Effect of Monitoring and Self-checking Tests Effectiveness Index of Back-Up Protection System on the Optimum Routine and Self-checking Test Intervals of Protection System

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Abstract: In order to maximize the availability of protection system and minimize the risk of mal-operation, usually protective relay test carry out in power electrical industry. Determination of precise optimum routine test and self-checking intervals plays a vital role in decrease of maintenance and reparation cost of protective system. Self-checking and monitoring facilities increase the reliability and optimum routine test interval of a protection system. Modern digital relays are equipped by self-checking and monitoring tests in addition to routine test however, electromagnetic and static relays are just equipped by routine test. In the previous studies, the back-up protection system is assumed to be perfectly reliable for reliability analysis. This assumption is not correct in the operation because back-up relay has the same structure on the primary relay, so back-up relay can also has mal-trip when not required and may fail to trip when required which may cause power system blackout due to cascading failure. Therefore, In this paper, an extend Markov model is proposed for reliability analysis when back-up relay is not perfectly reliable considering self-checking and monitoring facilities in the protective system. Results show that, the optimum routine and self-checking tests interval of protection system increase significantly by increasing of monitoring and self-checking tests effectiveness of back-up protection system.

Keywords: back-up protection, monitoring, self-checking, optimum routine and self-checking tests interval

1 Introduction

Recently, competitive electric industry, power system expansion, and use of the lines in their stability boundaries have made reliability more important than the past in the power system design. Many factors can affect maintaining power system reliability. The operation of protection systems of power system is one of the effective factors in power system reliability, because protection systems with appropriate operation can prevent blackout in power system caused by fault occurrence, and consequently decrease possible damages caused by the blackout. To have an appropriate operation of protection systems, these systems should go under routine tests in specific periods. But this point should be noted that time interval of doing routine tests on protective systems should be determined optimally, because doing routine tests in the interval except optimum interval not only includes untimely costs but also prevents maximum optimum reliability.

Given the importance of determining optimum routine test interval of protection system, many researchers have discussed it up to now. In [1] optimum routine test interval of protection system is determined without considering the probability of failure in backup protection system, self-checking, and monitoring tests. Reference [2] has determined optimum routine test interval of protection system by supposing the probability of doing the self-checking test and considering the zero probability of failure for backup protection system. Reference [3] has considered the effect of redundancy of protection system on optimum routine test interval of transmission line protective system without considering the failure probability of backup protection system. In [4], the effect of maintenance frequency on repairs costs has been investigated. In this reference, the effect of primary and back-up protection systems has been considered. Reference [5] has determined the optimum routine test interval of pilot protection system without considering the failure probability of protection system and has assumed that only self-checking test is possible. In [6] and [7], optimum routine test interval of transmission line and transformator protection systems has been determined by considering different effectiveness indices for self-checking test and monitoring test, respec-In these references, back-up protection system has been assumed perfect reliable. The effect of effectiveness index primary protection system self-checking test on optimum self-checking test interval has also been analyzed. erence [8] has determined the optimum routine test in- of protection system by minimizing the average index of protection system annual economic loss without considering

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the failure probability for back-up protection system. In references [9] and [10] optimum routine test interval of transmission line protection system has been determined considering the failure probability for back-up protection system and possibility of self-checking test. In these references, it has been assumed that back-up protection system goes under routine test temporally after primary protection system or at the same time with primary protection system, respectively. Reference [11] has determined the optimum routine test interval and self-checking test by considering protection system hardware and software failures, accessories failure and human error. While, in theses references, remote back-up protection system has been assumed perfect reliable, failure probability has been considered for local back-up protection system.

In this paper, the manner of change in protection system optimum routine and self-checking tests interval and reliability indices has been examined with the change in effectiveness index of back-up protection system monitoring and self-checking tests. Markov modeling method is used for determining the optimum routine test interval. In the proposed Markov model, it is assumed that the primary and back-up protection systems go under routine test simultaneously. According to the results, it is seemed considering the effect of back-up protection system in determining the routine test interval seems necessary.

2 The proposed Markov model

Markov modeling method has been used for determining the protection system optimum routine test interval and self-checking test. In the proposed Markov model, failure probability has been considered for back-up protection system.

To form the proposed Markov model for the transmission line protection system considering back-up protection system, the proposed Markov model with five states (Figure 1) in reference [6] has been used for modeling the protection system. Proposed Markov model in Figure 2 is composed 21 states. The Markov model in Figure 2 has been suggested with these assumptions:

- There is possibility of monitoring and self-checking tests for protection systems.
- Both primary and back-up protection systems are taken out of service to be inspected.
- An inspection or fault must occur in order to detect a protection system failure.
- The time required to test a protection system is equal to the time required to repair or replace a failed protection system.
- Inspection of protection system always detects failures and does not cause failures.
- Second back-up protection system operates properly when primary and back-up protection systems have been failed.

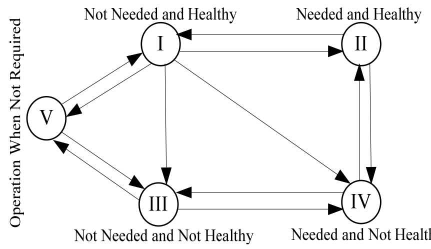

Figure 1 Reliability model of a protective system

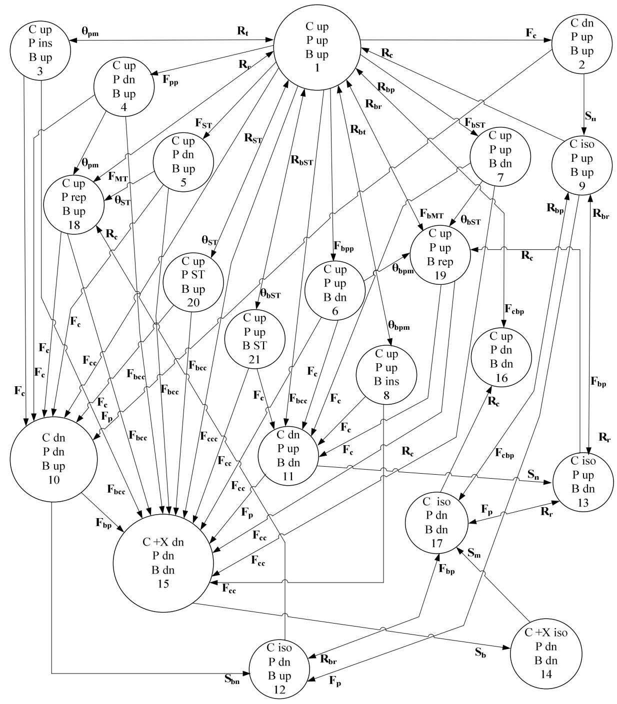

Figure 2 Proposed extended Markov model of protected component and protection systems

The states of the proposed Markov model are explained as follows:

In state (1), system is in the normal condition. In this state, energized protected element, primary, and back-up protection systems are under normal conditions. When an fault occurs on the line, the model transfers to state (2); and with the operation of primary protection system, the protected element is isolated and the model goes to state (9). In state (9), the defective line is repaired and becomes energized again, and the model returns to state (1). In state (3), primary protection system and in state (8) back-up protection system goes under routine test. Whenever protection system failure is specified by monitoring test, the model returns to state (18) for primary protection system, and returns to state (19) for the back-up protection system. Primary and back-up protection systems go under self-checking test in states (20) and (21), respectively. When primary protection system failure is determined by self-checking test, it leads to the replacement of model from state (1) to state (2). If also the back-up protection system failure is specified by the help of self-checking test, the model transmits from state (1) to state (7). By doing self-checking test, the model replaces from states (5) and (7) to states (18) and (19). If routine test results in specifying failures in back-up and primary protection systems, the model transmits from states (4) and (6) to states (18) and (19) for primary and back-up protection systems, respectively. The model returns from states (18) and (19) to state (1), by repairing primary and back-up protection systems, respectively. In state (10), primary protection system and protected element encounter failures, and the model transmits to state (12) by the operation of back-up protection system. In state (11), back-up protection system and protected element encounter failures, and the model returns to state (13) by the operation of the primary protection system. If back-up protection system in state (10), and primary protection system in state (11) encounter failures, the model transmits to state (15). The model in state (15) isolates from the network by the operation of backup protection system of layer 2, protected element, and the additional element connected to it, and the model transmits to state (14). By isolating the additional element, the model transmits from state (14) to state (17), and after repairing the protected element, the model transmits to state (16), and if primary and back-up protection systems are repaired in this state, the model returns to state (1).

The state abbreviation and transition rates are defined as follows:

C	Protected component;
P	Primary protection system;
B	Back-up protection system;
X	Additional component connected to C;
C_{up}	Protected component is energized;
C_{dn}	Protected component is destroyed;
P_{up} and B_{up}	Primary and back-up protection relays have appropriate operation, respectively;
P_{dn} and B_{dn}	Primary and back-up protection relays are failed, respectively;
F_p and F_{bp}	Primary and back-up protection relays failure rates respectively, (reciprocal of protection system Mean Time Between Failures (MTBF));
F_{MT} and F_{bMT}	Primary and back-up protection relays failure rates which are detected by monitoring test, respectively;
F_{ST} and F_{bST}	Primary and back-up protection relays failure rates which are detected by self-checking test, respectively;
F_{pp} and F_{bpp}	Primary and back-up protection system failure rates which are not detected by self-checking test, respectively;
F_c	Protected component failure rate;
F_{cc}	Common-causes failure rate of protected component and primary protection relay;
F_{cbp}	Common-causes failure rate of protected component and back-up protection relay;
F_{ccc}	Common-causes failure rate of protected component, primary and back-up protection relays;
MT_p and MT_b	Monitoring test effectiveness indices of primary and back-up protection relays, respectively;
ST_p and ST_b	Self-checking test effectiveness indices of primary and back-up protection relays, respectively;
R_c	Protected component repair rate;
R_t and R_{bt}	Primary and back-up relay inspection rates using routine test, respectively;
R_r and R_{br}	Primary and back-up protection relay repair rates, respectively;
R_t and R_{bt}	Primary and back-up relay inspection rates using self-checking test, respectively;
R_{bp}	Primary and back-up protection relay repair rate simultaneously;
S_n and S_{bn}	Normal tripping operations of primary and back-up protection systems, respectively,(reciprocal of fault clearing time of primary and back-up protection systems);
S_b	Normal tripping operations of second back-up protection system (reciprocal of fault clearing time of second back-up protection system);
S_m	Manual switching rate;
θ_{pm} and θ_{bpm}	Reciprocal of primary and back-up protection systems inspection interval, respectively.
θ_{pm} and θ_{bpm}	Reciprocal of primary and back-up protection systems self-checking interval, respectively.
iso	Item is isolated
ins	Item is being inspected
up	Item is in a good state
dn	Item is in a failed state

By considering failure probability for monitoring and self-checking tests circuit, failure probability of these circuits should be applied in transition rates which are related to these tests. Unavailability to these circuits is calculated by Equation 1. In Equation 1, T_c is the routine test interval, U_{ST} and U_{MT} are unavailability to self-checking and monitoring tests circuit, respectively; λ_{ST} and λ_{MT} are failure indices of the mentioned circuits [6].

$$
\begin{aligned}
U_{ST} &= 1-\frac{1}{\lambda_{ST}T_c}\left(1-\exp\left(-\lambda_{ST}T_c\right)\right) \\
U_{MT} &= 1-\frac{1}{\lambda_{MT}T_c}\left(1-\exp\left(-\lambda_{MT}T_c\right)\right)
\end{aligned}
\tag{1}
$$

F_{MT}, F_{bMT}, F_{ST}, F_{bST}, F_{pp} and F_{bpp} parameters in Figure 2. can be computed by Equation 2.

$$
\begin{aligned}
F_{ST} &= F_p \times ST_p \\
F_{MT} &= F_p \times MT_p \\
F_{pp} &= F_p \times (1 - ST_p - MT_p) \\
F_{bST} &= F_{bp} \times ST_b \\
F_{bMT} &= F_{bp} \times MT_b \\
F_{bpp} &= F_{bp} \times (1 - ST_b - MT_b)
\end{aligned} \tag{2}
$$

To calculate the reliability indices, the state probabilities in Markov model in Figure 2 should be calculated. State probabilities are calculated using Equation 3 where ***P*** is stochastic transitional matrix stochastic and ***p*** is the vector of the state probabilities [12].

$$pP = p \tag{3}$$

Equation system in (3) is linearly dependent; therefore, an additional equation is required to calculate the state probabilities. This equation is defined using (4). In Equation 4 p_i is state probabilities. This equation is obtained based on this fact that summation of state probabilities should be equal to one, i.e.:

$$\sum_{i=1}^{21} p_i = 1 \tag{4}$$

Equation 5 shows the manner of calculating the probability of protection system operational states [6] with regarding to the proposed Markov model for determining optimum routine and self-checking protection system test intervals. In this equation, *P(I)*, *P(II)*, *P(III)*, *P(IV)* and *P(V)* are availability, dependability, unavailability, abnormal unavailability and security of protection system. Optimum routine test time interval is determined based on maximization of desired indices (*P(I)* and *P(II)*), and also, minimization of undesired indices (*P(III)*, *P(IV)* and *P(V)*).

$$
\begin{aligned}
P(I) &= p_1 \\
P(II) &= p_2 + p_9 + p_{10} + p_{11} + p_{12} + p_{13} \\
P(III) &= p_3 + p_4 + p_5 + p_6 + p_7 + p_8 \\
&\quad + p_{16} + p_{18} + p_{19} + p_{20} + p_{21} \\
P(IV) &= p_{14} + p_{15} \\
P(V) &= p_{17}
\end{aligned} \tag{5}
$$

3 Simulation results

For determining protection system optimum routine test interval, transition indices shown in Table 1 have been used [2]. Transition index R_{ST} has been assumed 720 tests per hour [6]. In addition, transition rates related to back up protection system have been selected like primary protection system transition index.

Table 2 Case study data for reliability analysis

Item	Value
R_c	0.5(repairs per hour)
R_t	1(test per hour)
R_{bt}	1(test per hour)
R_r	0.5(repairs per hour)
R_{br}	0.5(repairs per hour)
R_{bp}	0.5(repairs per hour)
F_{cc}	10^{-6} (failures per hour)
F_{bcc}	10-6(failures per hour)
F_{bp}	10-6(failures per hour)
F_{ccc}	10-9(failures per hour)
S_n	43200(operation per hour)
S_{bn}	21600(operation per hour)
S_b	14400(operation per hour
S_m	0.5(operation per hour
$\lambda_{ST}=\lambda_{bST}$	0.002(failure/year)
$\lambda_{MT}=\lambda_{bMT}$	0.0005(failure/year)

3-1 Optimum routine test interval of protection system

In this part, the manner of changes in optimum routine test interval by changing effectiveness indices of back-up protection system self-checking and monitoring tests have been investigated. Results of Figures 3 to 5 show the manner of changes in reliability indices based on protection system routine test interval in MT_b=0 and ST_b =0.9. Also, it is assumed that MT_p= ST_p = 0.45 and F_c=3 (failures/year). Self-checking test interval for protection system has been considered 25 hours. Table 2 shows more comprehensive information about different states.

According to Figures 3 to 5 and Table 2, optimum routine test interval of protection system in MT_b=0 and ST_b= 0.90 can be obtained which is equal to 15505 hours. In this optimum interval, desirable reliability indices are in their maximum, and undesirable reliability indices are in their minimum. Results of Table 2. show that protection system optimum routine test interval and reliability increases, by increasing monitoring test effectiveness in comparison with self-checking test effectiveness index of back-up protection system.

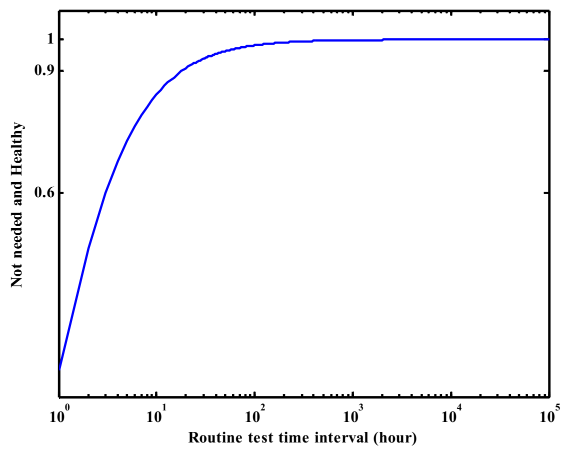

Figure 3 System availability with respect to routine test interval

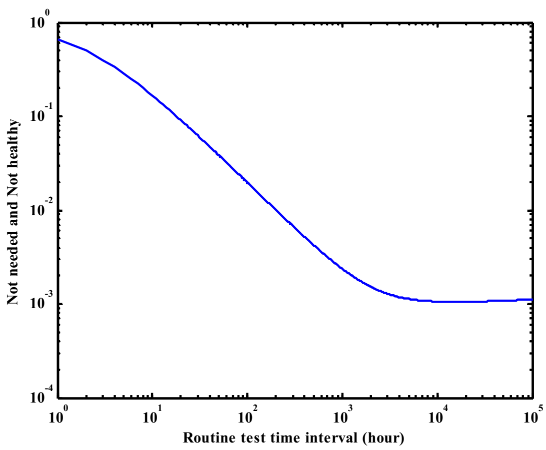

Figure 4 System unavailability with respect to routine test interval

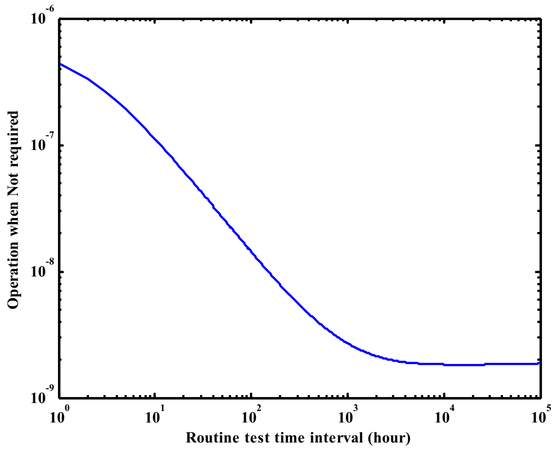

Figure 5 System security with respect to routine test interval

Table 1 Effect of monitoring and self-checking test for back-up protection system on reliability indices and optimum routine test time interval

STb (%)	MTb (%)	P(I)	P(III)	P(V)×10^{-9}	T_c (hour)
90	0	0.998256	0.001056	1.828348	15505
70	20	0.998264	0.001048	1.822682	15811
20	70	0.998286	0.0010026	1.808445	16724
0	90	0.998294	0.001018	1.802717	17170

3-2 Optimum self-checking test interval of protection system

In this part, optimum self-checking test interval of protection system has been determined. For doing simulation, routine test interval is assumed to be 16000 hours and of monitoring test effectiveness index for protection system has been considered equal to zero. Changes of reliability indices based on self-checking test interval have been shown in Figures 6 to 8 with changes of back-up protection system self-checking test effectiveness index. Also, self-checking test effectiveness index for primary protection system is equal to zero. A more comprehensive analysis has been presented in Table 3.

Results of Figures 6 to 8, and Table 3 show that self-checking test interval in zero effectiveness index for back-up and primary protection systems self-checking test interval will be equal to infinite. This means that there is no need for self-checking test. Also, by increasing effectiveness index of back-up protection system self-checking test in the specific effectiveness index for self-checking test for primary protection system, optimum self-checking test interval decreases. The reason is that for determining a more number of protection system failures by self-checking test, failure probability in self-checking test circuit increases. Therefore, it is necessary that self-checking test is done in a shorter time interval. For example, if effectiveness index of primary protection system self-checking test is 90%, optimum self-checking test interval decreases from 46 hours to 41 hours by increasing the effectiveness index of back-up protection system self-checking test from 0% to 100%.

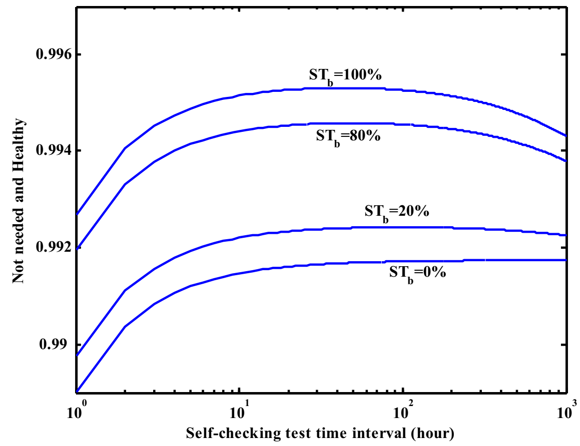

Figure 6 System availability with respect to self-checking test interval

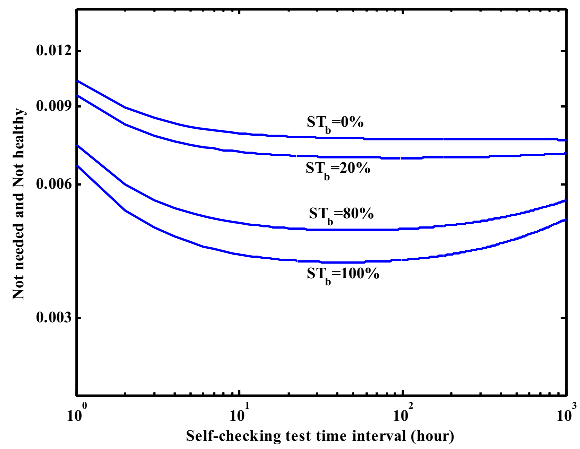

Figure 7 System unavailability with respect to self-checking test interval

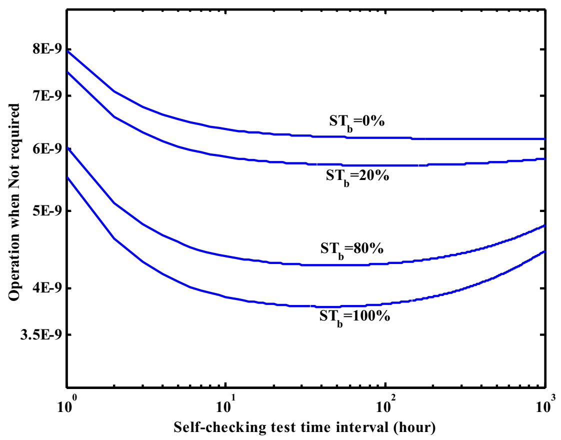

Figure 8 System security with respect to self-checking test interval

Table 3 Effect of self-checking effectiveness for back-up protection system on reliability indices and optimum self-checking test time interval

STp (%)	STb (%)	P(I)	P(III)	P(V)×10^{-9}	T_c (hour)
0	0	-	-	-	>1000
	20	0.992422	0.006890	5.714673	99
	80	0.994582	0.004730	4.276043	49
	100	0.995309	0.004002	3.791375	43
90	0	0.994946	0.004365	4.032782	46
	20	0.995675	0.003637	3.547290	41
	80	0.997874	0.001438	2.082619	33
	100	0.998610	0.000701	1.592061	31

4 Conclusion

In this paper, effectiveness index of back-up protection system monitoring and self-checking tests on protection system optimum routine test interval and self-checking test has been analyzed. For doing the analysis, a Markov model has been proposed by considering failure probability for back-up protection system. According to the results of this study, optimum routine test interval of protection system increases by increasing effectiveness index of monitoring and self-checking tests. Also, optimum self-checking interval decreases by increasing effectiveness index of back-up protection system self-checking test. Therefore, more accurate results in determining protection system optimum routine test interval and self-checking test can be specified by considering the effect of back-up protection system.

1 Anderson P M, Agarwal S K. An improved model for protective system reliability. IEEE Trans. on Rel,1992, 41(3), 422-426

2 Kumm J J, Weber M S, Hou D, Schweitzer E O. Predicting the optimum routine test interval for protection relays. IEEE Trans. on Power Del, 1995, 10(2), 659-665

3 Anderson P M, Chintaluri G M, Magbuhat S M, Ghajar R F. An improved reliability model for redundant protective systems Markov models. IEEE Trans. on Power Sys, 1997, 12(2), 573-578

4 Vermeulen S T J A, Rijanto H, Schouten F A D. Modeling the influence of preventive maintenance on protection system reliability performance. IEEE Trans. on Power Del, 1998, 13(4), 1027-1032

5 Kangvansaichol K, Pittayapat P, Eua-Arporn B. Optimal routine test intervals for pilot protection schemes using probabilistic methods. IEEE Power System Protection Conference, 2001, 254-257

6 Billinton R, Fotuhi-Firuzabad M, Sidhu T S, Determination of the optimum routine test and self-checking intervals in protective relaying using a reliability model. IEEE Trans. on Power Sys, 2002, 17(3), 663-669

7 Seyedi H, Fotuhi-Firuzabad M, Sanaye-Pasand M. An extended markov model to determine the reliability of protective system. IEEE Power India Conference, 2006

8 Wang L, Wang G, Sun Z. Determination of the optimum routine maintenance intervals for protective systems. IEEE Power Engineering Society General Meeting, 2009

9 Damchi Y, Sadeh J. Considering failure probability for back-up relay in determination of the optimum rutine test interval in protective system using Markov model. IEEE Power Engineering Society General Meeting, 2009

10 Damchi Y, Sadeh J. Considering the effect of back-up protection system on the optimum routine test intervals of protection system, ICEE 2010

11 Etemadi A H, Fotuhi-Firuzabad M. New considerations in modern protection systemquantitative reliability assessment. IEEE Trans. on Power Del, 2010 25(4), 2213-2222

12 Billinton R, Allan R N. Reliability Evaluation of Engineering Systems. New-York: Plenum, 1994