EVALUATION OF REDUNDUNCY AND EFFECT OF PROTECTIVE COMPONENTS ON PROTECTION SYSTEM RELIABILITY

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ABSTRACT

One way of improving the reliability of protection systems is to carry out routine test with specified time intervals. In this paper the previously proposed model in [5] is modified to suit the Directional Overcurrent scheme. In the modified model, the individual protective components effects are taken into account and a sensitivity analysis is conducted to analyze the failure rate effect of protective components on the reliability of protection system. Finally, redundancy consideration in different parts of the system is examined using the developed model.

I. INTRODUCTION

Protection system performance is of great importance in the operation of today highly developed electric transmission networks. The two primary failure modes of a power system protection are failure to operate and incorrect operation. In other words, reliability of protection systems is decoupled into two aspects of dependability and security. Dependability is defined as the probability that a relaying system operates when required. Security is the system ability in restraining on those situations where tripping is not required. Therefore, sending trip signals and opening the associated breakers if and only if a fault occurs in the protection zone is enough for a protective system to be reliable. Properly designed relaying commences the isolation of the faulted area in conjunction with continuous operation in the healthy parts of the power system. Disconnection must be fast enough to prevent succeeding mal-operations and multiple outages.

Protection system normally requires routine maintenance testing to maximize its availability and minimize risk of misoperation. To achieve this goal, an appropriate routine test interval is required for protective devices.

Anderson and Agraval [1] presented a Markov Model for a protection zone and its protected equipment. However, self-testing was not included in their model. Kumm et al [2] illustrated the difference between the optimum test interval of traditional and digital relays with and without self-test functions. Anderson, et al [3] presented an improved reliability model for redundant protective systems using Markov model. Self-test function is still not included in this model. It is shown that redundant protective systems could enhance the reliability of overall system. Kangvansaichol, et al [4] determined the optimum test intervals and compared the reliability indices among several configurations of over current relay protection scheme.

Billinton, Fotuhi-Firuzabad and Sidhu presented a Markov model to examine routine test and self-checking and monitoring facilities [5]. The model also recognizes common-cause failures, backup protection and relay maltrips. In this paper, the model described in [5] is extended for Directional Over current scheme to determine the optimum routine test intervals, taking the effect of individual components into account. In this way, sensitivity of reliability to failure rate of different components is investigated and the effect of adding redundancy to various parts of the protection system is considered in the next step.

II. RELIABILITY MODELING OF PROTECTION SYSTEMS

In this paper, the general five state reliability model introduced in [5] and shown in Figure 1 is extended to a 65-state Markov Model to examine different reliability aspects of a none-pilot Directional Overcurrent Protection of a transmission line shown in Figure 2.

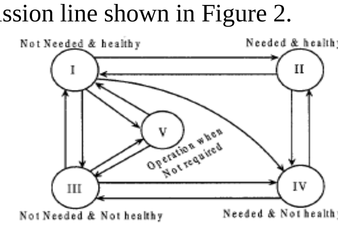

Fig.1 General reliability model of a protective system

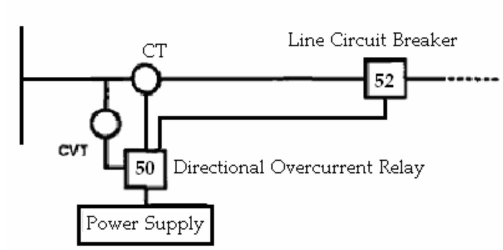

Fig.2 Overcurrent system protection of a feeder

A. General Reliability Model

A general reliability model for any protective system can be shown as Figure 1. In this model, state I represents 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 on the protected component. It is not ready since some part of protective system is either failed, under 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 more the probability associated with this state, the lower is the system security. It should be noted that the probability of State II depends mainly on the fault rate and equipment restoration time. This simplified model can be expanded for different relaying schemes and state probabilities can be determined using the frequency balance approach [7].

B. Detailed Reliability Model of Directional Overcurrent Protection System

To put a step toward expanding the general reliability model, a 23-state Markov Model is presented in Figure 20 which refers to a more detailed model of a protection/component system where the component is a transmission line and the protection scheme is based on directional overcurrent logic. This model is not completely expanded yet to show exactly the transition rates and different states. Although 23 states are shown in Figure 20, some of these states consist of several sub-states leading to a 65-state Markov Model.

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, protection system is ready to respond if it called upon. In states 2 and 4, a permanent and transient fault occurs respectively on the line and the line is isolated by circuit breaker operation in states 3 and 5. Isolated line is reenergized in case of transient fault. The model transfers from state 1 to 6 when the relay undergoes 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 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, after isolation of the line, reenergizing action can be taken place by switching action transferring 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 the situation. Depending upon which component to be defective, the model moves to 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 will enter state 16 by isolating the line and additional healthy component X by backup protection system which is known to be fully reliable. 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 can fail or the routine test inspection of different components can occur. Occurrence of the relay potential mal-trip failure in this condition will transfer the model to states 18 and 20 in which the defect can be detected respectively by self-checking and routine

test inspections transferring the system 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 coordination or settings. In this case the model transfers from state 13.1 to 14.1 isolating the line and then reenergizing by manual switching operation getting back to state 1. Human error in performing routine test on the relay can transfer the model from state 7.4 to state 13.1. Abbreviations used in the model are as following:
UP: Operational state;
Dn: failed state;
Du: Unrevealed failure of protection system
iso: Isolation of the line or neighbouring 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.

III. STUDY RESULTS

Since the parameters used here are just typical ones, a sensitivity analysis is required to show the extent of dependency between reliability indices of the components and reliability of the overall protection system. Versatile simulations were conducted to examine the effects of different parameters on abnormal unavailability of protection system and to establish a schedule for determining the frequency of performing preventive maintenance on the protective system. Abnormal unavailability is the sum of probabilities associated with states 15-17 in the model.

A. Sensitivity Analysis

Parameters to be studied here are failure and repair rates of the components, monitoring and self-checking functions effectiveness, human errors, common-cause failures of the relay and the line and redundancy in different parts of the system.

A.1. Protected Line

The line permanent and transient failure rate and repair rate impact on dependability of the system with respect to routine test intervals can be seen in Figures 3-5. It can be seen from these Figures that as the failure rate increases and the repair rate decreases, the protective system dependability decreases. This can clearly be seen by upwards trends of the curves.

A.2. Power Supply Unit (PSU)

The impact of PSU failure rate on reliability of the protection system with respect to routine test intervals can be seen in Figure 6. It can be seen form this figure that an increase in the failure rate from 0.03 to 0.5 failure/year results in a decrease in system dependability. Under these conditions, the optimum routine test interval decreases from 675 to 325 hours.

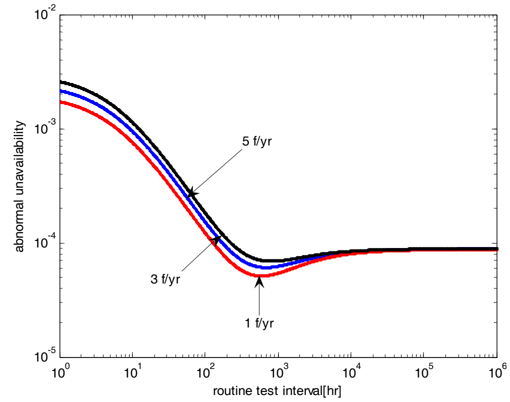

Fig.3. Line Permanent failure rate effect on dependability

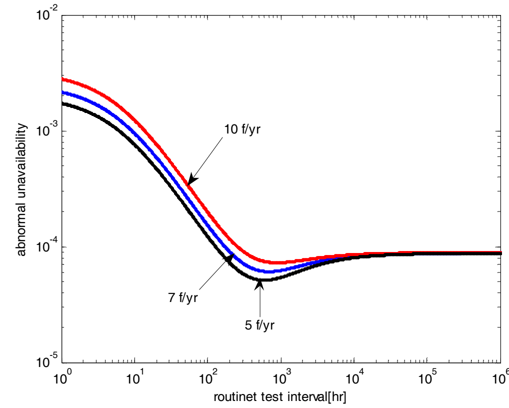

Fig.4: Line temporary failure rate effect on dependability

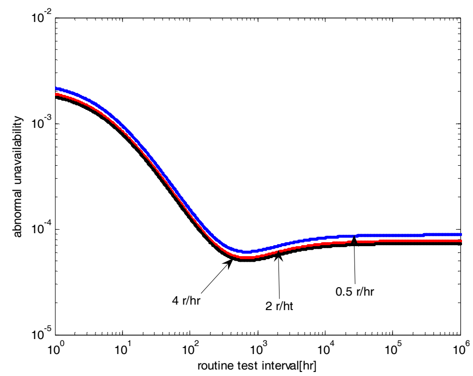

Fig.5. Line repair rate effect on dependability

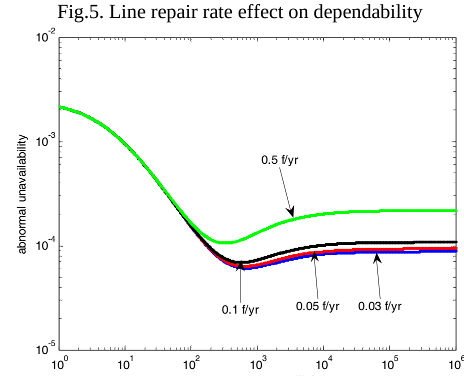

Fig.6. PSU failure rate effect on dependability

A.3. Current Transformer

The CT failure rate effect on dependability with respect to routine test intervals is shown in Figure 7. It can be seen that as the failure rate is increased from 0.05 to 0.2 f/yr, the system abnormal unavailability increases and the optimum routine test interval decreases from 675 to 500 hours.

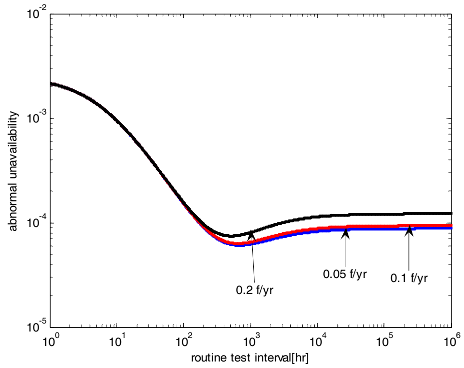

Fig.7. CT failure rate effect on dependability

A.4. Voltage Transformer

The VT failure rate effect on dependability with respect to routine test intervals is shown in Figure 8. It can be seen that as the failure rate is increased from 0.04 to 0.2 f/yr, the system abnormal unavailability increases and the optimum routine test interval decreases from 675 to 480 hours.

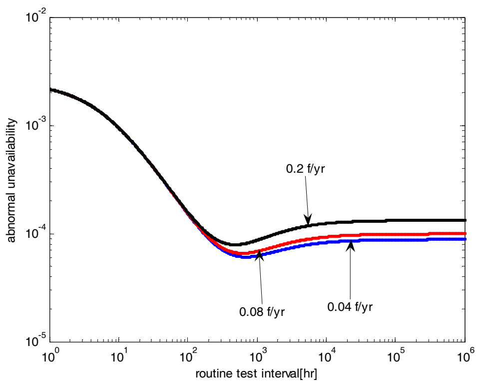

Fig.8: VT failure rate effect on dependability

A.5. Relay

The Relay failure rate and potential mal-trip failure rate impact on reliability with respect to routine test intervals is shown in Figures 9 and 10. It can be seen from the results that increase of failure rate from 0.08 to 0.3 f/yr leads to increase of abnormal unavailability and decrease of optimal routine test interval from 675 to 500 hours. Increase of potential mal-trip failure rate leads to a decrease in security of protection system. From security points of view, the optimum routine test interval is to be decreased to 765 hours for 0.02 f./yr; while the optimum test interval was 1165 hours for 0.01 f/yr.

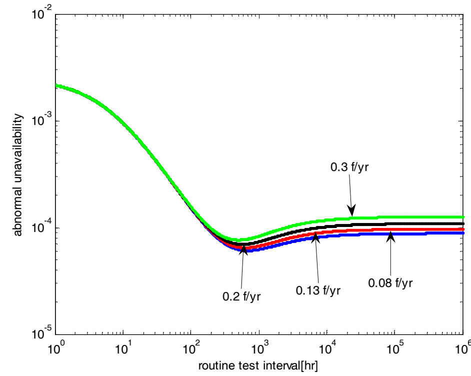

Fig.9: Relay failure rate effect on dependability

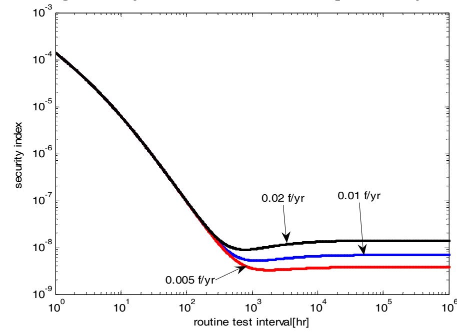

Fig.10: Relay potential mal-trip effect on security

A.6. Trip Coil

The impact of Trip Coil failure rate on dependability with respect to routine test intervals is shown in Figure 11. It can be seen from this figure that as the trip coil failure rate is increased from 0.035 to 0.1 f/yr, the system optimum routine test interval decreases from 675 to 575 hours.

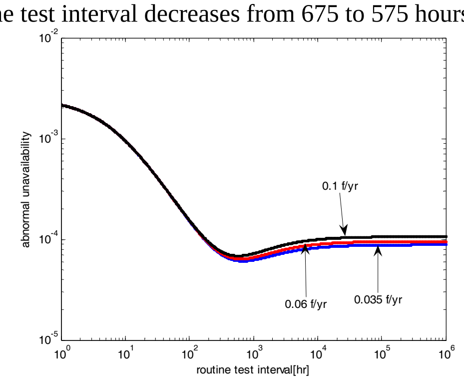

Fig.11: Trip coil failure rate effect on dependability

A.6. Breaker

The Breaker failure rate and inadvertent opening rate impacts on reliability with respect to routine test intervals are shown in Figures 12 and 13. It can be seen that increase of failure rate from 0.06 to 0.15 f/yr leads to increase of abnormal unavailability as well as a decrease in optimum routine test interval from 675 to 540 hours. Figure 13 indicates that increase of inadvertent opening rate has negative effect on security index.

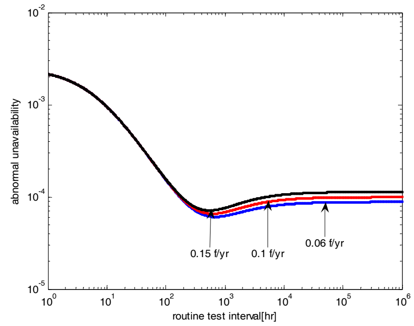

Fig.12: Breaker failure rate effect on dependability

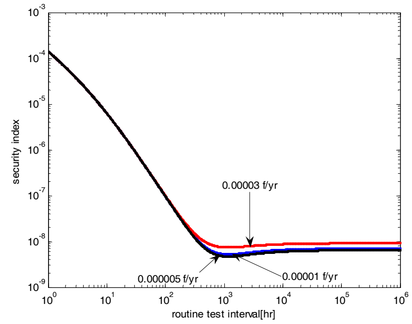

Fig.13 Breaker inadvertent opening rate effect on security

B. Effects 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.

B.1. Redundant CTs

According to Figure 14, using double current transformers causes an extension of optimum routine test and improvement of reliability.

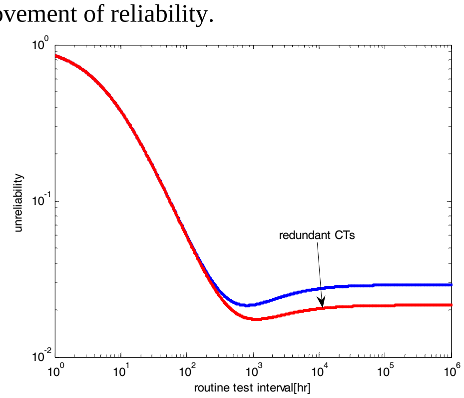

Fig.14: CT redundancy effect on reliability

B.2. Redundant Relays

Effects of redundant relays on security and overall reliability of the system are shown in Figures 15 and 16 respectively. It can be inferred that redundant relays improves dependability but aggravates security aspect for long test intervals. It also results in an extension of routine tests from dependability points of view.

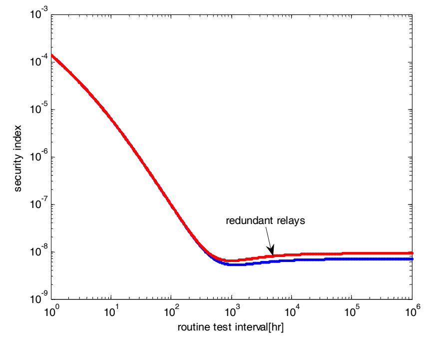

Fig.15: Relay redundancy effect on security

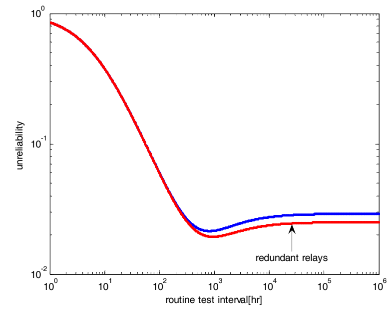

Fig.16: Relay redundancy effect on reliability

B.3. Redundant Trip Coils

Redundant trip coils enhance the dependability and extend the optimum routine test intervals as shown in Figure 17.

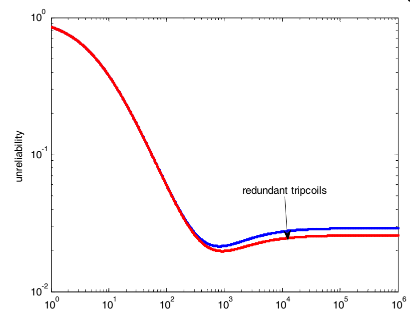

Fig.17: Trip Coil redundancy effect on reliability

B.4. Breaker Redundancy

Breaker redundancy effects on security and overall system reliability are shown in Figures 18 and 19, respectively. From the overall reliability points of view, redundant breakers cause the optimum routine test interval increases from 800 to 1000 hours.

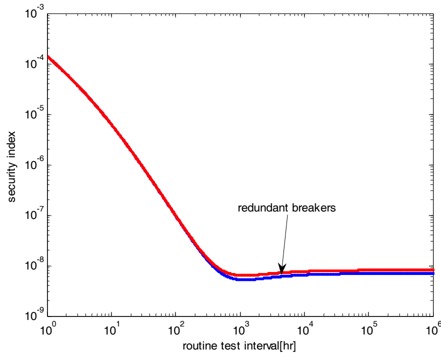

Fig.18: Breaker redundancy effect on security

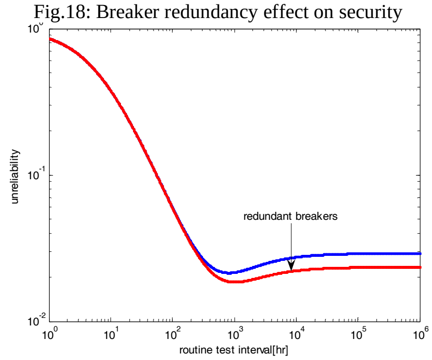

Fig.19: Breaker redundancy effect on reliability

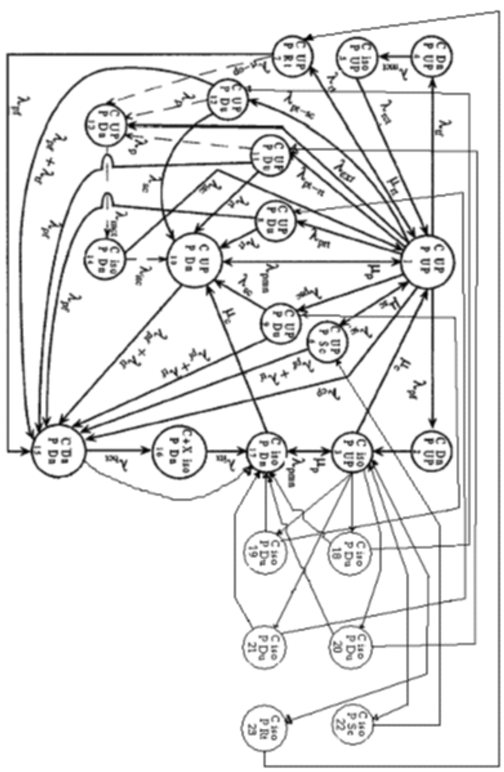

Figure 20. Detailed Reliability Model

IV. CONCLUSION

An extended Markov model is developed for protection system reliability studies. Sensitivity analysis of protection system reliability with respect to reliability indices of protective components is done for directional over current protection scheme to identify weak parts of the system. Effects of redundancy on different parts of the system are also included. These investigations help protection system designers and planners to optimally make use of redundant configuration systems in a cost effective manner.

REFERENCES

[1] P. M. Anderson and S. K. Agarwal, "An Improved Model for Protective-System Reliability," IEEE Transactions on Reliability. Vol. R-41, no. 3, September 1992**,** pp. 422-426.

[2] J.J. Kumm, M.S. Weber, D. Hou and E.O. Schweitzer, 111, "Predicting the Optimum Routine Test Interval for Protective Relays," IEEE Transactions on Power Delivery, vol. 10, no. 2, April 1995**,** pp. 659-665

[3] P.M. Anderson, G.M. Chintaluri. S. M. Magbuhat and R. Ghajar, "An Improved Reliability Model for Redundant Protective System – Markov Models," IEEE Transactions on Power Systems, vol. 12, no. 2, May 1997, pp. 573-578.

[4] K. Kangvansaichol, P. Pittayapat, B. Eua-arporn, "Routine Test Interval Decision For Protective Systems Based on Probabilistic Approach", IEEE 2000.

[5] R. Billinton, M. Fotuhi-Firuzabad, and T. S. Sidhu, "Determination of the Optimum Routine Test and Self-Checking Intervals in Protective Relaying Using a Reliability Model", IEEE Transactions On Power Systems, Vol. 17 , No.3, August 2002.

[6] R.N Allan, "Effects of protection system operation and failures in composite system reliability evaluation", Journal of Electric Power Energy Systems., Vol. 10, pp. 180-189, July 1988.

[7] R. Billinton; R. N. Allan, "Reliability Evaluation of Engineering Systems" 2nd Edition, Plenum Press, 1996.