer (CT), Voltage Transformer (VT), Relay, Trip Coil and Circuit Breaker. Program output is the frequency of performing routine test on each device to minimize unreliability. Unreliability in the proposed model is the sum of probabilities associated with state 3, 4 and 5 in the general reliability model shown in figure 2 and sum of states 6 to 65 probabilities in the detailed model. The probabilities associated with different states are calculated using the concept of stochastic transitional matrix [8]. It will be shown that testing of protective components with different rates, specified in an optimization process, improves the reliability more compared with the traditional case where all component were inspected with the same rate. Testing protective system with unique frequencies devoted to each component results in time saving as well as labor cost or manpower saving.

At the first step assume that routine test intervals for CT, VT, Relay, Trip Coil and Breaker are equal to 2000 hours. Assumptions about failure rates of other components in the system are shown in Table 1.

Unreliability profile with respect to routine test intervals of PSU is shown in figure 4. It can be seen from this figure that the maximum system reliability is 0.976566 for which the optimum routine test intervals is 1410 hours.

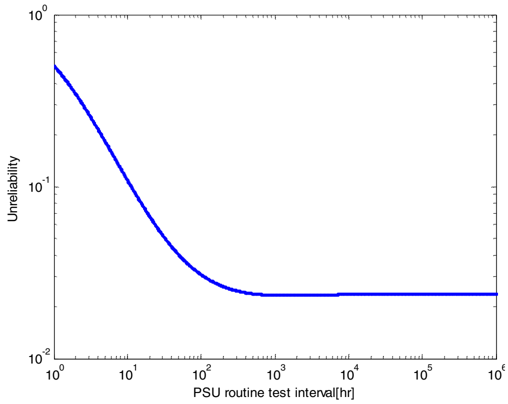

Fig.4: Unreliability with respect to PSU routine test intervals

Taking 1410 hours as the routine test intervals for PSU, optimization with respect to CT test intervals is done. Under this condition, the protective system reliability is 0.977675 and the optimum routine test interval for CT is 530 hours as shown in figure 5.

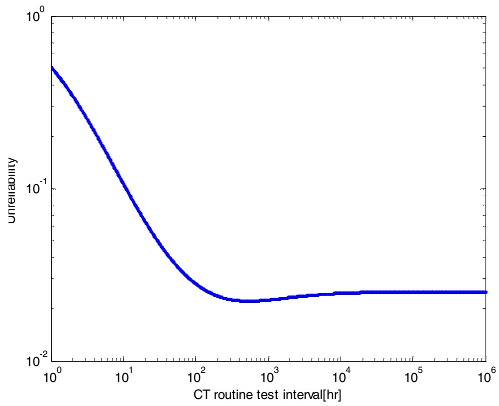

Fig.5: Unreliability with respect to CT routine test intervals

Using the results obtained in the previous two steps, the optimum routine test intervals associated with VT is determined. The result shown is figure 6 indicate that the optimum routine test intervals for VT is 1000 hours and protective system reliability improves to 0.977818.

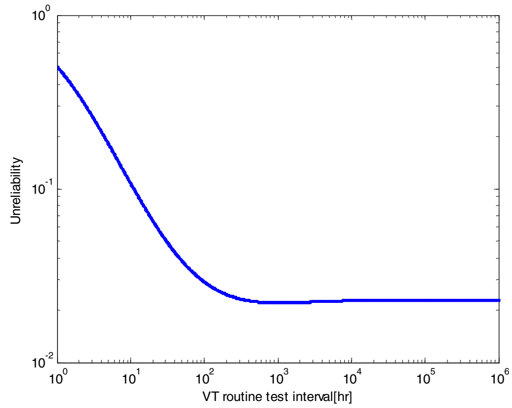

Fig.6: Unreliability with respect to VT routine test intervals

Updating the routine test intervals of VT, optimization continues for the relay unit. The result is shown in figure 7 which indicates that the optimum test interval of the relay is 750 hours. Also the reliability improves to 0.978232. Updating the routine test intervals of the relay, optimization continues for trip coil. The results shown in figure 8 indicate that the optimum test interval of the trip coil is 1165 hours. Also the reliability increases to 0.978307.

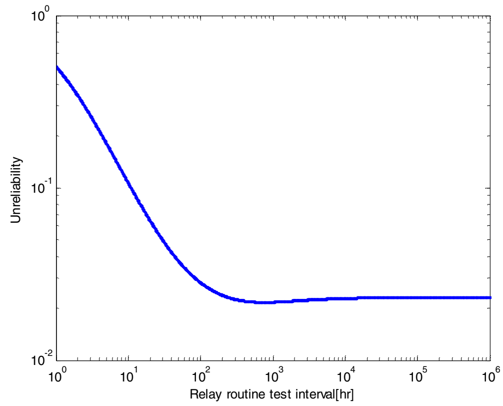

Fig.7: Unreliability with respect to Relay test intervals

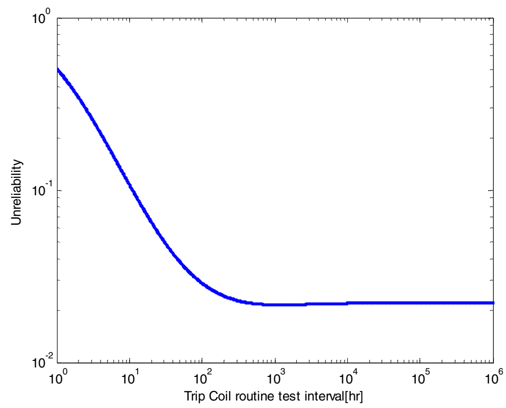

Fig.8: Unreliability with respect to Trip Coil test intervals

The process continues for circuit breaker. Figure 9 shows unreliability with respect to circuit breaker routine test intervals. It can be seen from the results that a routine test interval of 675 hours for circuit breaker will results in reliability of 0.978866.

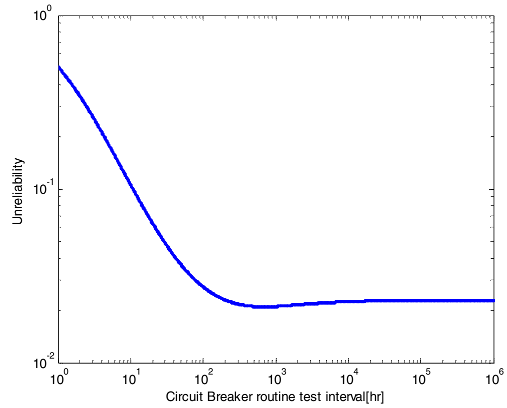

Fig.9: Unreliability with respect to Circuit Breaker routine test intervals.

Continuation of the process from the first point with the updated values of routine test intervals had no effect on the reliability profile since components failures are considered to be independent. Therefore optimum routine test intervals are as follows:

PSU: 1410 hrs
CT: 530 hrs
VT: 1000 hrs
Relay: 750 hrs
Trip Coil: 1165 hrs
Circuit Breaker: 675 hrs

Figure 10 shows a comparison between conventional method in which the protective system is considered as a unit set to perform routine tests with the case in which routine test is considered individually for protective components.

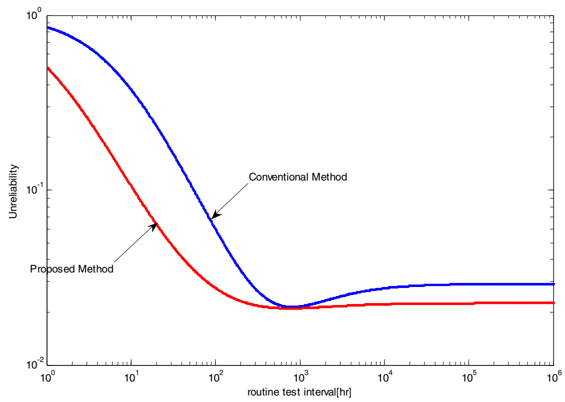

Fig.10: Comparison of different strategies for routine test

The upper curve in this figure shows unreliability with respect to common routine test intervals and the lower curve is the result obtained by the proposed approach with respect to routine test intervals of PSU. It is evident that the proposed method is preferred to the conventional approach from both the reliability and economic viewpoint. It is to be noted that figure 11 is the same sketch around the optimum point of the upper curve which clearly indicates the preference of the proposed method.

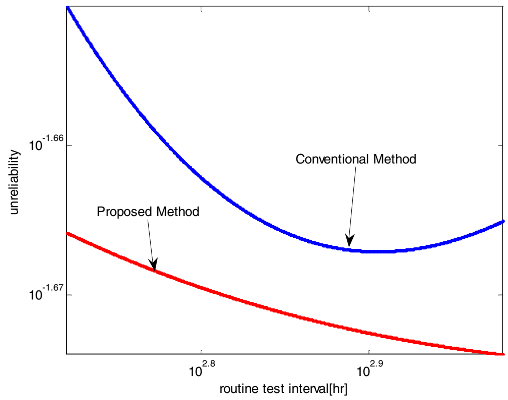

Fig.11: Comparison around the ambiguous point

5. Sensitivity Analysis

The parameters of a model are usually selected based on experience. Therefore conducting a sensitivity analysis to show the extent of dependency of protective system reliability to numerical parameters is necessary. Versatile simulations were conducted to examine the effects of different parameters on security and abnormal unavailability of protection system. The parameters to be studied here are the circuit breaker inadvertent opening rate, the required time for routine test, human errors, self-checking and monitoring effectiveness and redundancy of PSU and VT.

5.1 Circuit Breaker Inadvertent Opening

The impact of circuit breaker inadvertent opening rate with respect to routine test intervals is shown in Figure 12. It can be seen from this figure that as the above mentioned failure rate increases, so does the security index resulting in decrease of security aspect of reliability. Security index is the probability of state V in the general reliability model and sum of probabilities associated with states 13 and 14 in the detailed model.

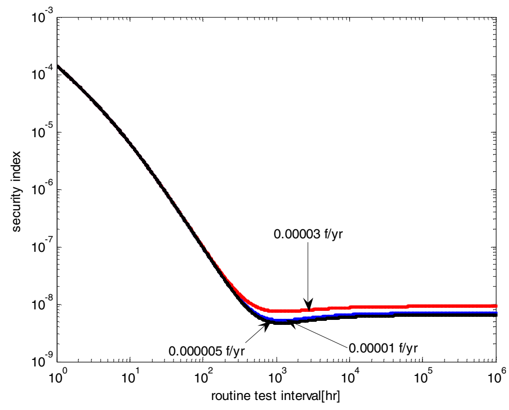

Fig.12: Impact of breaker inadvertent opening on security

5.2 Required time for performing routine test

The impact of required time for performing routine test, in other words rate of return from inspection, on abnormal unavailability of protective system is shown in figure 13. It is evident that the decrease of the time required for routine test leads to decrease of abnormal unavailability and enhancement of overall system reliability. Another issue is that if a protective system can be tested in a shorter period of time, the optimum routine test intervals decreases.

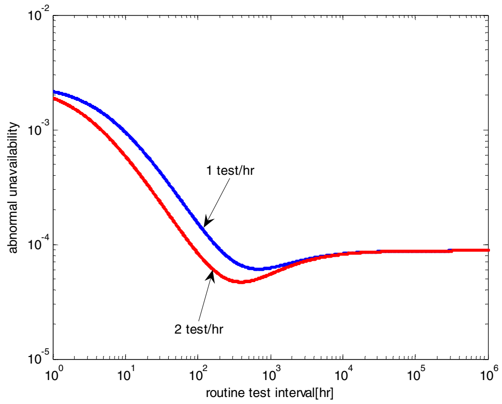

Fig.13: Impact of routine test time on abnormal unavailability

5.3 Human Errors

The impact of human mistakes in performing routine test on the relay is shown in figure 14. It can be seen from this figure that an increase in the human errors from 0.001 mistake/routine test to 0.1 mistake/routine test results in a decreasing trend in system security. Routine test intervals should therefore be increased as can be seen in the figure.

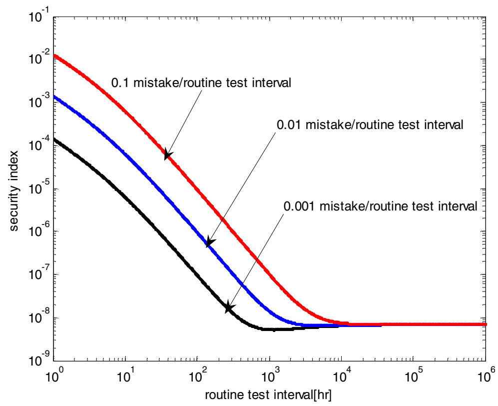

Fig.14: Impact of human mistakes on security

5.4 Self-checking and Monitoring

The relay remains in service and is capable of clearing faults during a monitoring test while in self-checking test the whole relay or some parts will be out of service, thus creating temporary unavailability. Self-checking and monitoring effectiveness are evaluated with indices SE and ME respectively which correspond to the percentage of relay failures which can be revealed automatically. Effect of self-checking and monitoring effectiveness on abnormal unavailability with respect to routine test intervals is shown in figure 15 and 16 respectively. It can be seen from these figures that as self-checking or monitoring effectiveness increases, the abnormal unavailability of protective system decreases resulting in overall protective reliability enhancement. Also the optimum routine test intervals in increased.

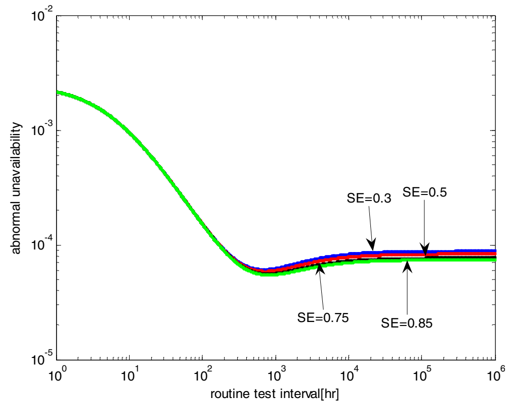

Fig.15: Impact of self-checking on abnormal unavailability

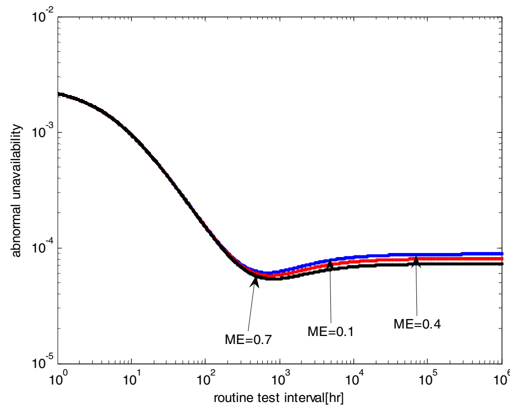

Fig. 16: Impact of monitoring on abnormal unavailability

5.5 Effect of Redundancy

Redundancy consideration enhances dependability of protection systems; but deciding where to use and to what extent requires an overall intuition based on the fact that "as reliable as possible" is not always the best choice; cost and other implementation limits are to be considered. In this part, unreliability index is evaluated which is the sum of probabilities associated with the states in which protection system is not available; In other words, the reliability is the sum of states 1 to 5 in the 65-state Markov model.

5.5.1 Redundancy of PSU

According to figure 17, using double power supply units causes an extension of the optimum routine test intervals and decrement of unreliability or improvement of reliability**.**

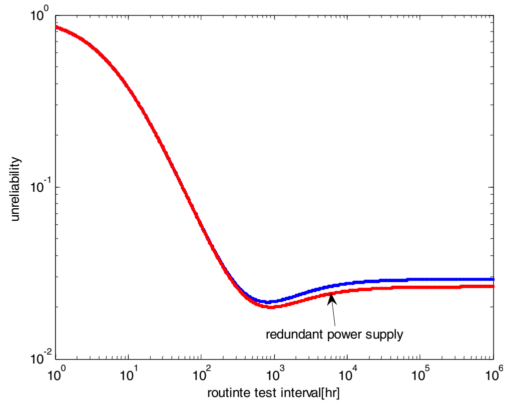

Fig.17: Impact of redundant PSU

5.5.2 Redundant voltage transformers

According to figure 18, using double voltage transformers causes an extension of the optimum routine test intervals and improvement of reliability.

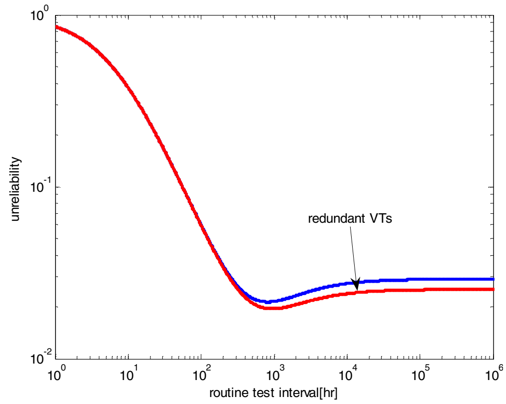

Fig.18: Impact of redundant Voltage transformers

Table 1: Numerical default values used for components

line permanent failure rate (λ_f)	3 f/yr
line transient failure rate (λt)	7 f/yr
power supply unit failure rate (λ_{PSU})	3 f/yr
current Transformer (λ_{CT})	0.08 f/yr
voltage transformer failure rate (λ_{VT})	0.04 f/yr
trip coil failure rate (λ_{TC})	0.035 f/yr
breaker failure rate (λ_B)	0.06 f/yr
relay failure rate (λ_r)	0.08 f/yr
relay potential mal-trip failure rate (λ_{rs})	0.01 f/yr
breaker inadvertent opening rate (λ_{bs})	0.00001 f/yr
inspection and repair rate of all components	1 operation/hr

7. Conclusion

In this paper, a novel routine test schedule is presented for protective systems in order to improve all aspects of protective system reliability. It was shown that using proposed approach results in more enhanced protective system reliability than would be gained by conventional method. A sensitivity analysis was conducted for directional overcurrnet scheme to show the dependency extent of protective system reliability and the optimum routine test interval on protective components reliability indices, redundancy and human performance.

References

[1] David C. Elizondo, J. de la Ree, Arun G. Phadke, Stan Horowitz, Hidden Failures in Protection Systems and their Impact on Wide-area Disturbances, *Proc. IEEE Winter Power Meeting, vol. 2*, 2001, 710–714.

[2] J. J. Kumm, M.S. Weber, D. Hou and E.O. Schweitzer, Predicting the Optimum Routine Test Interval for Protective Relays, *IEEE Transactions on Power Delivery, vol. 10*, No. 2, April 1995, 659-665.

[3] P.M. Anderson, G.M. Chintaluri, S.M. Magbuhat and R.F. Ghajar, An Improved Reliability Model for Redundant Protective System – Markov Models, *IEEE Transactions on Power Systems, vol. 12*, May 1997, 573–578.

[4] K. Kangvansaichol, P. Pittayapat, B. Eua-Arporn, Optimal Routine Test Intervals for Pilot Protection Schemes Using Probabilistic Methods, Conference Publication No.479, IEE 2001.

[5] R. Billinton, M. Fotuhi-Firuzabad, T. S. Sidhu, Determination of the optimum routine test and self checking intervals in protective relaying using a reliability model, *IEEE Trans. on power systems, vol. 17*, No. 3, Aug. 2002.

[6] A. Abbarin, M. Fotuhi-Firuzabad, Evaluation of Redundancy and Effect of Protective Components on Protection System Reliability, 5th International Conference on Electrical and Electronics Engineering, 5-9 December 2007, Bursa, TURKEY, ELECO2007.

[7] Surachet Tamronglak, Analysis of Power System Disturbances due to Relay Hidden Failures, Ph.D. Dissertation. Virginia Polytechnic and State University, Blacksburg, Virginia, March 1994.

[8] R. Billinton and R. N. Allan, *Reliability Evaluation of Engineering Systems* (New York, Plenum, 1994).

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