Effect of Remote Back-Up Protection System Failure on the Optimum Routine Test Time Interval of Power System Protection

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Abstract--Appropriate operation of protection system is one of the effective factors to have a desirable reliability in power systems, which vitally needs routine test of protection system. Precise determination of optimum routine test time interval (ORTTI) plays a vital role in predicting the maintenance costs of protection system. In the most previous studies, ORTTI has been determined while remote back-up protection system was considered fully reliable. This assumption is not exactly correct since remote back-up protection system may operate incorrectly or fail to operate, the same as the primary protection system. Therefore, in order to determine the ORTTI, an extended Markov model is proposed in this paper considering failure probability for remote back-up protection system. In the proposed Markov model of the protection systems, monitoring facility is taken into account. Moreover, it is assumed that the primary and back-up protection systems are maintained simultaneously. Results show that the effect of remote back-up protection system failures on the reliability indices and optimum routine test intervals of protection system is considerable.

Keywords: Markov model; Monitoring; Primary and remote back-up protection systems; Reliability; Routine test time interval

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1. Introduction

Nowadays, with the power systems expansion and the growing demand for electrical energy, power system protection has vital role in maintaining high degree service reliability to consumers, since power system failures have undesirable effects on social welfare and the economy of each country [1]. One of the main causes of cascading outages in power system is protection system failure [2], [3]. In a study performed by North American Electrical Reliability Council (NERC), it has been shown that protection systems are involved in about 75% of major disturbances. The New York City blackout on July 1977 and Southern Idaho system instability on December 1995 are examples for this claim in which the main was the inappropriate operation of protection systems [4]. Appropriate operation of protection system can be effective in decreasing such events. Therefore, performing the routine test is necessary to maximize the availability and minimize the risk of mal-operation of protection system [5]. Modern digital protection systems are usually equipped with self-checking and monitoring facilities to detect protection system failures; while in electromagnetic and static protection systems, routine test is the only way to detect such failures. Self-checking and monitoring facilities can considerably improve the reliability of protection systems and hence, the routine test time interval can be increased [6], [7].

Different papers have focused on determining the ORTTI of protection system. In [8], ORTTI of protection system has been determined without considering self-checking and monitoring facilities, when back-up protection system was considered perfectly reliable. As an improvement in [5], the self-checking facility has been considered to determine the optimum routine test interval considering perfect operation for back-up protection system. Furthermore, the effect of digital and old protection systems on ORTTI has been analyzed. Reliability analysis of transmission line protection system and determination of ORTTI have been done in [9], considering redundancy in protection system while failure probability for back-up protection system was not considered. Variations of maintenance cost in respect to maintenance frequency have been analyzed in [10] considering the effect of primary and back-up protection systems. In [11], ORTTI has been determined for several configurations of over-current relays, while just self-checking facility was taken into account in protection system. It is assumed that back-up protection has perfect operation. Estimation of the ORTTI and comparing abnormal unavailability index for several pilot protection configurations have been performed in [12] using Markov model and event tree methods. It was supposed that there is no failure probability for back-up protection, and protection systems are only equipped with self-checking facility. Markov model has been proposed by [6] for reliability analysis of the protection system of transmission line considering self-checking and monitoring facilities while the back-up protection was assumed to be perfectly reliable. The optimum self-checking test time interval has been determined at specific routine test time interval for different self-checking effectiveness. In [7], the ORTTI and optimum self-checking interval has been estimated using Markov model for protection system of a power transformer. In this paper, protection systems are equipped with both self-checking and monitoring facilities, while back-up protection has been assumed to have appropriate operation to isolate the component from the faulted area when primary protection is failed. An index has been defined in [1], namely the annual average economic losses, to determine the ORTTI in protection system using semi-Markov process. Reliability analysis is also performed without considering failure probability for back-up protection system and it is assumed that there is only self-checking facility in protection system. In [13], a Markov model has been proposed to estimate ORTTI considering monitoring facility and failure probability for back-up protection system. It is supposed that routine test for primary and back-up protection systems has been performed sequential. In [14], ORTTI for protective relay have been determined by considering the cost of routine test, losses due to incorrect operation and mal-operation of protective relay.

Precise determination of routine test time interval has a significant role on predicting maintenance cost of protection system and decreasing of the damages which can be caused by protection system failure. Therefore, in this paper an extended Markov model is proposed to determine ORTTI of protection system. In the proposed method, monitoring facility for primary and remote back-up protection systems is taken into account. Failure probability for remote back-up protection system is also considered when the Markov model is being constructed. Furthermore, it is assumed that routine test for both primary and remote back-up protection systems can be performed simultaneously. In this study, the effect of monitoring test effectiveness and failure rate of remote back-up protection system on the reliability indices and ORTTI are investigated. The presented results show that the effect of remote back-up protection system failures on the reliability indices and ORTTI is significant.

2. Proposed method

Several methods have been developed for reliability analysis such as event tree, fault tree and Markov model. In this paper, Markov model is used to perform reliability analysis. Therefore, a Markov model for transmission line protection system is proposed to determine the ORTTI considering failure probability for remote back-up protection system. The proposed Markov model consists of 17 states which, is shown in Fig. 1. The following assumptions are taken into account in the proposed Markov model

- Both primary and remote 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.

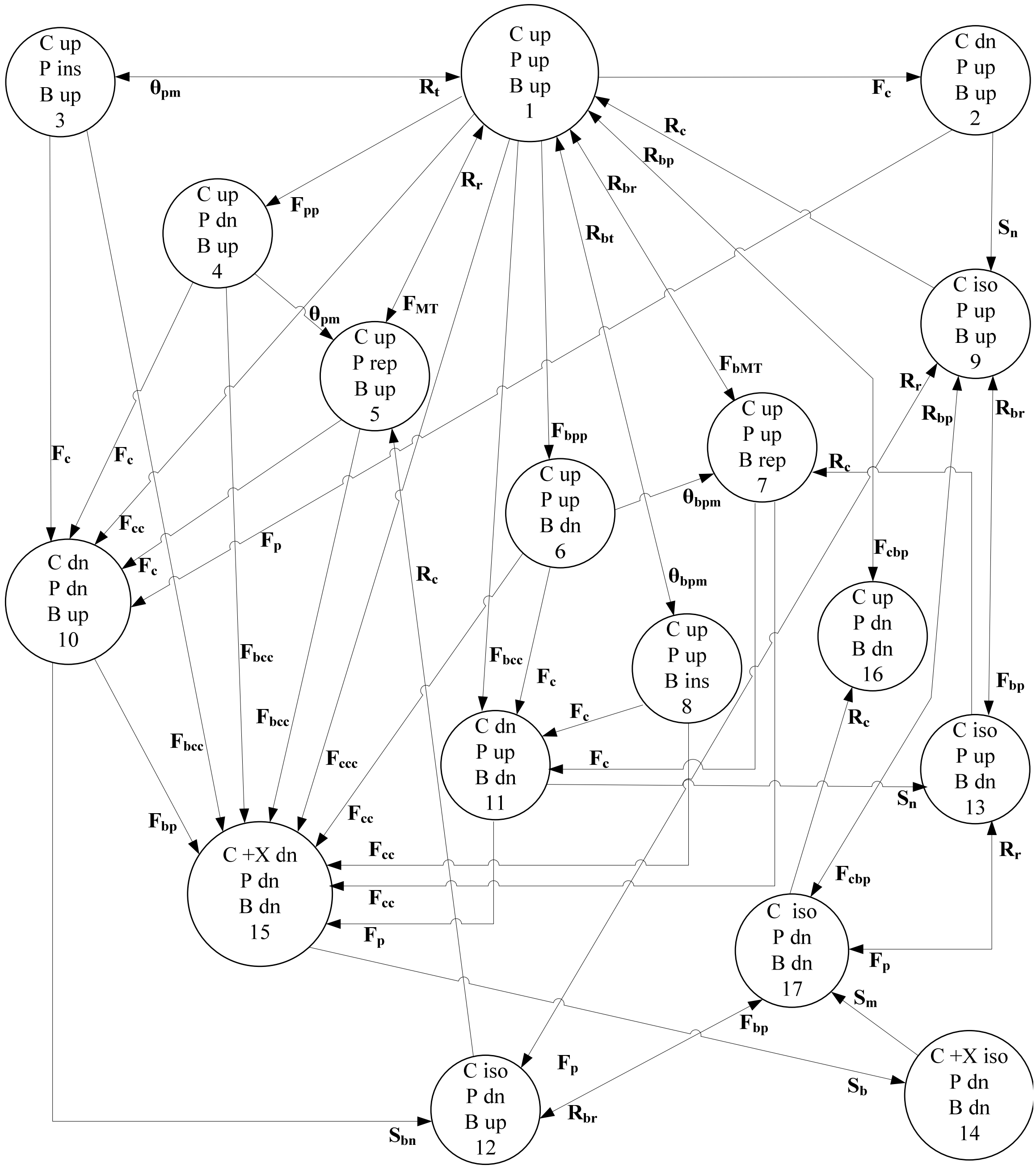

Fig. 1. Proposed extended Markov model of protected component and protection systems

In Fig. 1, C, X, P and B are protected component, additional component connected to C, primary protection system and remote back-up protection system, respectively. Furthermore, in this figure, up, dn, iso, ins and rep are energized component, failed component, isolated component, component under inspection and component under repair, respectively.

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

In state 1, protected component and protection systems are in normal condition. This means that protected component is energized and protection systems operate appropriately if they are called upon. When, a fault occurs on the line, the model transfers from state 1 to state 2. In this state, protected component is isolated by the operation of the primary protection system and the model transfers from state 2 to state 9. In state 9, faulted line is repaired and reenergized, and then model comes back to state 1. Primary and remote back-up protection systems are under routine test in states 3 and 8, respectively. The model goes from state 1 to state 5 when primary protection system failure is detected by monitoring test. If remote back-up protection system failure is detected by monitoring test, the model goes from state 1 to state 7. When, protection system failures are not detected by monitoring test, the model transfers from state 1 to states 4 and 6 for primary and remote back-up protection systems, respectively. If a simultaneous failure occurs for the primary protection system and protected component, the system enters to state 10 directly from state 1. State 10 transfers to state 12 by proper operation of remote back-up protection system. The model goes to state 13 by the appropriate operation of primary protection system through state 11 on conditions that remote back-up protection system and protected component are failed. If remote back-up protection system in state 10 and primary protection system in state 11 are failed, the model transfers to state 15. The proposed model moves into state 15 through state 1 if the protected component and the primary and remote back-up protection system failures occur simultaneously. In state 15, protected and additional components are isolated by second backup protection system and model enters state 14. Then the model transfers to state 17 by manual isolation of additional component. The model moves into state 16 from state 17 when protected component is repaired. Then by repairing primary and remote back-up protection systems, the model comes back to state 1.

The most parameters which are used in the proposed Markov model in Fig. 1 are defined in "Nomenclature" part of the paper. However, F_{MT}, F_{bMT}, F_{pp} and F_{bpp} are related to the defined parameters as follows:

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

In this study, in order to perform the reliability analysis and to determine ORTTI, a five-state reliability model is considered for protection system that is shown in Fig. 2 [6].

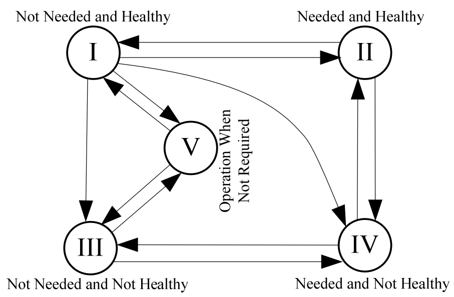

Fig. 2. Reliability model for protection systems [6].

The states shown in Fig. 2 are explained as follows:

- State I: Protection systems are ready and no fault is occurred. Probability of this state is defined as availability of protection system.
- State II: Fault is occurred and protection systems operate successfully to clear it. Probability of this state is demonstrated as dependability of protection system.

- State III: No fault is occurred but protection systems are not ready to operate. Probability of this state is illustrated as unavailability of protection system.
- State IV: Protection systems are not ready to operate while fault is occurred. Probability of this state is defined as abnormal unavailability of protection system.
- State V: Protection systems operate when not required. High probability of this state shows that protection system has low security.

ORTTI is determined based on maximizing each of desirable reliability indices (availability and dependability indices) and also minimizing each of undesirable reliability indices (unavailability, abnormal unavailability and operation when not required indices) are minimum.

To calculate the reliability indices, the state probabilities in Markov model in Fig. 1 should be calculated. State probabilities (p_i) are calculated using (3) where ***S*** is transitional matrix that is defined by (2) and p is the vector of the state probabilities [15]. In (2), a_{ij} is transition rate from state i to state j. Equation (2) shows that the summation of the elements in each row of the transitional matrix must be equal to one

$$S = \begin{cases} S_{ij} = a_{ij} & j \neq i \\ S_{ii} = 1 - \sum_{j, j \neq i} a_{ij} & \end{cases} \tag{2}$$

$$pS = p$$
$$p = [p_1, p_2, p_3, \ldots\ldots\ldots, p_{15}, p_{16}, p_{17}] \tag{3}$$

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

$$\sum_{i=1}^{17} p_i = 1 \tag{4}$$

According to Markov model shown in Fig. 1, the previous defined reliability indices are calculated using (5):

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

As mentioned above, ORTTI is occurred at the point in which each of the desirable reliability indices (*P(I)* and *P(II)*) are maximized or each of undesirable reliability indices (*P(III)*, *P(IV)* and *P(V)*) are minimized. In the proposed method, at first, desirable and undesirable reliability indices are calculated using (5) as a function of RTTI based on the proposed Markov model. Then, the enumeration method [16] is used to find ORTTI. In this method, reliability indices are calculated for the intervals of ΔRTTI, which is an arbitrary numbers (in this paper ΔRTTI has been considered 1(hour)) and then the maximum of desirable reliability indices values or the minimum of undesirable reliability indices is chosen as ORTTI.

3. Simulation results

In order to analyze the reliability of component/protection systems and determining the ORTTI, various cases are considered and these studies are performed using proposed extended Markov model in the previous section. Most of transition rates which are used in the simulations are taken from [5]. These data can be found in Appendix. It is worth noting that some required transition rates are not found in [5], so we select these transition rates as arbitrary respect to transition rate values in [5]. These transition rates are R_{bp}, F_{bcc}, F_{bp}, F_{ccc} and S_b.

3.1. Basic Situation

In this study, one case is defined as basic situation for comparing the influence of remote back-up protection system on ORTTI and reliability indices. In this situation, it is assumed that there is no monitoring facility in primary and remote back-up protection systems. Moreover, MTBF for primary and remote back-up protection systems are assumed to be 50 (years) and the number of faults on the protected component has been considered to be equal 2 (faults per year). Simulation results are shown in Fig. 3.

Regarding to Fig. 3, it can be seen that the ORTTI in protection system is equal to 780 hours where availability and dependability indices are in their maximum values that are equal to0.9939739 and 4.6040423×10^{-4}, respectively. Furthermore, the unavailability, abnormal unavailability and operation when not required probability indices are in their minimum values in ORTTI (780 hours) that are equal to 0.0055657, 1.3115819×10-8 and 4.6829101×10-9, respectively. This figure shows that in long routine test time interval, availability and dependability indices are greater than their values in short routine test time interval while unavailability, abnormal unavailability and operation when not required probability indices are less than their values in short routine test time interval. The reason for these results is that protection system is out of service more frequently when routine test time interval is short.

3.2. Effect of considering monitoring facility for remote back-up protection system on the ORTTI

To investigate the effect of remote back-up protection system monitoring facility effectiveness on the ORTTI, the protection system reliability indices are determined for different values of monitoring test effectiveness and other parameters are assumed to be similar to the basic situation ones. In this investigation, values 0, 90%, 95% and 100% are assumed for primary protection system monitoring test effectiveness while remote back-up protection system monitoring test effectiveness changes from 0 to 100% for each primary protection system monitoring test effectiveness. Results of simulations are shown in Fig. 4 and Table 1.

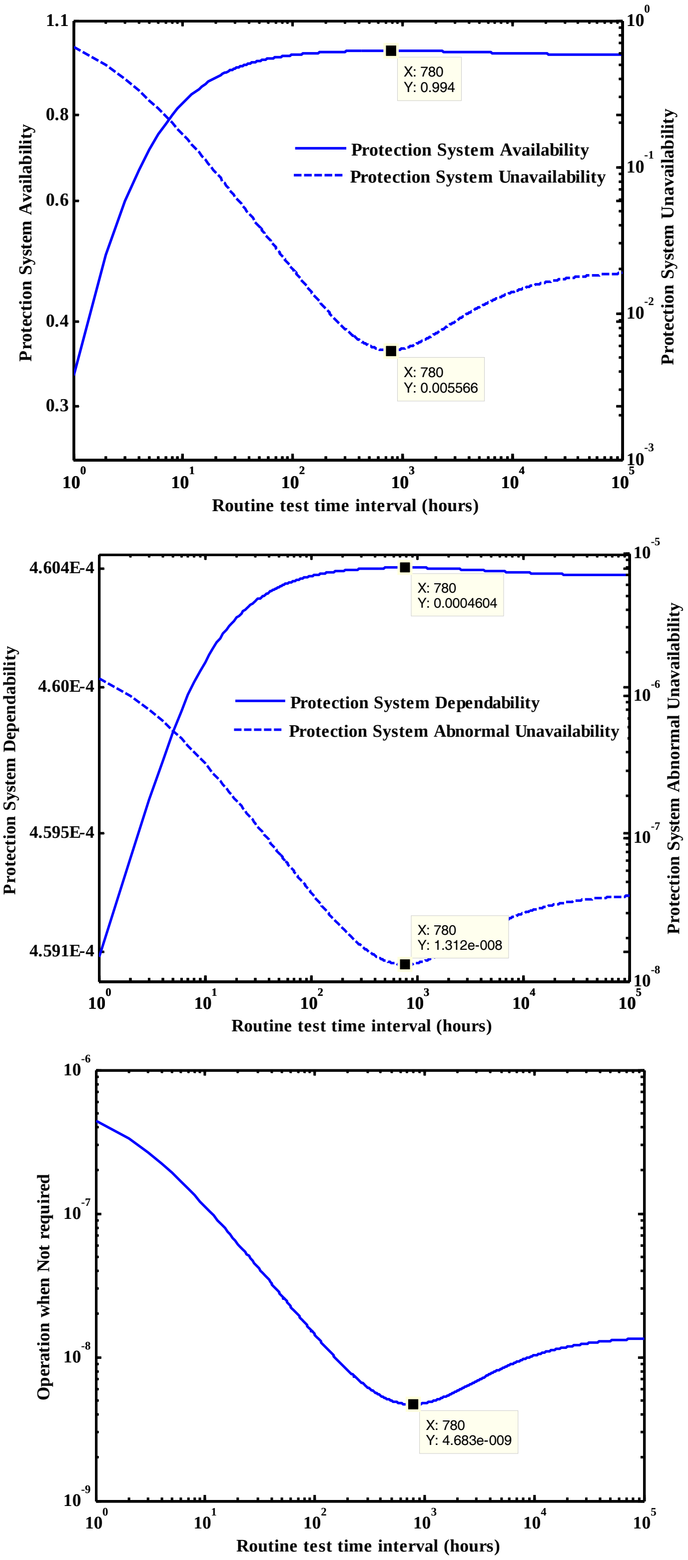

Fig. 3. Protection/component system reliability indices for basic situation

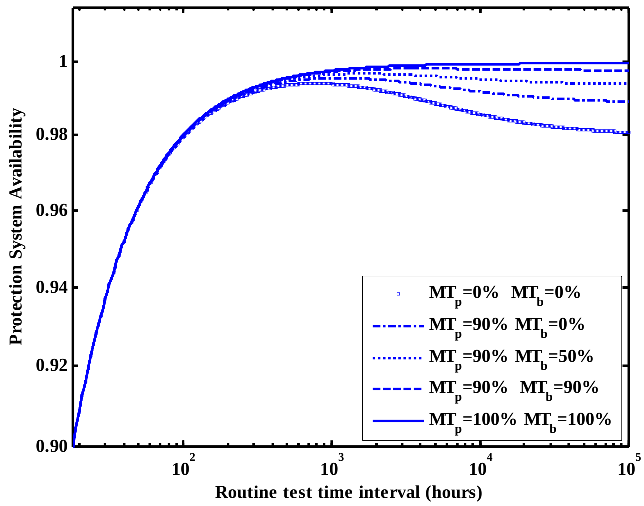

Fig. 4. Protection system availability with respect RTTI for different values of monitoring test effectiveness

Table 1. Effect of MT_p and MT_b on reliability indices and ORTTI

MT_p (%)	MT_b (%)	P(I)	P(II) $\times 10^{-4}$	P(III)	P(IV) $\times 10^{-9}$	P(V) $\times 10^{-9}$	ORTTI (hours)
90	0	0.9955201	4.6040732	0.0040195	10.002640	3.6525134	1122
	50	0.9966833	4.6040965	0.0028563	7.7021545	2.8775249	1672
	90	0.9980757	4.6041224	0.0014639	4.9201558	1.9499280	4025
	95	0.9983309	4.6041294	0.0012087	4.4101900	1.7798980	5421
	100	0.9986338	4.6041355	0.0009058	3.8049546	1.5781111	9213
95	0	0.9956223	4.6040752	0.0039173	9.8221813	3.5843981	1156
	50	0.9968234	4.6040994	0.0027161	7.4222108	2.7841540	1776
	90	0.9983310	4.6041294	0.0012086	4.4100643	1.7798024	5421
	95	0.9986339	4.6041355	0.0009058	3.8048005	1.5779938	9215
	100	0.9990289	4.6041433	0.0005107	3.0154808	1.3148285	104330
100	0	0.9957270	4.6041532	0.0038126	9.6129922	3.5146255	1192
	50	0.9969701	4.6041023	0.0025695	7.1291382	2.6864031	1901
	90	0.9986340	4.6041355	0.0009056	3.8046468	1.5778767	9231
	95	0.9990290	4.6041433	0.0005105	3.0152632	1.3146627	104330
	100	-	-	-	-	-	>1000000

Based on the presented results in Fig. 4 and Table I, it can be concluded that ORTTI of protection system and desirable reliability indices are increased by increasing remote back-up protection system monitoring test effectiveness in a certain value of primary protection system monitoring test effectiveness. Furthermore, undesirable reliability indices are decreased in this condition. For example, if monitoring test effectiveness index of primary protection system is assumed to be 90%, increasing of remote back-up protection system monitoring test effectiveness from 0% to 100%, leads to an increase in the ORTTI from 1122 (hours) to 9213 (hours), i.e. 8.21 times. Furthermore, unavailability, abnormal unavailability and operation when not required probability indices decrease to 77.47%, 61.96% and 56.79%, respectively. Availability and dependability indices will also increase but this increase is not significant in comparison with the decrease of undesirable reliability indices.

Moreover, according to the presented results in Table 1, the increase of the ORTTI and the improvement of the reliability indices while remote back-up protection system monitoring test effectiveness varies from 0 to 100% are greater when the primary protection system monitoring test effectiveness is higher. For example, ORTTI increases 1.35 times if monitoring test effectiveness of primary protection system is considered to be equal 90% and monitoring test effectiveness of remote back-up protection system is increased from 90% to 95%. Another case is when monitoring test effectiveness of primary protection system is assumed to be 95% and monitoring test effectiveness of remote back-up protection system is varied from 90% to 95%, ORTTI is 1.7 times of the previous case.

Furthermore, if monitoring test effectiveness of primary and remote back-up protection systems is equal to 100%, ORTTI will be equal to infinite. This means that protection systems do not require routine test because all of protection system failures is detected by monitoring test.

3.3. Effect of remote back-up protection system failure rate on the ORTTI

To analyze the effect of remote back-up protection failure rate on the ORTTI, reliability analysis has been performed considering different MTBF values for remote back-up protection system. In this analysis, monitoring test effectiveness of primary and remote back-up protection system is assumed to be 90% and other parameters are similar to the basic situation ones.

Primary protection system MTBF is also considered to be equal 25, 50, and 75 and 100 years and for each one, remote back-up protection system MTBF increase from 25 years to 100 years with step of 25 years. The obtained results are presented in Table 2. Results in Fig. 5 illustrate variations of reliability indices with respect to routine test time interval and MTBF of 50 (years) for primary protection system and by changing MTBF of remote back-up protection.

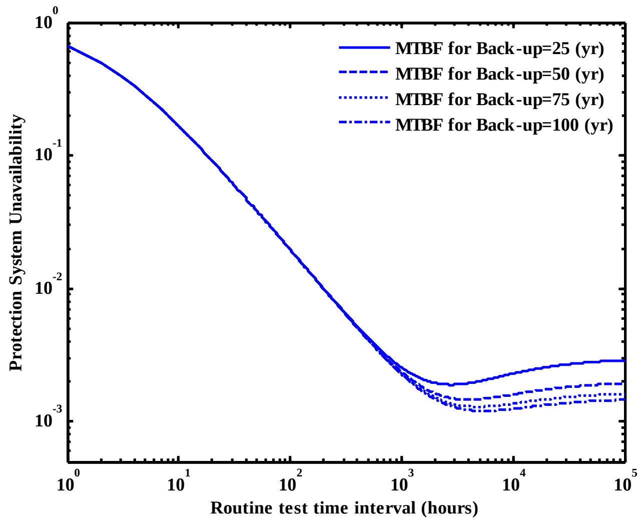

Fig. 5. Protection system unavailability with respect to RTTI for different values of $MTBF_b$

Table 2. Effect of $MTBF_p$ and $MTBF_b$ on reliability indices and ORTTI

$MTBF_p$ (yr)	$MTBF_b$ (yr)	P(I)	P(II) $\times 10^{-4}$	P(III)	P(IV) $\times 10^{-9}$	P(V) $\times 10^{-9}$	ORTTI (hours)
25	25	0.9972782	4.6041084	0.0022614	6.5135408	2.4870184	2240
	50	0.9976432	4.6041157	0.0018964	5.7843308	2.2399240	2810
	75	0.9977780	4.6041183	0.0017616	5.5149498	2.1487738	3102
	100	0.9978485	4.6041197	0.0016910	5.3739782	2.1010995	3280
50	25	0.9976432	4.6041157	0.0018963	5.7841496	2.2415689	2810
	50	0.9980757	4.6041224	0.0014639	4.9201558	1.9499280	4025
	75	0.9982432	4.6041276	0.0012964	4.5855009	1.8371631	4835
	100	0.9983332	4.6041294	0.0012064	4.4056412	1.7766008	5421
75	25	0.9977781	4.6041183	0.0017615	5.5146936	2.1509516	3102
	50	0.9982391	4.6041276	0.0013005	4.5936068	1.8438566	4835
	75	0.9984283	4.6041314	0.0011112	4.2154422	1.7132135	6220
	100	0.9985296	4.6041334	0.0010099	4.0130850	1.6451838	7375
100	25	0.9978487	4.6041197	0.0016909	5.3736811	2.1035407	3280
	50	0.9983292	4.6041294	0.0012104	4.4137018	1.7834890	5421
	75	0.9985242	4.6041334	0.0010154	4.0239585	1.6535632	7375
	100	0.9986385	4.6041355	0.0009011	3.7956953	1.5724388	9215

The presented results in Fig. 5 and Table 2, indicate that ORTTI for protection system increases 1.46 times by increasing MTBF for remote back-up protection system from 25 years to 100 years when MTBF of 25 years is considered for primary protection system. In this situation, unavailability, abnormal unavailability and operation when not required probability indices decrease to 25.22%, 17.5% and 15.51%, respectively. It is noticeable that availability and dependability indices increase but this increase is not considerable in comparison with the decrease of undesirable reliability indices.

Regarding to Table 2, although the ORTTI becomes longer as remote back-up protection system MTBF increases, the increment of this time interval also depends on the primary protection system MTBF. For example, the ORTTI increases 2.38 times (i.e. from 3102 (hours) to 7375 (hours)) considering MTBF of 75 years for primary protection system while the increment of this interval time is equal to 2.81 times (i.e. from 3280 (hours) to 9215 (hours)) when MTBF of 100 years is assumed for primary protection system. In both mentioned cases, remote back-up protection system MTBF increases from 25 to 100 years.

According to Tables 1 and 2, it can be seen that sensitivity of ORTTI to variations of remote back-up protection system monitoring test effectiveness is more than its sensitivity to remote back-up protection system MTBF. Therefore, this result emphasizes that in order to increase the ORTTI, considering monitoring facility is more effective than improving MTBF in protection system.

Furthermore, the effect of monitoring test effectiveness of protection systems along with variation of remote back-up protection system failure rate is investigated on the ORTTI. Results are shown in Table 3.

The presented results in Table 3, show that by increasing monitoring test effectivenesses of primary and remote back-up protection systems and MTBF of remote back-up protection system, ORTTI will increase. For example, by increasing of remote back-up protection system MTBF from 25 to 100 years, ORTTI becomes 2.3 times in monitoring test effectiveness to be equal to 85% for protection systems, while the increment of this time becomes 15.51 times considering monitoring test effectiveness to be equal to 95%.

Table 3. Variation of ORTTI with respect to increase of $MTBF_b$ and increase of MT_p and MT_b

$MTBF_p$ (yr)	$MTBF_b$ (yr)	MT_p and MT_b (%)	ORTTI (hours)
100	25	85	2355
	50		3605
	75		4596
	100		5422
100	25	90	3282
	50		5422
	75		7375
	100		6215
100	25	95	6734
	50		15809
	75		34832
	100		104479

4. Conclusion

In this paper, an extended Markov model for protection system is proposed to determine ORTTI considering failure probability of remote back-up protection and monitoring facility. Moreover, variation of ORTTI in protection system is analyzed taking into account the different values for remote back-up protection system monitoring test effectiveness and the mean time between failures. Presented results indicate that ORTTI will increase by increasing monitoring test effectiveness and remote back-up protection system MTBF, while these parameters are assumed constant for primary protection system. As a result, by increasing remote back-up protection system monitoring test effectiveness from 0 to 100% and considering monitoring test effectiveness to be equal to 90% for primary protection system, the ORTTI increases 8.21 times.

Furthermore, if remote back-up protection system MTBF changes from 25 to 100 years while primary protection system MTBF is assumed to be 50 years, the ORTTI is increased 1.46 times in monitoring test effectiveness to be equal to 90% for primary and remote back-up protection systems. Based on the obtained results, it is strongly recommended to consider the remote back-up protection system failure probability in determining the ORTTI in protection system.

Nomenclature

F_c	Protected component failure rate;
F_p and F_{bp}	Primary and remote back-up protection system failure rates respectively, (reciprocal of protection system Mean Time Between Failures (MTBF));
F_{MT} and F_{bMT}	Primary and remote back-up protection system failure rates, which are detected by monitoring test, respectively;
F_{pp} and F_{bpp}	Primary and remote back-up protection system failure rates, which are not detected by monitoring test, respectively;
F_{cc}	Common-causes failure rate of protected component and primary protection system;
F_{bc}	Common-causes failure rate of protected component and remote back-up protection system;
F_{ccc}	Common-causes failure rate of protected component, primary and remote back-up protection systems;
MT_p and MT_b	Monitoring test effectiveness index (MT) of primary and remote back-up protection systems, respectively;
R_c	Protected component repair rate;
R_t and R_{bt}	Primary and remote back-up system inspection rates, respectively;
R_r and R_{br}	Primary and remote back-up protection system repair rates, respectively;
R_{bp}	Primary and remote back-up protection systems repair rate simultaneously;
S_n and S_{bn}	Normal tripping operations of primary and remote back-up protection systems, respectively, (reciprocal of fault clearing time of primary and remote back-up protection systems);
S_b	Normal tripping operations of second remote back-up protection system (reciprocal of fault clearing time of second remote back-up protection system);
S_m	Manual switching rate;
θ_{pm} and θ_{bpm}	Reciprocal of primary and remote back-up protection systems routine test time interval ($RTTI_p$ and $RTTI_b$), respectively.

Appendix

Case study data for reliability analysis:

R_c=0.5 (repairs per hour)	$F_{bcc}=10^{-6}$ (failures per hour)
R_t= 1 (test per hour)	$F_{bp}=10^{-6}$ (failures per hour)
R_{bt}=1 (test per hour)	$F_{ccc}=10^{-9}$ (failures per hour)
R_r= 0.5 (repairs per hour)	S_n=43200 (operations per hour)
R_{br}=0.5 (repairs per hour)	S_{bn}=21600 (operations per hour)
R_{bp}= 0.5 (repairs per hour)	S_b=14400 (operations per hour)
$F_{cc}= 10^{-6}$ (failures per hour)	S_m=0.5 (operations per hour)

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