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TEST METHOD ANALYZING OF PROTECTION EQUIPMENT AND OPTIMAL TIME DEFINING FOR PET IN ZANJAN REGIONAL ELECTRICITY COMPANY

A. Ebrahimi [1] M. Ojaghi [2] K. Mazlumi [2]

1. Department of Electrical Engineering, Science and Research Branch, Islamic Azad University, Zanjan, Iran a67_ebrahimi@yahoo.com
2. Department of Electrical Engineering, University of Zanjan, Zanjan, Iran, mojaghi@znu.ac.ir, kmazlumi@znu.ac.ir

Abstract- Nowadays, maintaining and enhancing system reliability and reducing maintenance costs is the top priority of electricity companies. Currently, power companies including Zanjan Regional Electricity Company (ZREC), perform periodic testing annually in addition to various condition monitoring and effective maintenance, while optimum testing period depends on many factors and change dynamically. Among the important reasons for the need to study the subject at ZREC, is the change in relays' structure (about 50% of the relays are microprocessor based) and the high number of human-related accidents occurring on the network during periodic tests. Markov model has been used to determine the optimal test interval. However, being sensitive to the model reliability parameters, difficulty of determining these parameters and their change during the time are main disadvantages of this model. Due to its limitations, this model can't be implemented in the real conditions of power system. In this paper, an optimal time interval is provided to test the protective equipment periodically, which is based on actual conditions in the sub-transmission and transmission substations. According to various test instructions of the relays and considering the factors affecting the relays testing intervals, various test programs under different conditions are implemented and optimal testing intervals are obtained. This method is implemented in two real substations with different structure of the relays in ZREC and optimal interval of periodic tests of their relays is obtained. The system reliability increase as well as the maintenance cost reduction is the important outcomes of the implementation of these guidelines.

Keywords: Reliability, Maintenance, Protective Relays, Optimum Test Interval.

I. INTRODUCTION

Electrical energy due to its unique characteristics compared to other forms of energy, is the most used energy in the public. After production in the power plant, this energy is transmitted into electrical substations through transmission lines and after the voltage adjustment process is given to consumers through the distribution substations.

By joining the equipment associated with the production, transmission and distribution of electrical energy, the power grid is created. Harmonic operation of power system equipment in maneuvers and other occurred events is very important. In addition to the proper switching equipment design, prediction and control of protective devices in accordance with the specifications and requirements of the power system and also preserving high accuracy and speed of the devices are essential for correct, proper and safe use of modern power grids.

Therefore, protective equipment with newer technology and higher accuracy are required. Because protective relays play very serious role in the protection system, errors should be reduced in them as far as possible. So when buying new relays, they are required to periodically be tested under conditions similar to the actual working conditions to ensure their roles in errors [1].

Problem with protection systems is that they may need to perform only once in a year. This is while if they are damaged, this damaged part will remain unknown and when required to act, they will not respond to power grid problems. To overcome this disadvantage, relays should be tested at appropriate intervals to ensure the accuracy of their performance. Periodic maintenance tests after installation causes system reliability, stable range of accuracy, fault and depreciation detection of equipment, accuracy detection of trip circuits and setting adjustments.

To determine the optimal time of testing, methods such as CBM (Condition Based Monitoring) and CBRM (Condition Based Risk Monitoring) has been suggested that efficiently and effectively determine the maintenance time with respect to indices indicating the occurrence of faults in the equipment. However, these methods are based on real-time data to monitor the state of equipment to ensure its health. Hence, cannot be implemented in distribution and transmission substations due to practical and administrative conditions [2].

Maintenance and repair activities bring challenges of rising costs, depreciation of equipment and keeping and improving the reliability and quality of power in electrical companies. This has caused a need to implement an effective technique for repair and maintenance of protective equipment to create power with high quality and reliability for customers [3]. Currently the maintenance programs of all companies are time-based [method communicated and implemented within the company]. It is essential to move from time-based strategy to state-centered strategies (looking for higher performance of resources and more impact on category of maintenance).

In Zanjan Regional Electricity Company (ZREC) network, due to major changes in network equipment and technology changes in protective equipment such as the use of new generation of relays, time-based strategy should move towards state-centered strategies in order to achieve cost management, stable energy transfer from production to consumption, increased reliability and improved performance of protective devices. This topic is the main objective of this research. Finally, an optimal guideline is suggested for testing time interval of protective relays, taking into account previous studies and real situations and practical implementation capabilities. Case study results in ZREC are presented as well.

II. FACTORS AFFECTING THE TEST PERIOD

Periodic testing is very important. If the test is performed periodically in short intervals, the number of blackouts will increase (network reliability decreases), and also periodic testing with long intervals cause a failure in detection of errors in protection system and when needed to function, the protection system cannot perform its duty [4]. Several factors influence the testing methods and intervals of relays, which are given as follows.

A. Relays Construction Technology

Based on their construction technology, protective relays are divided into mechanical relays, static relays with transistor, electromechanical relays, and numerical relays with digital circuits and microprocessor. This division will have a direct impact on their test intervals.

B. Protection Function

Test interval of protective relays differs according to the type of protection they are responsible.

C. The Voltage Level of Installation

This factor in addition to operating interval is effective on technique and quality of protective system testing.

D. Year of Manufacture

This factor combined with relay construction technology generally affects test interval setting.

E. Number of Successful Operations

A relay with a high number of successful operations requires longer test interval. If different functions of relay solve the failure, the relay status would be detected as normal and healthy.

F. Equipment to Be Protected

The protected equipment type that can be a transformer, power line, reactor, feeder or capacitor, is essential for determining the test interval.

G. Storage Conditions

Environmental conditions such as temperature, humidity, vibration or electrical conditions of environment such as electromagnetic inductions should be considered. It should be noted that favorable environment for stocking of relays before installation also influences relays' test intervals which should be considered.

H. Relay Protection Plan

Being main or backup protection, single or multi-unit protection relay and its stability also has a direct impact on relays' test interval.

I. Test Equipment

Testing equipment differ from simple primary injection to highly advanced automatic systems. The closer test devices can take test conditions to the real situation of the network, the longer test intervals can be considered.

J. Test-Man

Knowledge and mastery of relay test-man about concepts of protection and power grid analysis, is highly effective on protective relays' testing.

K. The Level of Dependability and Security

According to two principles of protection in which security is more important in the transmission part due to stability maintenance and dependability is more important in distribution network, time, testing methods and requirements are different and affect relays' test intervals.

L. The Amount of Required Off State

Calculations of reliability and availability of relays show that relay test interval increases with the relay that accompanies too much off time of the consumer.

M. Installation Year of the Relay

Apart from the lifetime of the relay, the time relay has been installed and also entered to circuit affects tests interval. Considering this parameter that the year of relay production and its installation are different, is useful for some cases.

N. Detected Failure and Fault Rate

A relay with failures at small intervals and a relay with failures at large intervals have a different impact in calculating relays' test intervals.

O. Network, Settings and Configuration Changes

Modifications, development plans, optimization and preservation and also annual maintenance tests result in conditions that can cause changes in maintenance tests interval.

P. Visibility Capabilities in Equipment

Visibility of relays' information from a distance using new technologies such as DCS which contain relay availability and their monitoring, have a direct impact on relays' test interval setting.

Some other sub-factors including the preparation of appropriate relay test sheet according to the manufacturer's recommendation, training relay test-men and preparing the appropriate database of relay operations affect directly the relays' test interval improvement which were not covered due to the instruction implementation of relay testing but must be considered. To determine the optimal time interval for periodic testing of protective relays, Group No. I11 of Institute of Electrical and Electronics Engineers (IEEE) Relay Committee had some surveys about a number of power companies in 1971, 1991 and 2001. Table 1 shows a number of power companies interviewed in the survey along with a number of their transmission, power plant and distribution substations [5].

Table 1. Number of power companies interviewed and their covered substations [5]

Year of study	Number of power companies	Number of power plant substation	Number of transmission substation	Number of distribution substation
1971	125	1157	5096	17849
1991	146	1229	9814	26680
2001	79	632	8461	12499

In this survey, effective factors in determining the periodical testing interval of protective relays have been defined based on actual condition and operation in electric power networks. In the survey, a large number of respondents believe factors such as "analysis of past events", "voltage level", "limitations of specialized human resources" and "performance or non-performance of relay" as the most influential parameters in determining testing intervals. Survey respondents' opinion about the effectiveness of each factor such as "ultra-high levels of voltage", "relay type", "relay structure", "automatic testing capability of relay" and other factors in shortening periodical testing intervals, is shown in Table 2 and Figure 1 [6].

Table 2. Survey results about criteria of selecting a shorter time interval in relays' periodic testing [6]

Effective factors	Number of Positive responses	Percentage of positive responses
Relays structure (electromechanical-digital)	6	10.17%
High voltage level	23	38.98%
Type of load	5	8.47%
Type of relay (distance-differential-over current and …)	17	28.81%
Relay automatic testing capability	4	6.78%
Variety of installed relays in a substation	2	3.39%
other	2	3.39%

It can be seen that 38.98% of the respondents suggest voltage level of the system and 28.81% of them suggest the type of relay as important factors in shortening time intervals for periodic testing of protective relays. Although longer intervals in periodic tests reduce system, maintenance costs but also reduces the ability of detecting the hidden errors of system.

As shown in Table 3 and Figure 2, 34.33% of respondents agree with the lengthening the interval between periodic tests of protective relays equipped with automated testing capabilities [6].

Table 3. Survey results about criteria of selecting a longer time interval in relays' periodic testing [6]

Effective factors	Number of Positive responses	Percentage of positive responses
Relays structure (electromechanical-digital)	16	23.88%
High voltage level	3	4.48%
Type of load	7	10.45%
Type of relay (distance-differential-over current and …)	9	13.43%
Relay automatic testing capability	23	34.33%
Variety of installed relays in a substation	6	8.96%
other	3	4.48%

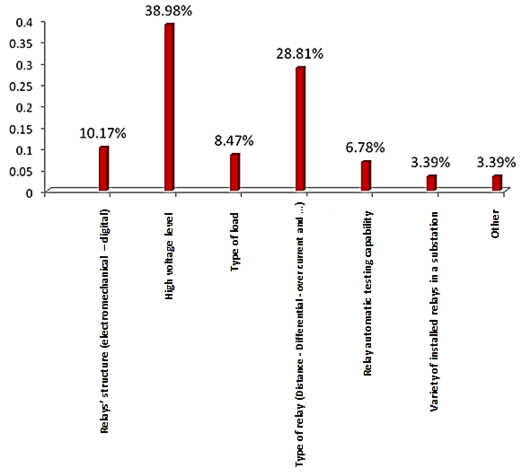

Figure 1. The effectiveness of criteria of selecting a shorter time interval in relays' periodic testing [6]

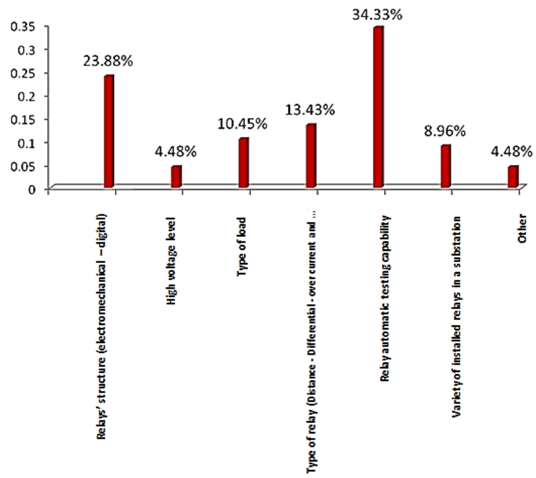

Figure 2. The effectiveness of criteria of selecting a longer time interval in relays' periodic testing [6]

As in previous survey, factors such as "type of relay" and "relay structure" are other important factors in prolonging the interval between the tests.

III. FACTORS INFLUENCING THE RESEARCH FOR OPTIMAL RELAY TESTING TIME IN ZREC

Two following factors are effective in researching the optimal time for protective equipment test in ZREC [6]:

1- According to data collected by the network of ZREC, currently about 8.37% of network's installed relays are electromechanical, 41.37% of them are electronic and 49.90% of them are numerical. Due to this fact, we can offer the following two proposals. First, due to the valuable features of numerical relays, such as high flexibility, automatic registration of events and errors, better performance in terms of error than their older versions, and most importantly the ability to self-examine and constant monitoring of health status of relay.

It is recommended to quickly replace the old and inefficient electronic and electromechanical relays with a variety of numerical ones and educate operator personnel with proper training, testing and repairing to maximize their protection capabilities. Second, since a limited number of relays used in network are of kind that are not capable of automated testing, some regular and accurate periodic tastings should be organized even if they are limited because only way to detect hidden errors in such relays is periodic test and repair. If it is not done well, it increases risk of improper functioning of relay and puts entire network at risk of serious and irreparable dangers.

2 - According to event statistics in ZREC network, around 13.40% of problems in the network are due to human errors that 44.98% of them are because of the lack of sufficient accuracy in the repairs and 10.04% of it is because of wrong relay setting. Therefore, with some trainings of test and repair personnel, advising them to afford adequate care during labor, adequate supervision of test personnel, and thinking of other necessary measures, human errors should be avoided where possible and increase the test efficiency to maximum and also prevent the periodic test to cause problems rather than improving system performance. In this regard, it is recommended to refuse opening connections and changing relay settings in tests as far as possible and instead use relevant plates test.

IV. SIMULATION RESULTS

A. Markov Model in Determining Relay Test Intervals

Protection systems play a vital role in maintaining the high degree of service reliability required in present day power systems. The two primary failure modes of a relay are fail to operate and incorrect operation. Relay reliability considerations are usually separated into the two different aspects of dependability and security [7]. Dependability is defined as the probability of correct operation of the relaying system. In other words, dependability is a measure of the relay's ability to operate when required. Security is defined as the probability that a relay will not operate in those situations when tripping is not desired [8].

It order to enhance both dependability and security, appropriate testing and inspection of the protective system should be performed. Considerable work has been done to examine different reliability aspects of protection systems. Reference [9] introduces a method to calculate the probability of failure of protective relay systems. A reliability index designated as "unreadiness probability" is defined in [10] as probability that the relay system fails to respond when called upon to operate in presence of a fault.

The proposed model in [10] has been extended and also improved in [11] 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 phenomena. Modern digital relays are normally equipped with self-checking and monitoring facilities. The impact on the performance of relay and the benefits to be expected from use of these facilities are discussed in various papers [12].

Reference [13] illustrates a Markov model to predict the optimum routine test interval for a protective relay with and without self-testing capabilities. Two different indexes of "abnormal unavailability" and "protection unavailability" are defined as the probability that the relay will be out of service while the system is energized and the probability that the relay does not respond when a fault occurs. An improved reliability model for redundant protective systems is presented in [14]. Hidden failures in protection systems and a methodology for identifying them are discussed in [15].

The failures are considered as the key contributors in the degradation of power system wide-area disturbances. A general five-state Markov model is first developed in this paper followed by a detailed 17-state model for a protection/component system where the two main relay failure modes of "failure to trip when required" and "mal-trip when not required" are included. The detailed model considers inspection of routine test, self-checking and monitoring of the relays, common-cause temporary, permanent faults and failures and the associated clearing times, operation of back-up protection, and relay mal-tripping.

The basic objective is to determine the optimum self-checking and routine test intervals using the developed models. The condition is formulated as an optimization problem in which, for a given set of data, the probabilities associated with the different states of the 17-state model are first determined. The five-state model probabilities are then calculated by classifying the associated states of the 17-state model. The optimum self-checking and routine test intervals can be determined by minimizing or maximizing the probabilities associated with the different states in the five-state model.

B. Monitoring and Self-Checking

There are many different methods, which can be used to improve the reliability of a relay system. These include different operating principles, redundancy within the relay system, local and remote back-up methods, etc. The redundancy approach is not generally applied due to its excessive cost and complexity. The reliability of a protection relay can also be improved by adding built-in self-checking and monitoring facilities during the design stages. These features allow a utility to increase the traditional routine relay maintenance interval.

A self-checking facility can significantly reduce the possibility that a failed relay could remain in service for a significant amount of time. Reliance on only routine test inspections could result in a failure occurring in a relay and remaining undetected until the next routine test or until a fault occurs in the equipment being protected. Monitoring techniques normally operate continuously and can be used for unavailability detection, and possible tendencies to mal-trip. The self-checking facilities in a digital relay operate periodically and for a very short time.

They are used to identify proper operation of critical relay components. The relay remains in service and is capable of clearing faults during a monitoring test. The whole relay or some parts will, however be out of service during a self-checking test, thus creating temporary unavailability. Monitoring and self-checking have the ability to reduce the relay unavailability at relatively little cost and complexity. They may not, however be able to monitor or self-check every part of the relay at an affordable cost.

The degree to which relay failures can be detected by relay self-checking or monitoring is designated as the effectiveness index. Effectiveness will depend largely on how these facilities are designed and implemented and also on the number of components in the relaying system equipped with these facilities. In addition, there is also the possibility that the monitoring and self-checking circuits will fail. If these circuits fail, they are detected and repaired or replaced at the next routine test inspection. Consider that the time to failure of the monitoring and self-checking circuits are exponentially distributed and that the time between periodic inspections is T_C. Then, the average unavailability of device is Equations (1) and (2):

$$U_{SC}=\frac{1}{T_C}\int_0^{T_C}\left(1-\exp(-\lambda_{SC}t)\right)dt= =1-\frac{1}{\lambda_{SC}T_C}\left(1-\exp(-\lambda_{SC}T_C)\right) \quad (1)$$

$$U_{mn}=\frac{1}{T_C}\int_0^{T_C}(1-\exp(-\lambda_{mn}t))dt= =1-\frac{1}{\lambda_{mn}T_C}(1-\exp(-\lambda_{mn}T_C)) \quad (2)$$

where, U_{mn} and U_{sc} are the respective probabilities that the monitoring or self-checking circuits fail during the time interval T_c, and λ_{mn} and λ_{sc} are the failure rates of the monitoring and self-checking circuits, respectively [16].

C. General Reliability Model

A general five-state reliability model is shown in Figure 3, considering the two major protective relay failure modes, i.e., not responding when required and operating when not required. Relay spends a large portion of its life in an energized but quiescent state. In this state, the relay is in a healthy condition and it is monitoring an operating component within its protective domain. This state is designated as "Not Needed & Healthy" in the model shown in Figure 3. The term "healthy" refers to the case where the protection system is ready and capable of performing its intended function.

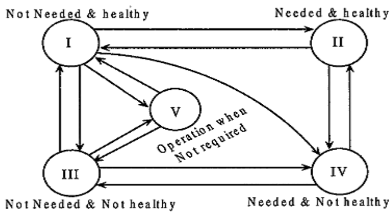

Figure 3. General reliability model of a protective relay [16]

In State II, designated as "Needed & Healthy," the relay operates successfully when called upon. In this state, the relay is in the healthy condition and responds to any abnormal condition associated with the component under protection. The probability associated with this state represents the degree of relay dependability. In State III, designated as "Not Needed & Not Healthy," the relay is neither required nor ready to operate. It is not required because no fault has occurred. It is not ready because the relay is either failed or under routine test or self-checking inspections.

It should be noted that during the routine test and self-checking, some parts or the whole relay will be out of service and the relay is not actually available even though it may not be failed. This state can also be referred to as the "protection unavailability" state. In State IV, designated as "Needed and Not Healthy", the relay does not perform its intended function. This is the case in which a fault occurs while the relay is unavailable. This state can also be referred to as the "abnormal unavailability" state.

In State V, "Operation When Not Required," the relay operates when it is not required. A high probability of being in this state represents low relay security. States III, IV, and V are considered the failed and undesirable states. The basic objective is to minimize the probabilities associated with these three states and maximize the availability of protection or the probabilities of being in States I and II. It should be noted that the probabilities associated with State II depend mainly on the fault rate and also the equipment restoration time once the faulty equipment is isolated.

This simplified model can be applied to many different relays. Each state consists of a number of states which are illustrated in the detailed reliability model. The state probabilities and the associated transition rates can be determined using the frequency balance approach [16] and the detailed reliability model developed in Section III-B.

D. Detailed Reliability Model of a Protection Component System

Figure 4 shows a reliability model of a protection component system where the component refers to a power system element, such as transmission line, transformer, generator, Busbar, etc. Each state is shown by a circle in which C and P represent the protected component and the protection system, respectively. The state number is shown in each circle. The relay spends most of its time in State I where the component is energized and the relay is ready to operate if it called upon.

In States II and IV, permanent and temporary faults occur, respectively, and faulted component is isolated by circuit breaker operation at States III and V. The model transfers from States III and V to State I, respectively, by repairing and reenergizing or by restoring the component. The relay is under self-checking and routine test inspections in States VI and VII, respectively, where it is removed from service. The relay is under repair in State X.

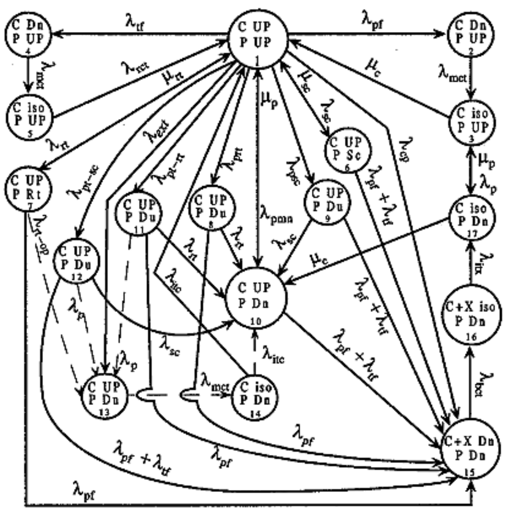

Figure. 4. Detailed reliability model of a protection component system [15]

The system transfers from State I to State X directly when a relay failure is detected by continuous monitoring. It enters State X through States VIII and IX when a relay failure is detected by routine test or self-checking, respectively. In this model, it is assumed that only a portion of the relay failure will be detected by the routine test inspection, which has not been detected by self-checking and monitoring facilities. The system enters State I from State X by repairing the failed relay.

Relay mal-trips are assumed to be either potential or instantaneous [15]. A potential mal-trip implies an unrevealed failure while an instantaneous mal-trip denotes a revealed failure. A revealed failure manifests itself immediately, whereas the potential mal-trip state of a relay needs appropriate input conditions to occur or additional relay failure to occur before an actual mal-trip can occur. In this model, it is assumed that the instantaneous mal-trip is caused by manual operating error. The system enters State X through States XI and XII when a relay potential mal-trip failure is detected by routine test or self-checking respectively.

The occurrence of an additional failure before detecting the potential mal-trip failures will transfer the model from States XI and XII to State XIII. The system enters State XIII from State VII due to instantaneous mal-trip caused by human error in the routine test inspection. In State XIII, the relay sends an operating signal to its associated breaker(s) and isolates the operating component inadvertently (State XIV). The isolated component is reenergized by switching action and the model transfers from State XIV to State X. In addition, the relay may operate incorrectly due to external faults. This has been represented by a direct transition from State I to State XIII.

In this case, once the component was isolated, it will be reenergized by switching action and the model transfers from State XIV to State I. In States VI to XII, the relay is either failed, under inspection, or in the repair process, and therefore is not available for trip if a fault occurs. The system enters State XV from States VI-XII under this situation. It can enter State XV directly from State I if a simultaneous failure of the relay and the component fault occurs. In this model, it is assumed that only permanent faults can occur while the relay is under routine test inspection (transition from State VII to State XV).

The system will enter State XVI by isolating the main component C and additional component X by the back-up relay operation assuming that back-up relay is fully reliable. If the relay fails while the component is isolated, the system will enter State XVII from State III. Reconnecting the isolated component X will transfer the system to State XVII from State XVI. The system will transfer from State XVII to States III or X, respectively, depending on the priority in repairing the relay or the component. Consider that SE and ME are the self-checking and monitoring effectiveness, respectively. Furthermore, assume that η percent of the relay failure rate are potential mal-trips as Equations (3) to (7):

$$\lambda_{psc} = (1-\eta)\lambda_p \times SE \tag{3}$$

$$\lambda_{pmn} = \lambda_p \times ME \tag{4}$$

$$\lambda_{prt} = (1-\eta)\lambda_p \times (1-SE-ME) \tag{5}$$

$$\lambda_{pt-sc} = \eta\lambda_p \times SE \tag{6}$$

$$\lambda_{pt-rt} = \eta\lambda_p \times (1-SE-ME) \tag{7}$$

where, $\lambda_{pt\text{-}sc}$ is portion of relay potential mal-trip failure rate detectable by self-checking, λ_{psc} is portion of relay failure rate detected by self-check, λ_{pmn} is portion of relay failure rate detected by monitoring, $\lambda_{pt\text{-}rt}$ portion of relay potential mal-trip failure rate detectable by routine test. λ_{sc}, λ_{rt} are self-checking and routine inspection rates, (reciprocal of the associated inspection interval), λ_p is relay failure and repair rates, respectively.

The probabilities associated with the different states can be calculated using Equation (8) where S is the stochastic transitional matrix and α is the vector of the state probabilities [17].

$$\alpha S = \alpha \tag{8}$$

Once the probabilities associated with the different states in the 17-state model are determined, the probability of each state in the five-state model of Figure 1 are calculated using the following classifications Equations (9) to (13):

$$P(I) = p_1 \tag{9}$$

$$P(II) = p_2 + p_3 + p_4 + p_5 \tag{10}$$

$$P(III) = p_6 + p_7 + p_8 + p_9 + p_{10} + p_{11} + p_{12} \tag{11}$$

$$P(IV) = p_{15} + p_{16} + p_{17} \tag{12}$$

$$P(V) = p_{13} + p_{14} \tag{13}$$

As noted earlier, the objective is to determine the optimum test intervals to maximize the protection availability (States I and II probabilities) and minimize the relay malfunctions (States III, IV, and V probabilities).

E. Case Study

Different case studies were conducted using the developed Markov models in order to examine the impact on relay reliability of implementing monitoring and self-checking facilities. The protected component in the detailed reliability model is assumed to be a transmission line. In the results presented in this paper, the following transition rates are used unless otherwise noted. In all the case studies, the probabilities associated with states in the five-state model are presented. It should be noted that the results presented are based on the given data and values for a specific protection system should be based on actual applicable data.

$\lambda_{pf} = 2$, $\lambda_{tf} = 15$ faullt/y , $\lambda_p = 0.01$ failure/y

$\lambda_{rct} = 10800$ operation/h (20cycles)

$\lambda_{mct} = 30857.14$ operation/h (7cycles)

$\lambda_{rt-op} = 0.001$ failure/routine.test.Interval

$\lambda_{cp} = 0.000001$ failure/h , $\mu_{sc} = 720$ test/h(5s/test)

$\lambda_{itc} = 0.5$ operation/h , $\lambda_{itx} = 0.5$ operation/h

$\mu_{rt} = 1$ test/h , $\eta = 0.1$ (10%)

Figure 5 shows results considering relay self-checking with different degrees of effectiveness from 0% to 99%. It should be noted that the results for the case of without self-checking are not exactly the same as those obtained with self-checking but with 0% effectiveness. The reason for this is that the relay is taken out of service in each self-checking interval for testing even though no failure is detected. Figure 5 shows that the optimum routine test interval increases by implementing relay self-testing.

Figure 6 shows the variation in the probability of the "Not Needed and Not Healthy" state or protection unavailability versus self-test interval. The relay self-test effectiveness is assumed to be 0, 20, 50, 80, 90, or 99%. Table I shows the optimum self-test interval for different relay self-test effectiveness (SE) and the associated probabilities of the "Not Needed and Not Healthy" state. Figure 7 shows the results considering continuous relay monitoring with different degrees of effectiveness (ME) of 0% - 99%.

V. ANALYSIS OF STUDIES IN OTHER PRESTIGIOUS COMPANIES TO DEVELOP OPTIMUM RELAY TEST INTERVAL

A. Test Methods Comparison between Companies in Other Countries

- Actual intervals of periodic tests in Sweden power company network: In the study of determining the optimal interval for periodic testing, Swedish power company expresses a formula for the relationship between periodic testing intervals of non-digital and digital relays (which are equipped with automated testing) as follows:

$$\Delta T_2 = \Delta T_1 / (1-\alpha) \tag{14}$$

In this Equation (14), ΔT_1 is periodic testing interval of non-digital relays, α is the percentage of automated tests covering of digital relays and ΔT_2 is periodic testing interval of digital relays. If the amount of α in digital relays is 50%, 80% and 90% and ΔT_1 is equal to 2 years, ΔT_2 will be 4, 10 and 20 years. It means if the relays are equipped with the automated test unit, the periodic testing interval will increase and maintenance and repair costs of relay will sharply decrease.

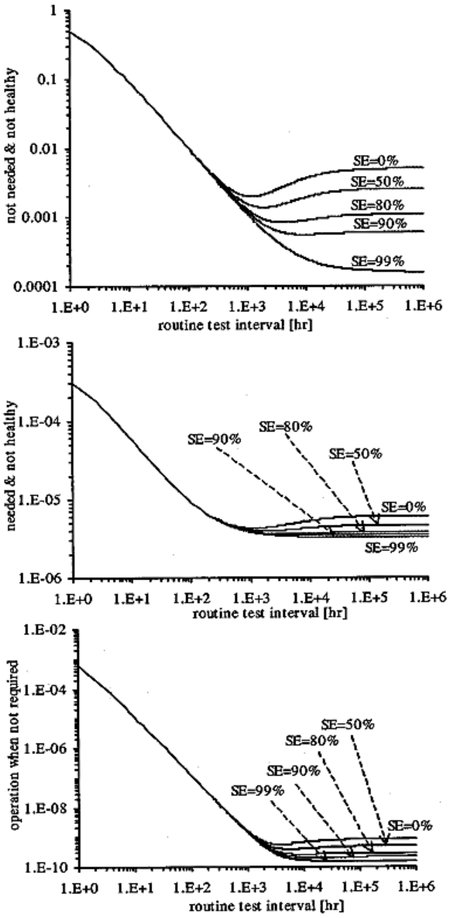

Figure 5. Optimum routine test interval with self-checking [18]

With the help of relay automatic testing capability, we discover the hidden errors in shorter intervals and start to resolve them as soon as possible. The larger the value of α is, more expensive relay will be, but instead the maintenance costs will greatly decrease. It should be noted that for the Equation (14) no theoretical or empirical reason is provided.

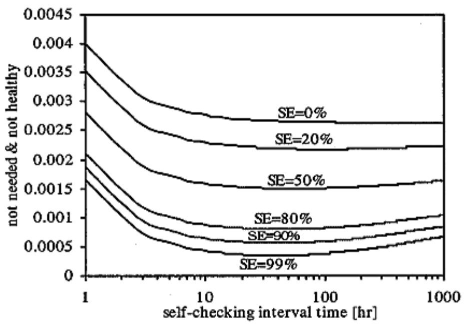

Figure 6. Optimum self-checking interval for different degrees of effectiveness [18]

- The actual intervals of periodic tests in power grid of Germany: Based on DIN VDE0105 resp. VDEW-AA standard, periodic tests of protection system equipment in power grid of Germany is carried out with an interval of 1 year for very old relays, 2 years for electromechanical and static relays and 4 to 6 years for digital relays [18].

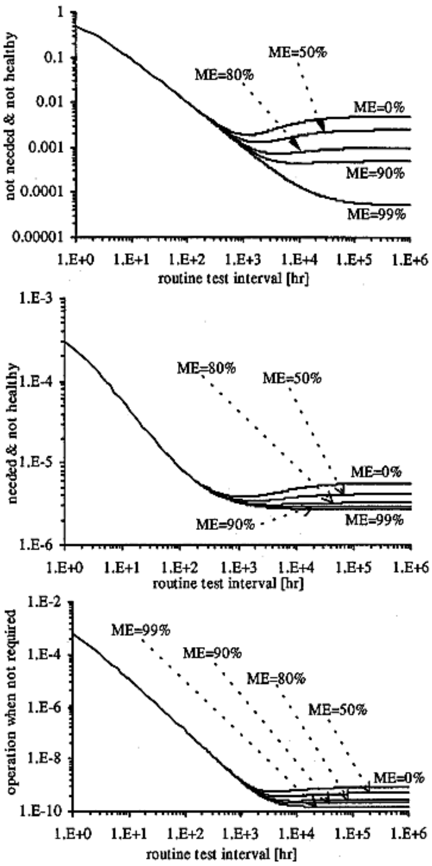

Figure 7. Optimum routine test interval with monitoring [18]

- The actual intervals of periodic tests of PJM Company: Table 4 indicates the actual minimum interval of relay testing and other equipment's by PJM Company [19]. The company is responsible for the repair and maintenance of protection equipment at American network upper than 230 kV.

- The actual interval of periodic tests of protection equipment in other countries in 2002: CIGRE Study Committee interviewed 14 Electrical Companies of nine countries including Australia (six companies), France, Germany, India, Japan, Norway, New Zealand, Korea and Spain (each one company) about the actual interval of periodic tests of protection equipment [20]. In this study, the minimum interval of periodic tests were 2 years for non-digital relays and the maximum interval of periodic tests were 12 years for digital relays.

Note 1- Since these devices are equipped with automated testing capabilities, periodic testing is not required. The analysis of events provided by these equipment's after the accident, indicates how they function. The accuracy of the measuring unit of analog signals and digital input/output (for relays) is approved by Function Test.

Note 2: Relays communication channels test is done with the same relays' testing interval.

Table 4. The interval of performed tests by PJM company [19]

Type of equipment		Periodic intervals (year)
Protection system of transmission substation	Electromechanical and static relays	4
	Digital relays	Note 1
Protection of power plant substation	Electromechanical and static relays	4
	Digital relays	Note 1
Frequency protection and load removing voltage relays	Electromechanical and static registers	4
	Digital relays	Note 1
Error reducing devices	Electromechanical and static registers	4
	Digital relays	Note 1
	Relay channels	Note 2
Communication channels	PLC	4
	Leased line	4
	Microwave	4
	Fiber optic	4

B. Determining the Optimal Time Interval Based on the Results of a Comprehensive Study of Iran's Power Grid

One of the goals of a comprehensive study of the Iran's power grid which is ongoing by Network Management Company is determining the parameters of network equipment reliability such as failure rate and the average time of fixing those [21]. We assume that:

1- The study includes the protection system of transmission lines and transformers.

2- Self-examining efficiency of non-digital and digital relays is considered to be 85%.

3- The average length of 400 kV lines is approximately 120 km and the average length of 230 kV lines is 70 km.

4- The time required for testing according to the information provided by the employer is three values of 2, 5 and 8 hours.

5- The time required to repair or replace the failed equipment is 12 hours.

By placing this information in a Markov model, the optimal interval between periodic tests is determined. The results are shown in Table 5 [22].

Table 5. The optimal time intervals between periodic tests (hour) based on the information of comprehensive research of Iran's electricity network [22]

Type of relay	The time required for the test (hours)	400 Kv transformer F = 0.6 f/yr, Rc = 28.8 hr	230 Kv transformer F = 0.3 f/yr, Rc = 97.9 hr	400 Kv line F = 2.66 f/yr, Rc = 9.7 hr	230 Kv line F = 3.47 f/yr, Rc = 6.2 hr
Non-digital	2	2787	2212	1408	1447
	5	12420	5758	2275	2437
	8	*	13680	2925	3240
Digital	2	*	*	3910	4472
	5	*	*	6729	8616
	8	*	*	9043	13100

In Table 5, the sign "*" indicates that the optimal interval between testing periods is very high and periodic and regular tests are not necessary. The reason is because many errors have occurred and relay has operated correctly under the actual conditions and there have been no problems. Therefore, continuous periodic tests will not be necessary.

C. Actual Interval of Periodic Tests for Protective Equipment in a Number of Electrical Companies in Iran

Based on "periodic tests of transmission substation protection and control equipment with No. 406-74" and "scheduling preventative maintenance and repair (NET)" provided by Tavanir Company, the exact time interval for periodic testing of protective equipment is not mentioned. By studying and analyzing the defined testing interval of protective relays in power companies of Isfahan, Khorasan, Tehran and Zanjan, it was found that the period for very old relays, electromechanical relays, static relays and digital relays is the same as once a year [23].

VI. THE PROPOSED OPTIMUM TIME INTERVAL FOR RELAYS TESTING IN THE POWER GRID

According to the research and analysis the events of the past 5 years, the installation of new generation of relays as well as parameters affecting the calculation of the periodic test interval, it's better to model the test intervals in accordance with actual conditions of transmission and distribution substations. The instructions provided on the circumstances have the following points which will be developed based on them:

- Possibility to go to substation for limited number of times
- Time of testing in accordance with the past practices
- Changes in network and development plans
- Comprehensive testing at certain intervals
- Considering sub-models for each part
- Considering a true function as a test
- Starting from the current situation with minimal changes

At the start of instruction's implementation, periodic testing of relays should be done once a year according to the constant procedure and no distinction should be considered between them. Over time, with the test results of two or three years ago and based on comprehensive data of influencing parameters on relay test interval of each equipment, the annual testing of next year can be changed.

For example, at the following year we can forget testing of some relays with acceptable test results in the past two years with no wrong operation which also have enough conditions for the test interval rise, or there is no need to fully perform some heavy tests such as voltage and current injection. Based on written instructions, tests that require no test equipment are reviewed every 6 months by relay expert group. At the beginning of the implementation of the instructions, the default period of all tests for all relays is one year. Then various parameters are considered one by one to increase or decrease this period.

Finally, the test interval is set on one, two or three years. It should be stated that the six-month review can be performed by substation operators or using DCS technology and prevent the cost of relay expert group's presence in substations and some further costs. In these guidelines the influential parameters in determining the optimal relays testing time will be considered. Due to the impact of a parameter in determining the test interval and the conditions associated with the parameter, a number is assigned to it.

This number is defined as the degree of impact and indicates the importance and role of that parameter. Thus, number 1 has the minimum and number 5 has the most influence. In a typical instruction, one can assume that if the mean value of the parameter impact is above three, increase in testing interval will be possible.

If during two periods (at the beginning of each period of a year), relay does not have a wrong function and instructions allow the rise of the test interval, the test interval will increase to two years and respectively. In the next two periods if relay properly removes all faults and doesn't have a wrong function and instructions allow the rise of the test interval, the test interval will increase to three and finally to four years. If an error occurs in the protected area and relay properly removes the fault, this fault is considered as a successful and real dynamic testing.

Nevertheless, if the relay can't remove the fault, some complete tests should be done on it in the shortest possible time and then relay test interval changes to one year. The above process is repeated. Obviously, this method is not very accurate, but given only four testing intervals of one year, two years, three years or four years and the fact that each period is kind of long time and in the entire process a high safety margin of accuracy is considered. The accuracy of this method has little impact on the selection of the desired interval.

As an example, in the past year the instruction in the ZREC for two substations with old generation relays and the new generation relays was collected along with the actual data of parameters affecting the testing interval of relays, in which relay testing was done once a year in the first substation and once in two years for the second one.

VII. CONCLUSIONS

This paper reviews existing methods and guidelines for optimal testing period of protective equipment and provides an optimal instruction for periodic testing time of mentioned equipment in Zanjan Regional Electricity Company. Considering 49.9 % use of the new generation relay and case study results in two substations with different structures in terms of relay technology and other conditions, as well as taking into account the actual conditions in the calculation of optimal interval of periodic tests in Zanjan Regional Electric Co., one can implement these instructions with high confidence.

Important consequences of implementing this instruction are reducing blackout caused by the testing of relays, the incorrect function of relays due to increase in the intervals, the economic costs that result from them and reduction in the costs of annual tests resulting from increases in relays testing intervals. Cost management in particular, is considerable and can be up to 50 percent in the first step and more than that in the next.

NOMENCLATURES

C_{up}: Protected component is energized and operable
CD_n: Component is faulted
Pup: Relay is operational
PD_n: Relay failed and has been detected (revealed failure)
PD_n: Relay failed but has not been detected (unrevealed failure)
Ci_{so}: Faulty component is isolated
PS_c: Relay is removed from service for self-checking
PR_t: Relay is removed from service for routine test inspection
X: Additional equipment connected to C which is isolated by back-up protection in the case of fault on C
$\lambda_{pt\text{-}sc}$: Portion of relay potential mal-trip failure rate detectable by self-checking
λ_{pf}: Component failure rate, permanent faults per year
λ_{tf}: Component failure rate, temporary faults per year
λ_{cp}: Common cause failure rate of C and P
λ_{ixt}: Manual switching rate to restore X
λ_{ext}: Mal-trip failure rate due to external faults
λ_{rct}: Reclosing switching rate
λ_{itc}: Manual switching rate to restore C
λ_{psc}: Portion of relay failure rate detected by self-check
λ_{pmn}: Portion of relay failure rate detected by monitor
λ_{prt}: Portion of relay failure rate not detected by self-checking and monitoring
$\lambda_{pt\text{-}rt}$: Portion of relay potential mal-trip failure rate detectable by routine test
λ_{sc}, λ_{rt}: Self-checking and routine inspection rates, (reciprocal of the associated inspection interval)
μ_{sc}, μ_{rt}: Number of relays tested by self-checking or inspected by routine test per time period
$\lambda_{rt\text{-}op}$: Relay instantaneous mal-trip failure rate
λ_p, μ_p: Relay failure and repair rates, respectively
λ_{mcb}, λ_{bct}: Main and back-up switching rates, respectively, (reciprocal of the associated fault clearing time)

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BIOGRAPHIES

Ahad Ebrahimi was born in Zanjan, 1976. He received the B.Sc. degree from Ardabil Branch, Islamic Azad University, Ardabil, Iran. Currently, he is M.Sc. degree's student in Science and Research Branch, Islamic Azad University, Zanjan, Iran. He is working at Zanjan Regional Electric Company, Zanjan, Iran since 2002.

Mansour Ojaghi was born in Zanjan, Iran. He received the B.Sc. degree in from Shahid Chamran University, Ahwaz, Iran, in 1989, and the M.Sc. degree from University of Tabriz, Iran in 1994, and the Ph.D. degree from University of Tehran, Iran in 2004 all in Electrical Power Engineering. He is currently an Assistant Professor with University of Zanjan, Zanjan, Iran.

Kazem Mazlumi was born in Tehran, Iran in 1976. He received the B.Sc. degree in Electrical Engineering from Amirkabir University of Technology, Tehran, Iran, in 2000, the M.Sc. degree from Sharif University of Technology, Tehran, Iran, in 2003, and the Ph.D. degree from Amirkabir University of Technology, Tehran, Iran in 2009. He is currently an Assistant Professor with University of Zanjan, Zanjan, Iran.