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An extended component-based reliability model for protective systems to determine routine test schedule*

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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 a directional over-current 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

A 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 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. When protection system does not perform its intended operation, catastrophic failures can occur which leads 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. Since these two features usually counteract each other, design and reinforcement plan shall be made based on a compromise. Reference [1] introduces a

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method to calculate the probability of failure of protective relay systems. A reliability index designated as the "Unreadiness Probability" is defined in [2] as the probability that the relay system fails to respond when it is called upon to operate in the presence of a fault. The proposed model in [2] has been extended and improved in [3] to redefine the unreadiness probability and unavailability of a protection system. The improved model recognizes the operation of back-up protection, the removal of protection for inspection, the occurrence of common-cause failures and the fault clearing phnomena. Arun G. Phadke, et al [4] 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 [5] statistically illustrated the differences in optimum test intervals of traditional and new relay designs. Anderson, et al [6] introduced an improved Markov model for redundant protective system. The result demonstrated that redundant protective system could improve overall system reliability. Kangvansaichol, et al [7] 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 [8]. Lisnianski, A et al [9] analyzed two configurations of protection system for high voltage lines from reliability point of view. Ying-Yi Hong, et al [10] assessed the reliability of protection system for a switchyard using the fault-tree method and minimum cut sets. A. Abbarin and Fotuhi-Firuzabad extended a previous Markov model and examined redundancy and protective components effects [11]. Shenghu Li, et al [12] studied the average unavailability based on the instantaneous state probability for evaluation of the short term reliability of protection system. 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 included in the study.

2. Hidden failures

Most of the time, 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 [13]. 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.[6].

Hidden failures are generally classified as 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 great importance. 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 special time intervals in order to increase protective system availability.

3. Protective system reliability modeling

In this paper, a general and detailed reliability modeling is used for enhancing the reliability of Directional Protective scheme, shown in Figure 1. The directional over current relay is a relay that will provide over current protection in a directional manner. The directional logic resembles a watt-hour meter. A potential transformer is required to provide a reference for direction. The CT and PT connections are made such that outgoing power causes the directional scheme to operate. The general five-state reliability model is shown in Figure 2. A more detailed 23-state Markov model of a protection/component system is shown in Figure 3, which can be expanded to a 65-state Markov model to examine different reliability aspects of a None-pilot directional over current protective system of a transmission line.

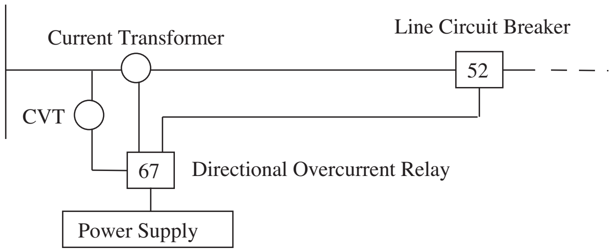

Figure 1. Overcurrent system protection of a transmission line.

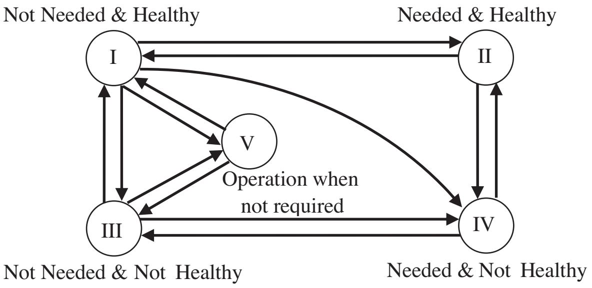

Figure 2. General reliability model for a protective system.

3.1. General reliability model

The general reliability model can be regarded as basis for modeling different relaying schemes. In this model, state I shows the state in which a protective system spends most of its life, in a healthy and perfect condition, monitoring an operating component within its protective zone. This state is designated as "Not Needed & Healthy." In State II, designated as "Needed & Healthy" whose probability is a direct measure of dependability, the system operates correctly in response to abnormal conditions. In State III, designated as "Not Needed & Not Healthy," the system is neither required nor ready to operate. It is not required since no fault has occurred in the protected zone. It is not ready since some part of protective system is found to be failed by the routine test or self-checking inspection. This state can be named "Protection Unavailability State." In State IV, designated as "Needed and Not Healthy," the system does not perform its intended function. In this case a fault occurs and no trip signal is sent to the breakers. The probability associated with this state is "Abnormal Unavailability." In State V, designated as "Operation When Not Required," the system operates when it is not required. The higher the probability associated with this state, the lower the system security. It should be noted that the probability of State II depends mainly on the fault rate and equipment restoration time.

3.2. Detailed reliability model of a directional over-current protection system

In the detailed reliability model of Figure 3, abbreviations are defined 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.

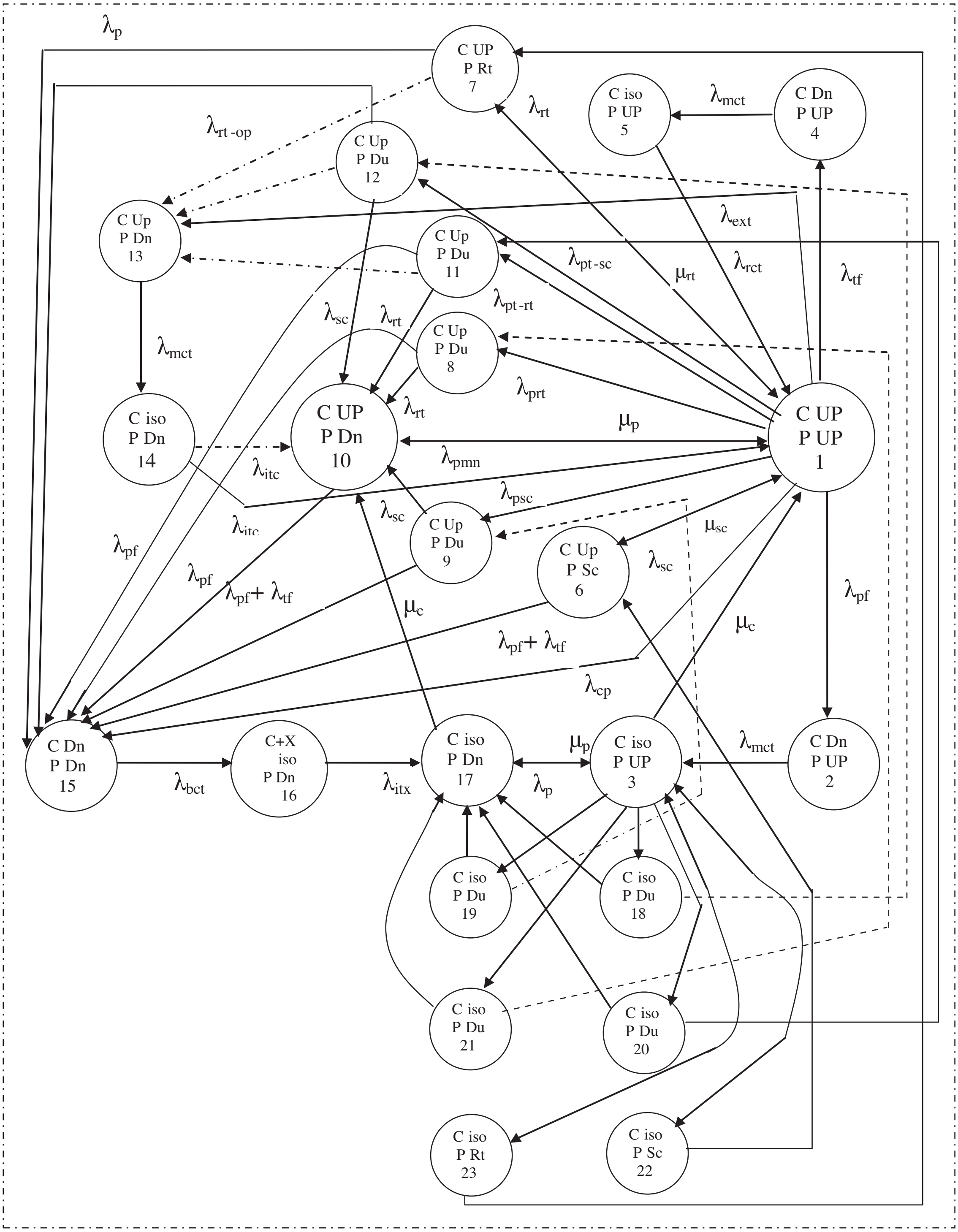

Figure 3. Detailed reliability model of a protective system.

The figure shows a more detailed model of a protection/component system, where the component is a transmission line and the protection scheme is based on directional over current logic. It is notable that some of the states, shown in this figure, consist of several sub-states, which actually represents a 65-state Markov Model and is defined as follows.

The system spends vast majority of its time on state 1 where both protective system and the line are perfect and operating successfully. In this condition, the protection system is ready to respond if it is called upon. In states 2 and 4, a permanent and transient fault respectively occurs on the line and the line is isolated by circuit breaker operation in states 3 and 5, accordingly. Isolated line is reenergized in case of a transient fault. The model transfers from state 1 to state 6, when the relay goes under the self-checking. State 7, which is composed of 6 sub-states, denotes the conditions in which Power Supply Unit, CT, VT, Relay, Trip Coil and Circuit Breaker is under routine test inspections, respectively. State 8, which is composed of 6 sub-states, represents the condition in which protective components with the same order as the above have failed and the failures is detectable by routine test inspections. The model transfers from state 8 to state 10 by detection of protective components failures. In this case, the transitions occur to the corresponding sub-states of state 10. The relay is failed in state 9 and the failure can be detected by self-checking function. State 10 is composed of 6 sub-states in which the protective components are known to be defective. In states 11 and 12, the relay is in potential mal-trip mode and the failure is detectable by routine tests and self-checking function respectively. The occurrence of an additional failure before detecting the potential mal-trip failures will transfer the model from states 11 and 12 to state 13.1 in which a trip signal is sent to the breaker and isolates the line in state 14.1. Breaker inadvertent opening transfers the model from state 1 to 13.2 and 14.2 in which the line is isolated. In these cases, following the line isolation, reenergizing action can take place by switching action which causes a transfer to states 10.4 and 10.6, respectively. State 15 is composed of 6 sub-states, denoting the condition in which a fault occurs and the protection system is not available to respond. Depending upon which component to be defective, the model moves to the corresponding states 15.1 to 15.6. The system can enter state 15.4 directly from state 1, if a simultaneous failure of the relay and the line occurs. The system enters state 16, when a fully reliable backup protection removes the line and an additional healthy component X. Depending upon which of the protection system components to be failed, a transition from states 15.1-15.6 to their corresponding states 16.1 to 16.6 will occur. Reconnecting the isolated component X will transfer the model to the corresponding states 17.1 to 17.6.

States 6–12 represent the failure, inspection or repair process of protection system. In these conditions, if a fault occurs on the line, the protection system will not be able to send a trip signal to its associated breaker and in this case, the model transfers to state 15.

While the line is isolated and the protection system is UP (state 3), the protection system may fail or the routine test inspection of different components may occur. In this condition, occurrence of the relay potential mal-trip failure causes a transfer to states 18 or 20, in which the defect can be detected by self-checking or routine test inspections respectively, which in turn leads to a transfer to state 17.4. The only difference between state 21 and state 8 is that the line is energized in the latter while it is isolated in the former. There is a similar condition between states 23 and 7, 22 and 6, 19 and 9. The direct transition from state 1 to state 13.1 may occur due to external faults in case of erroneous relay settings or coordination. In this case, the line isolation occurs by a transition from state 13.1 to 14.1, followed by manual re-closing operation, causing a transition to state 1. Human error in performing routine test on the relay can transfer the model from state 7.4 to state 13.1.

4. Optimum routine test schedule

A commonly used method for protection system reliability improvement 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 for each protective component are determined. Simulations are conducted based on directional over current scheme comprising 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 the unreliability. Unreliability is defined as the sum of probabilities associated with states 3, 4 and 5 in the proposed general reliability model of Figure 2 or, equivalently, as the sum of probabilities of states 6 to 65 in the detailed model. The probabilities associated with different states are calculated using the concept of stochastic transitional matrix [14]. The concept is based on the equation

$$\alpha P = \alpha, \tag{1}$$

in which α is the $1 \times N$ vector of states probabilities and P is the diagonal transitional matrix. Diagonal elements are sum of outward transition rates associated with each state and off-diagonal elements (P_{ij}), is the transition rate from state i to state j:

$$[P_1, P_2, ..., P_N] \begin{bmatrix} P_{11}, P_{12}, ..., P_{1N} \\ P_{21}, ..., P_{2N} \\ . \\ . \\ P_{N1}, ..., P_{NN} \end{bmatrix} = [P_1, P_2, ..., P_N]\,. \tag{2}$$

Since the above equations are not independent, one of them shall be replaced with the equation

$$\sum_{i=1}^{N} P_i = 1. \tag{3}$$

In this study, we solved a system of 65 equations with 65 state probabilities as unknowns. Routine test intervals are included in the Transitional Matrix as a changing parameter. It will be shown that testing of the protective components with different periods, determined in an optimization process, improves the reliability over traditional case where all the components were inspected with the same inspection intervals. Testing protective system with unique frequencies devoted to each component results in saving time as well as labor or manpower costs. At the first step, assume that routine test intervals for CT, VT, Relay, Trip Coil and Breaker are 2000 hours. Failure rates of the components are shown in Table. The values in Table are based on typical and experimental data. A comprehensive sensitivity analysis on the parameters of the model was conducted in [11].

The program was implemented in MATLAB. Unreliability profile with respect to routine test intervals of PSU is shown in Figure 4. The curve is obtained by solving equation (1) in a program loop with respect to routine test intervals. It can be seen from the figure that the maximum system reliability of 0.976566 is obtained for an optimum routine test interval of 1410 hours. Assuming 1410 hours as the routine test intervals of PSU, optimization with respect to CT test intervals is performed. The protective system reliability is improved to 0.977675 for an optimum CT routine test interval of 530 hours as shown in Figure 5.

Table. 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 components	1 operation/hr

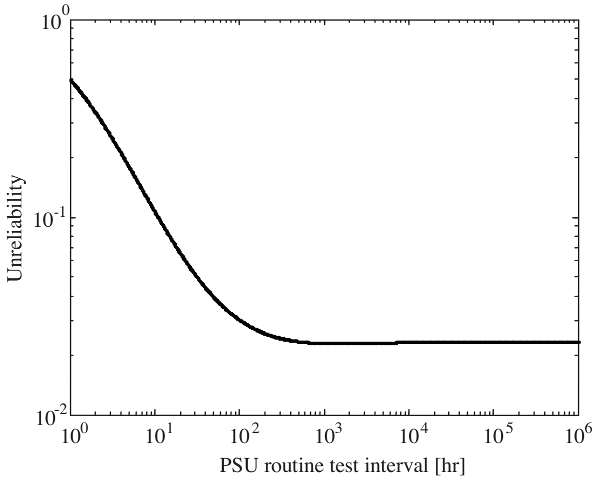

Figure 4. Unreliability with respect to PSU routine test intervals.

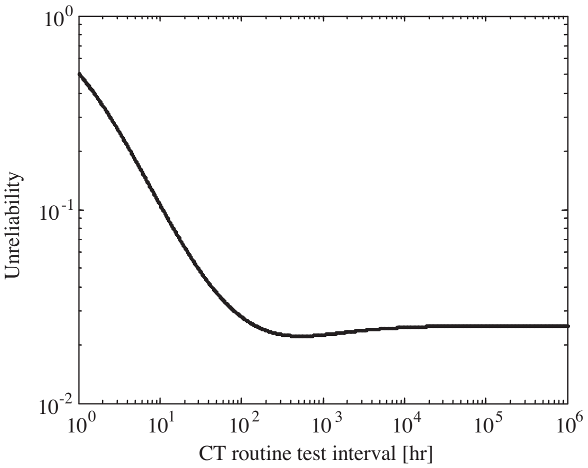

Figure 5. Unreliability with respect to CT routine test intervals.

Using the results of the previous two steps, the optimum routine test intervals associated with VT is determined. The result shown is Figure 6 indicates that the optimum routine test interval for VT is 1000 hours and the protective system reliability improves to 0.977818. The results of application of the same procedure to the relay unit are illustrated in Figure 7. It shows that the optimum test interval of 750 hours improves the reliability to 0.978232. Similarly, the optimum test interval of 1165 hours for the trip-coil increases the reliability to 0.978307. See Figure 8.

The process continues for the 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.

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

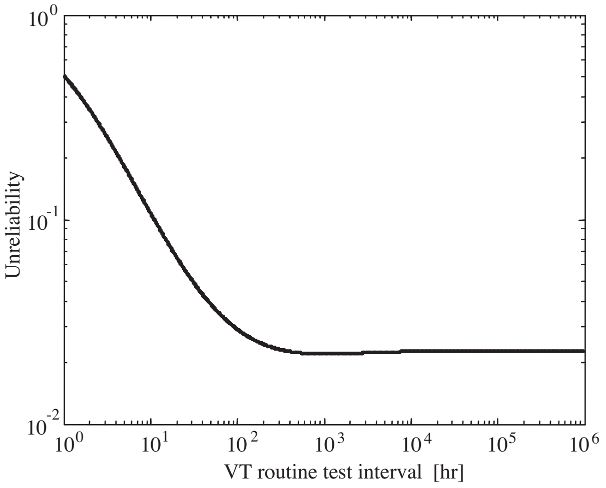

Figure 6. Unreliability with respect to VT routine test intervals.

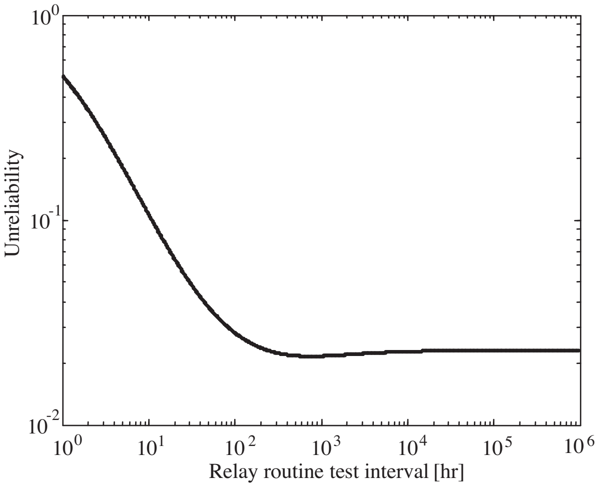

Figure 7. Unreliability with respect to relay test intervals.

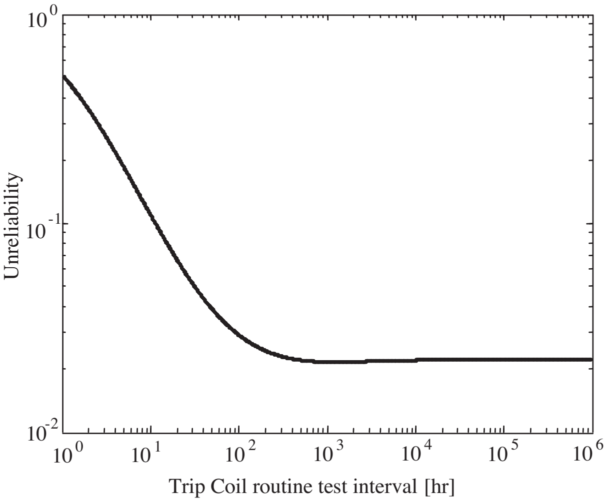

Figure 8. Unreliability with respect to trip coil test intervals.

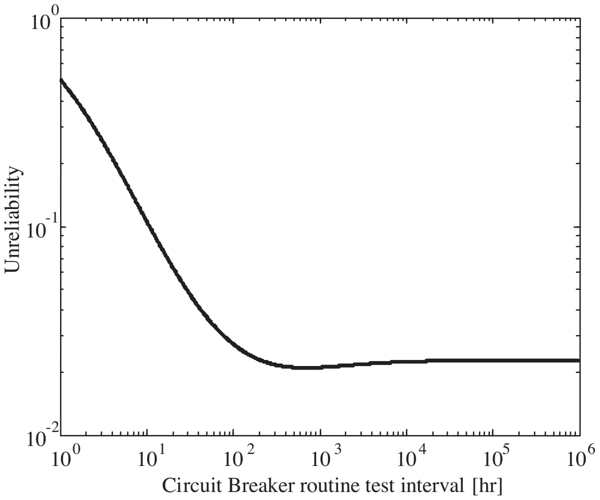

Figure 9. Unreliability with respect to Circuit Breaker routine test intervals.

Figure 10 shows a comparison between the unreliability of a conventional method where a fixed inspection period is assumed for all components and of the proposed method where different optimal inspection periods are determined for each protective component.

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 both from the reliability and from economical points of view. 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.

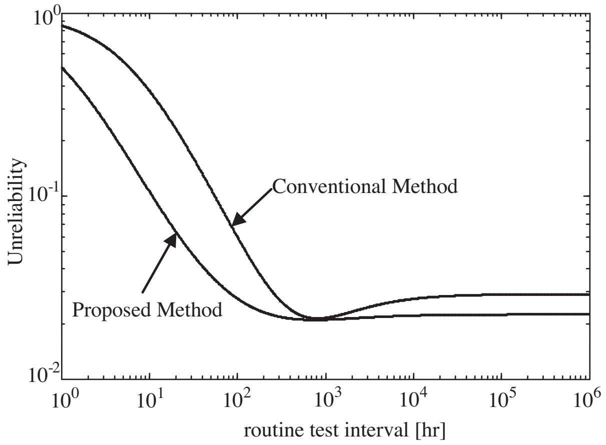

Figure 10. Comparison of different strategies for routine test.

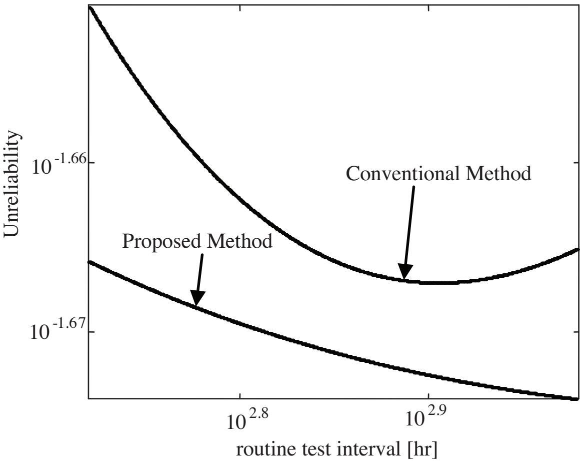

Figure 11. Comparison around the ambiguous point.

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 [11]. 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, which results in the decrease of security aspect of reliability. Security index is the probability of state V in the general reliability model or sum of probabilities associated with states 13 and 14 in the detailed model.

5.2. Required time for performing routine test

Impact of the time required for performing routine test, or in other words, the 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.

5.3. Human errors

The impact of human mistakes on system security by 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.

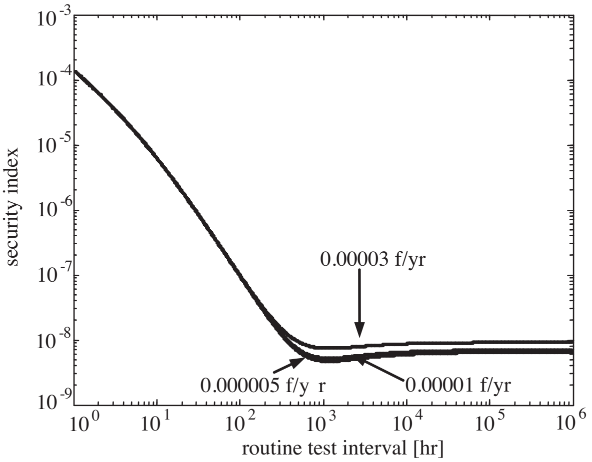

Figure 12. Impact of breaker inadvertent opening on security.

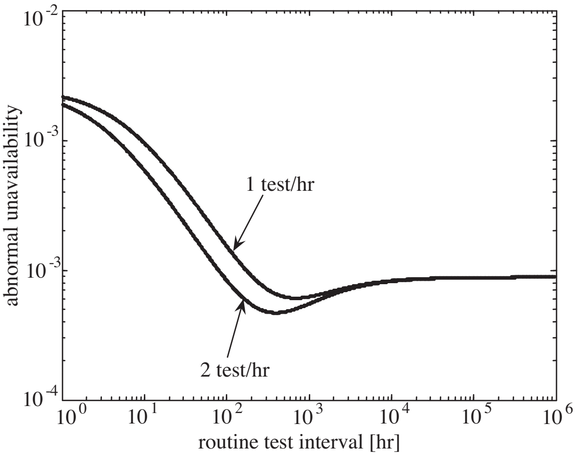

Figure 13. Impact of routine test time on abnormal unavailability.

5.4. Self-checking and monitoring effectiveness

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 Figures 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 is increased.

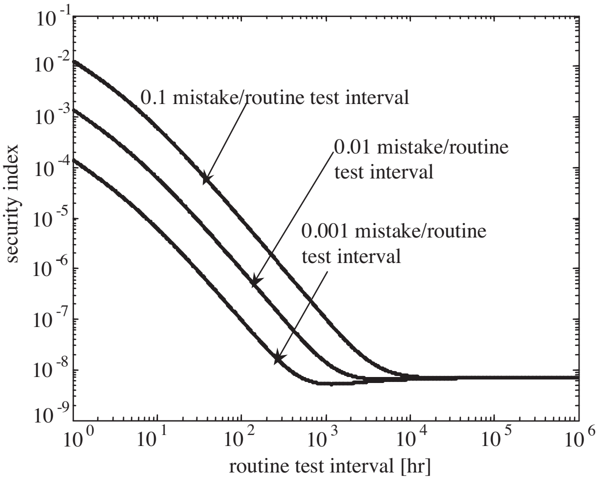

Figure 14. Impact of human mistakes on security.

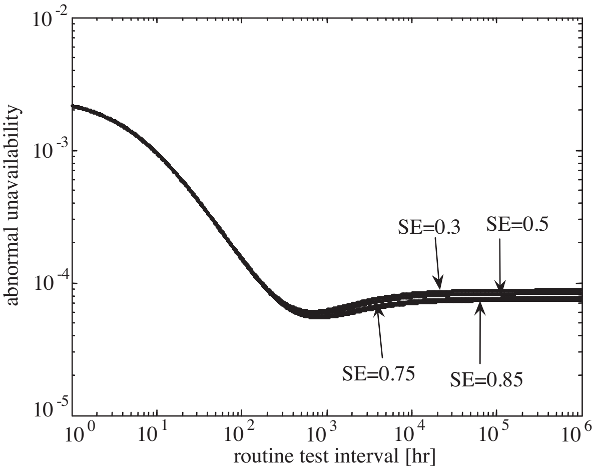

Figure 15. Impact of self-checking on abnormal unavailability.

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 probabilities 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.

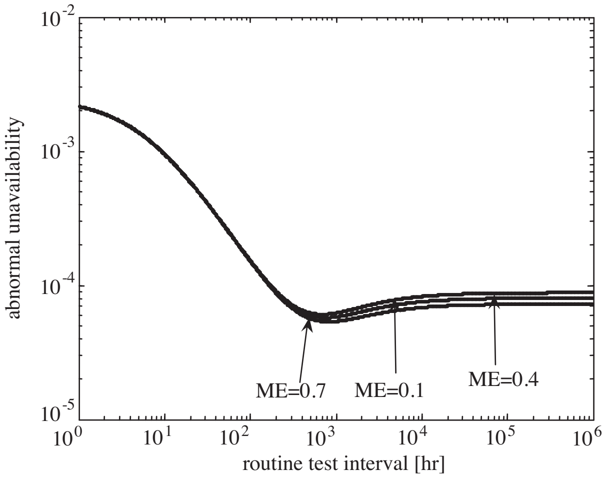

Figure 16. Impact of monitoring on abnormal unavailability.

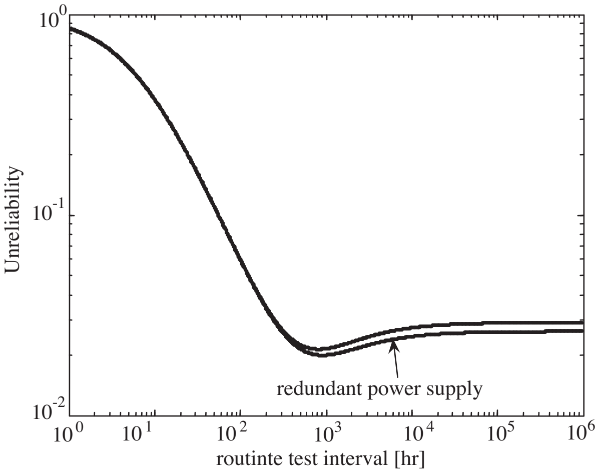

Figure 17. Impact of redundant PSU.

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.

6. Conclusion

On the basis of the general reliability model for protection systems [8], a 65-state Markov model is developed. In this paper, a novel routine test schedule is proposed for protective systems, in order to improve protective system reliability as well as to attain more economical maintenance procedure. Reliability indices of protective system components were included in the model. It was shown that choosing a separate routine test interval for each protective component, enhance protective system reliability more in comparison with what would be obtained by the conventional method. A sensitivity analysis was conducted for directional over current scheme to show the extent of dependency between protective system reliability, optimum routine test interval and protective components reliability indices, redundancy and human performance. Impacts of factors such as circuit breaker inadvertent opening, required time for performing routine test inspections, human mistakes, self-checking and monitoring effectiveness, redundancy of the protective system, permanent and transient faults on the protected zone, operation of backup protection and common-cause failures were analyzed by the simulations. Further studies including protection system-power system interaction, will yield more accurate description to the stochastic property of the overall system.

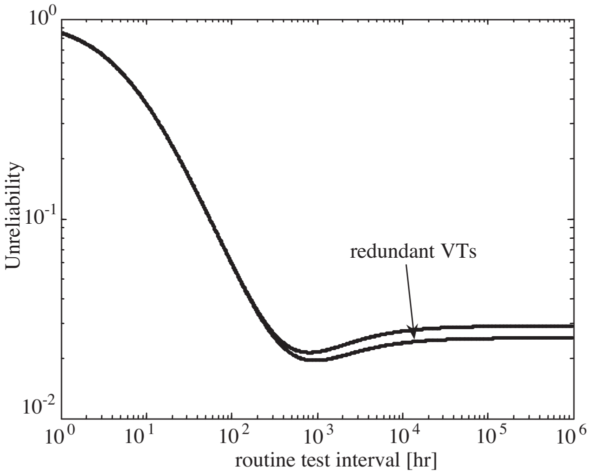

Figure 18. Impact of redundant Voltage transformers.

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