IUST Iran University of Science and Technology

Iranian Journal of Electrical and Electronic Engineering

Journal Homepage: ijeee.iust.ac.ir

Research Paper

Impact of Human Error Modeling on Failure Rate and Optimum Routine Test Interval of Protection System

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Abstract: Power systems should have acceptable reliability in order to operate properly. Highly available and dependable protective relays help to obtain the desirable reliability. The relays should be periodically evaluated during specific intervals to achieve the mentioned characteristics. The Routine Test Interval (*RTI*) should be optimized in order to economically maximize the reliability of the protection system. The failure rate of the relays plays a vital role in determination of the Optimum Routine Test Interval (ORTI). Human error is one of the effective factors in the failure rate of the relays. Therefore, in this paper, a Markov model is proposed to investigate the impact of human error on the failure rate and the ORTI of the protection system. The model is applied for the protection system of power transformer. The obtained results indicated that human error has a significant impact on the increase of protection system failure, the decrease of the desired reliability indices, and the reduction of ORTI of the protection system.

Keywords: Human Error, Failure Rate of Protection System, Reliability, Markov Model, Optimum Routine Test Interval.

Nomenclature

C	Protected component
P	Protection system
X	Additional component connected to C
UP	Item is in a good state
DN	Item is in a failed state
INS	Item is being inspected
ISO	Item is isolated
OC	Overcurrent relay
EF	Earth fault relay
REF	Restricted earth fault relay
DIF	Differential relay
λ_{OC}	OC failure rate
λ_{EF}	EF failure rate
λ_{REF}	REF failure rate
λ_{DIF}	DIF failure rate
λ_{H4}	Human error rate type 1
λ_{H3}	Human error rate type 2
λ_{H2}	Human error rate type 3
λ_{H1}	Human error rate type 4
μ_{OC}	OC repair rate
μ_{EF}	EF repair rate
μ_{REF}	REF repair rate
μ_{DIF}	DIF repair rate
μ_H	Repair rate of the protection system from its failure state which is caused by human error
μ_{tt}	Repair rate of the protection system from its failure state which is caused by errors except for human error
λ_p	Protection system failure rate
λ_c	Component failure rate
λ_{cc}	Failure rate of common-cause failure of the relay and component
λ_{pp}	Relay failure rate for failures which not detected by self-checking-test
μ_c	Repair rate of the protected component
μ_t	Repair rate of the protection system in inspection
μ_r	Repair rate of the protection system
S_n	Switching rate of normal tripping operation
S_b	Switching rate of backup tripping operation
S_m	Switching rate of manual isolation operation
PIR	Protection system inspection rate

Iranian Journal of Electrical and Electronic Engineering, 2021.
Paper first received 26 November 2019, revised 17 February 2020, and accepted 28 February 2020.
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https://doi.org/10.22068/IJEEE.17.1.1734

1 Introduction

HIGH reliability of the protection systems plays an important role in maintaining the reliability of the power systems at the desired level. In fact, a power system requires the highly dependable protective relays for preventing the failure extension and minimizing the load interruptions during the fault occurrence. Low reliable protection system can cause serious damages to the power system. For example, WSCC network suffered from a blackout due to false tripping of the protection system on August 10^{th}, 1996. Due to this event, 30 GW load and 27 GW generation lost and 7.5 million customers deprived of having electrical energy [1].

Human error is considered as one of the effective factors in increasing the failure rate of the protection system. Thus, it is a decreasing factor of the system reliability. Human error is a failure in performing the pre-described activity, which can result in equipment damages or its planned activities disruptions. In order to complete the definition of human error, the two following conditions are usually considered [2]:

- The operational conditions should be available. It is worth mentioning that the human activity is designed for these conditions.
- The human being should be physically and mentally conditioned to tolerate the pre-described activity.

Various studies have been conducted on the human error. A comprehensive classification of human error and its subsets are presented in [3]. In [4], types of human error, task analysis, and human reliability analysis models are explained. In [5], the effect of human error on troubleshoot of power plants is analyzed and classified. In [6], several mathematical models are used to model the human error rates for human reliability analysis of a structural designed task.

The impact of human factors on the operational reliability of the power system is analyzed in [7]. In [8], a method is developed in order to estimate the human error probabilities for decision-based errors. In [9], a human error quantification and identification framework is explained which deals with various forms of human error at different analysis levels. In [10], human's responses are investigated. The study aimed to increase human's knowledge about the responses to the alerts of the job conditions. Reliability indices are determined by considering the human error rate for redundant systems with the critical human error [11] for a two-state irreparable complex system [12], and the standby system in nuclear power plants [13].

Routine test of the protection system is momentous because it can detect the system failures. This test should be regularly performed during the optimum time in order to achieve high reliability for the protection system. In the modern relays, which are equipped with self-checking facility, the test is not usually performed with previous repetitions. The self-checking test is performed during a very short period of time. All or part of the protection system will be out of service [14] in this test. The coefficient of effectiveness in the self-checking test indicates the identification degree of the relay failures by the test. Moreover, effectiveness depends on the design and implementation of the facility and the number of components in the relay system equipped with the facility [15]. Until now, several studies have been conducted on the reliability of the protection system and the determination of ORTI.

In [16], an approach to test and maintain the protection system is discussed and a Markov model is presented to predict the ORTI either with or without the self-checking facility. The model is implemented to estimate the ORTI and the reliability indices (e.g. abnormal unavailability) are obtained for several different structures of overcurrent relays in [17]. In [18], the ORTI is estimated and the abnormal unavailability index for several protection plan structures are compared by using Markov model and Event Tree method. In [15], a Markov model is proposed to determine ORTI and the optimum time of self-checking test by considering self-checking and monitoring facilities. The adopted model in [15] is developed in [19] by considering the effect of different factors such as inadvertent opening of circuit breakers and required time for performing routine test. In [20], the reliability of the protection system is discussed from an economical aspect. Furthermore, a method is adopted to select optimally the hardware and software components of the digital relays in order to obtain the most reliability with a limited budget. In [21-23], a Markov model is proposed to analyze the reliability of the protection system and determine ORTI by considering self-checking and monitoring facilities while the backup relay is not fully reliable.

In this paper, a Markov model is proposed to investigate the impact of human error on the failure rate of the protection system. Moreover, the ORTI of the protection system is determined based on the obtained failure rate of the system. In this study, the proposed Markov model is developed for the protection system of power transformer including overcurrent, earth fault, restricted earth fault, and differential relays. It is worth mentioning that the model can be developed to analyze the impact of human error on the failure rate of protection system of other equipment in the power system.

The rest of the paper is organized as follows: the proposed Markov model for investigating the effect of human error on the failure rate of the protection system of power transformer is presented in Section 2. In Section 3, the presented method in [16] for obtaining the ORTI of the protection system is explained. The simulation results are illustrated in Section 4, and the conclusion is expressed in Section 5.

2 Proposed Markov Model for Evaluating the Impact of Human Error on Failure Rate of the Protection System of Power Transformer

A Markov model is proposed to investigate the impact of human error on failure rate of the protection system of power transformer. In the proposed model, it is assumed that the protection system of power transformer contains overcurrent, earth fault, restricted earth fault, and differential relays. The model has 17 states as shown in Fig. 1. The failure rate of the protection system as one of the effective factors on the ORTI is obtained by using the proposed model. The model is based on the following assumptions:

1. System failure made by human error is different from the system failure caused by the non-human error.
2. Whenever the system failure happened due to the non-human error, one of the relays has just been failed.
3. The failure, repair, and human error rates are constant.
4. The system failures are statistically independent of one another.
5. Human error is a critical one; that is, it causes the complete failure of the protection system.

The proposed Markov model will be explained as follow. According to the reliability perspective, because of the parallel connection of relays, the system does not fail in states 1-15 and it is available because at least there is one healthy relay. The abbreviated names of the healthy relays are given in the circles. In states 16 and 17, the protection system failed completely. When a human error is occurred in every state, the protection system is completely failed and the model transfers to

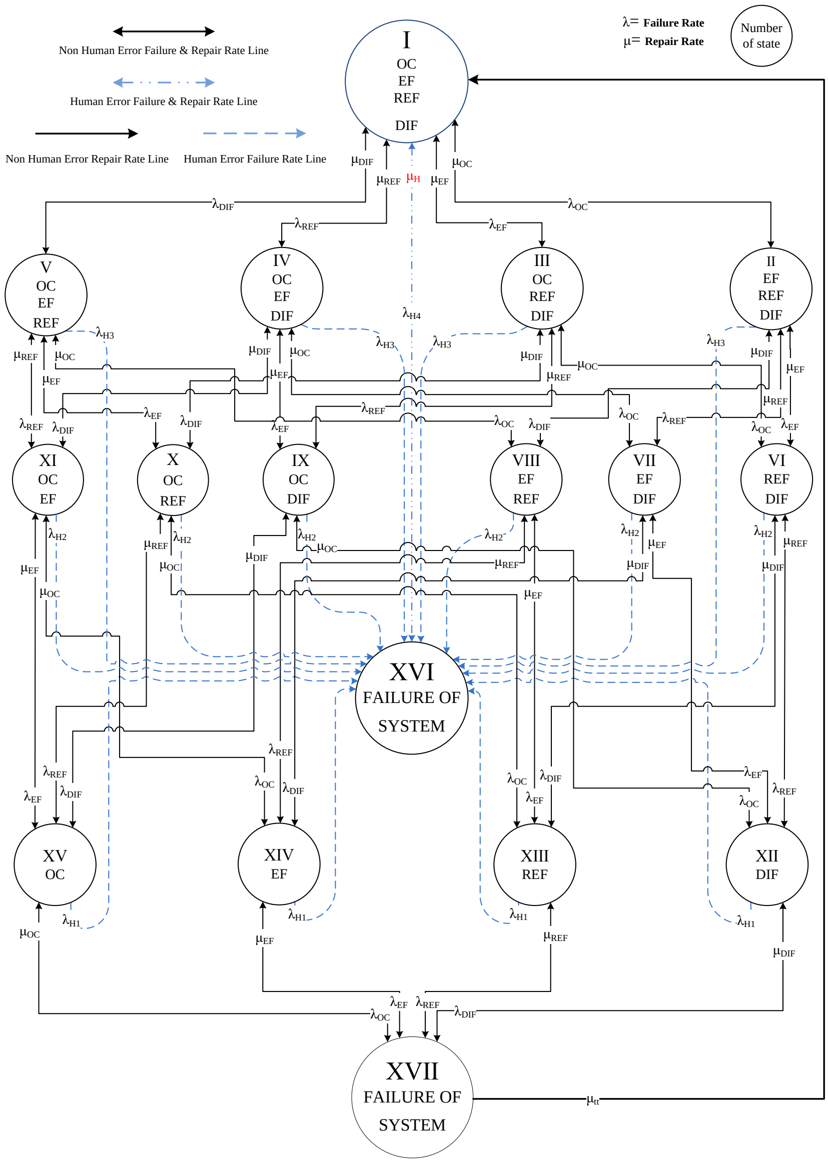

Fig. 1 Proposed Markov model to evaluate the impact of human error on the failure rate of the protection system of power transformer.

state 16. In state 1, all relays are healthy and the protection system is safe and available. When a relay fails, the model enters to states 2-5. The model enters to states 6-11 from states 2-5, when another relay fails. The model transmits to states 12-15 with the failure in another relay. In states 12-15, with the failure of the only healthy relay, the model enter to state 17 which means the complete failure of the protection system. In any of the states 2-15, if a relay is repaired, the model returns to its pre-failure state with the corresponding repaired relay. For example, if the differential relay is repaired in state 8, the model returns to state 2 and it returns to state 5 if the overcurrent relay is repaired. Moreover, the model returns to state 1 from states 16 and 17 by the protection system repairing.

The transition rates in the proposed Markov model are given in the "Nomenclature". The index of human error rate (HN) indicates that N relays are healthy in the case of human error. It is noticeable that the human error rate decrease by reducing the number of healthy relays. The failure rate of protection system (λ_P) is determined based on the following equations:

$$M_{ij} = \begin{cases} a_{ij} & i \neq j \\ 1 - \sum_{j,\, j \neq i} a_{ij} & i = j \end{cases} \tag{1}$$

$$P = [I - Q]^{-1} \tag{2}$$

$$MTTF = \sum_{k=1}^{j-2} P(1,k) \tag{3}$$

$$\lambda_P = \frac{1}{MTTF} \tag{4}$$

where M is a transient matrix, and a_{ij} is transient rate from state i to state j. Matrix Q is obtained by removing rows and columns relevant to the states of system failure from Matrix M. States 16 and 17 have been considered as absorbing states which the system fails at them. In (3), $MTTF$ could equal to the average time before the system enters the absorbing state. matrix I is an identity matrix with dimensions of matrix Q.

3 Determination of the ORTI

In this section, two models including general reliability model [15] and proposed Markov model [16] are explained. These models are used to investigate the effect of human error on ORTI of the protection system based on the obtained failure rate of the protection system by using proposed Markov model.

The general reliability model in [15] is considered to determine the reliability indices of the protection system. The model is shown in Fig. 2 and its states are presented in Table 1. The first state describes a situation that the protection system is healthy and fault does not occur on the protected equipment. This state shows the availability of the protection system. The second state describes that the protection system can operate if a fault occurs on the protected equipment. This state indicates the dependability of the protection system. The third state is relevant to the unavailability of the protection system. In this state, the protection system is unable to perform its own tasks because of routine or self-checking tests. The fourth state describes abnormal unavailability of the protection system. This occurs when the protection system is unable to run the function for which it is programmed. The last state is the security of the protection system in which the system operates at unnecessary time. It is worth noting that availability and dependability of the system should be maximized and unavailability, abnormal unavailability, and security of the system should be minimized in order to obtain the ORTI of the protection system.

The Markov model in [16] is used to determine the reliability indices and ORTI of the protection system. As shown in Fig. 3, the model has nine states which is explained in [16]. Most of the parameters used in Fig. 3 are defined in 'Nomenclature'. However, λ_{PP}, λ_{ST}, and PIR can be calculated by (5)

$$\begin{aligned} &\lambda_{PP} = \lambda_P \times (1 - SE) \\ &\lambda_{ST} = \lambda_P \times SE \\ &PIR = 1/RTI \end{aligned} \tag{5}$$

where SE is self-checking effectiveness coefficient.

The relation among the states of the two models (Figs. 2 and 3) is presented in (6) in order to determine the ORTI. In this equation, as desirable reliability indices, PI and PII are availability and dependability of the protection system, respectively, as undesirable reliability indexes, P_{III}, P_{IV}, and P_V are unavailability, abnormal unavailability, and security of the protection system, respectively. In addition, $\boldsymbol{T}$ and $\boldsymbol{p}$ are the transitional matrix and the vector of the state probabilities of presented model in Fig. 3, respectively. It is worth mentioning that ORTI of the protection system is obtained by either maximizing the desirable

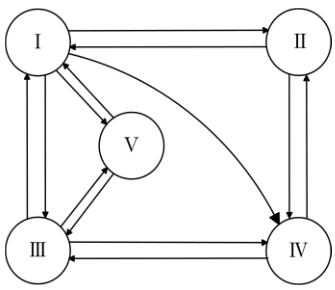

Fig. 2 General reliability model [15].

Table 1 The states of general reliability model [15].

State number	Describe of situation
State I	Not Needed & Healthy
State II	Needed & Healthy
State III	Not Needed & Not Healthy
State IV	Needed & Not Healthy
State V	Operation when Not required

indices or minimizing the undesirable reliability ones. In this paper, enumeration method is used for optimization.

$$
\begin{aligned}
&P_I = p_1 \\
&P_{II} = p_2 + p_6 \\
&P_{III} = p_3 + p_5 + p_9 \\
&P_{IV} = p_4 + p_8 \\
&P_V = p_7 \\
&\boldsymbol{pT} = \boldsymbol{p} \\
&\sum_{n=1}^{9} p_n = 1
\end{aligned}
\tag{6}
$$

4 Simulation Results

The transition rates presented in Table 2 are used for analysis of the impact of human error on the failure rate and ORTI of the protection system of power transformer in different scenarios, which are explained as in Table 2.

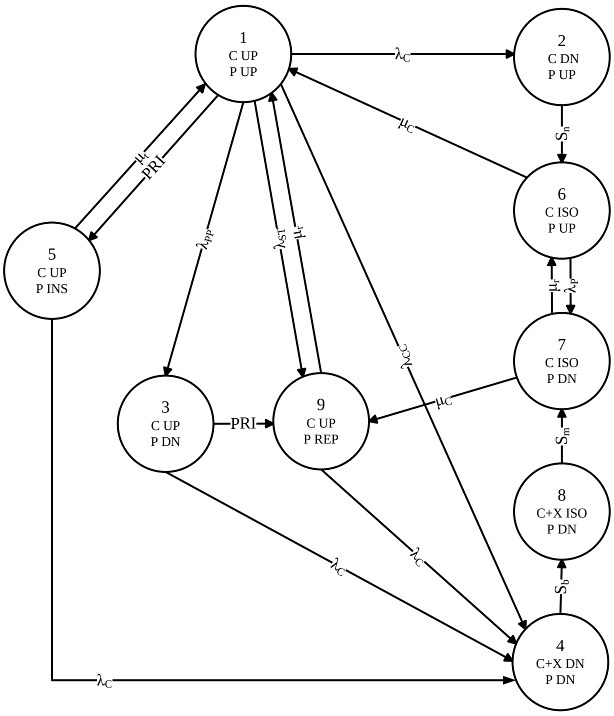

Fig. 3 Markov model of the protection system and protected component [16].

Table 2 Transition rates for simulation.

λ_{OC} [failure/year]	0.01	μ_{OC} [repair/hr]	0.5
λ_{EF} [failure/year]	0.01	μ_{EF} [repair/hr]	0.5
λ_{REF} [failure/year]	0.01	μ_{REF} [repair/hr]	0.5
λ_{DIF} [failure/year]	0.01	μ_{DIF} [repair/hr]	0.5
λ_{H4} [failure/year]	0.01	μ_H [repair/hr]	0.5
λ_{H3} [failure/year]	0.007	μ_r [repair/hr]*	2
λ_{H2} [failure/year]	0.004	μ_t [Inspection/hr]*	1
λ_{H1} [failure/year]	0.001	μ_c [repair/hr]*	0.5
λ_C [failure/year]*	1	S_n [operation/hr]*	43200
λ_{CC} [failure/million hr]*	1	S_b [operation/hr]*	21600
S_m [operation/hr]*	0.5	*These data are taken from [16]	

4.1 The Impact of Human Error Rate on the Failure Rate of the Protection System

In order to evaluate the impact of human error on the failure rate of the protection system, it is assumed that the failure rates relevant to the human error are increased by step size 0.001 in ten steps. The simulation results are presented in Table 3. Based on the presented results, the *MTTF* decreases and the failure rate of the protection system increases by the growth of the human error. For example, if the human error rates of types 4, 3, 2, and 1 are respectively 0.01, 0.007, 0.004, and 0.001 (failure/year), the *MTTF* will be 100.0003 years and the failure rate of the protection system will be 0.009999973 (failure/year). If the human error rates of types 4, 3, 2, and 1 are respectively 0.019, 0.016, 0.013, and 0.01 (failure/year), the *MTTF* will be 52.63166 years and the failure rate of the protection system will be 0.018999973 (failure/year). This change approximately equals to 47.5 years (47.4%) reduction in *MTTF* of the protection system through 0.009 (failure/year) growth in human error rates. This result indicates the high impact of human error on the failure rate of the protection system.

4.2 Determination of the ORTI Without Considering the Self-Checking Facility

In order to investigate the impact of human error on the ORTI of the protection system, the ORTI is determined based on the presented failure rates of the protection system in Table 3. The simulation results are shown in Table 4 and Fig.4. Figs.4(a) and 4(b) illustrate the availability and dependability of the protection system of power transformer. As shown in Table 4, by decreasing the *MTTF* from 100.0003 to 52.63166 years, the probability of these indices reduce from 0.99774861 and 0.000229764 to 0.99694347 and 0.000229726, respectively; that is, 0.08% and 0.0165% reduction of indices. Figs. 4(c), 4(d), and 4(e) illustrate the unavailability, abnormal unavailability, and security of the protection system, respectively. The probability of these indices increase from 0.00201868, 2.45644×10^{-6}, and 4.91382×10^{-7} to 0.0028223634, 2.63861×10^{-6}, and 5.2791×10^{-7}, respectively. These changes are 39.8%, 7.416%, and 7.433% increment of indices, respectively.

Table 3 The impact of human error rate on the protection system failure rate.

Number	λ_{H4} [failure/year]	λ_{H3}	λ_{H2}	λ_{H1}	*MTTF* [year]	λ_P [failure/year]
1	0.01	0.007	0.004	0.001	100.0003	0.009999973
2	0.011	0.008	0.005	0.002	90.90932	0.010999973
3	0.012	0.009	0.006	0.003	83.33353	0.011999972
4	0.013	0.01	0.007	0.004	76.92324	0.012999972
5	0.014	0.011	0.008	0.005	71.42871	0.013999972
6	0.015	0.012	0.009	0.006	66.66679	0.014999973
7	0.016	0.013	0.01	0.007	62.50011	0.015999973
8	0.017	0.014	0.011	0.008	58.82362	0.016999973
9	0.018	0.015	0.012	0.009	55.55564	0.017999973
10	0.019	0.016	0.013	0.01	52.63166	0.018999973

Table 4 ORTI of the protection system of power transformer without self-checking facility.

MTTF [year]	P_I	P_{II}	P_{III}	P_{IV}	P_V	ORTI [hour]
100.0003	0.99774861	0.000229764	0.00201868	245644×10^{-6}	4.91382×10^{-7}	1048
90.90932	0.99764472	0.000229759	0.002122572	2.47995×10^{-6}	4.96094×10^{-7}	994
83.33353	0.99754542	0.000229754	0.002221821	2.50241×10^{-6}	5.00597×10^{-7}	947
76.92324	0.99745023	0.00022975	0.002316998	2.52395×10^{-6}	5.04915×10^{-7}	906
71.42871	0.99735862	0.000229746	0.002408565	2.54468×10^{-6}	5.0907×10^{-7}	870
66.66679	0.99727029	0.000229741	0.002496901	2.56467×10^{-6}	5.13079×10^{-7}	837
62.50011	0.99718481	0.000229737	0.002582326	2.584×10^{-6}	5.16956×10^{-7}	808
58.82362	0.99710202	0.000229733	0.002665109	2.60274×10^{-6}	5.20714×10^{-7}	782
55.55564	0.99702168	0.00022973	0.002745478	2.62093×10^{-6}	5.24362×10^{-7}	758
52.63166	0.99694347	0.000229726	0.002823634	2.63861×10^{-6}	5.2791×10^{-7}	736

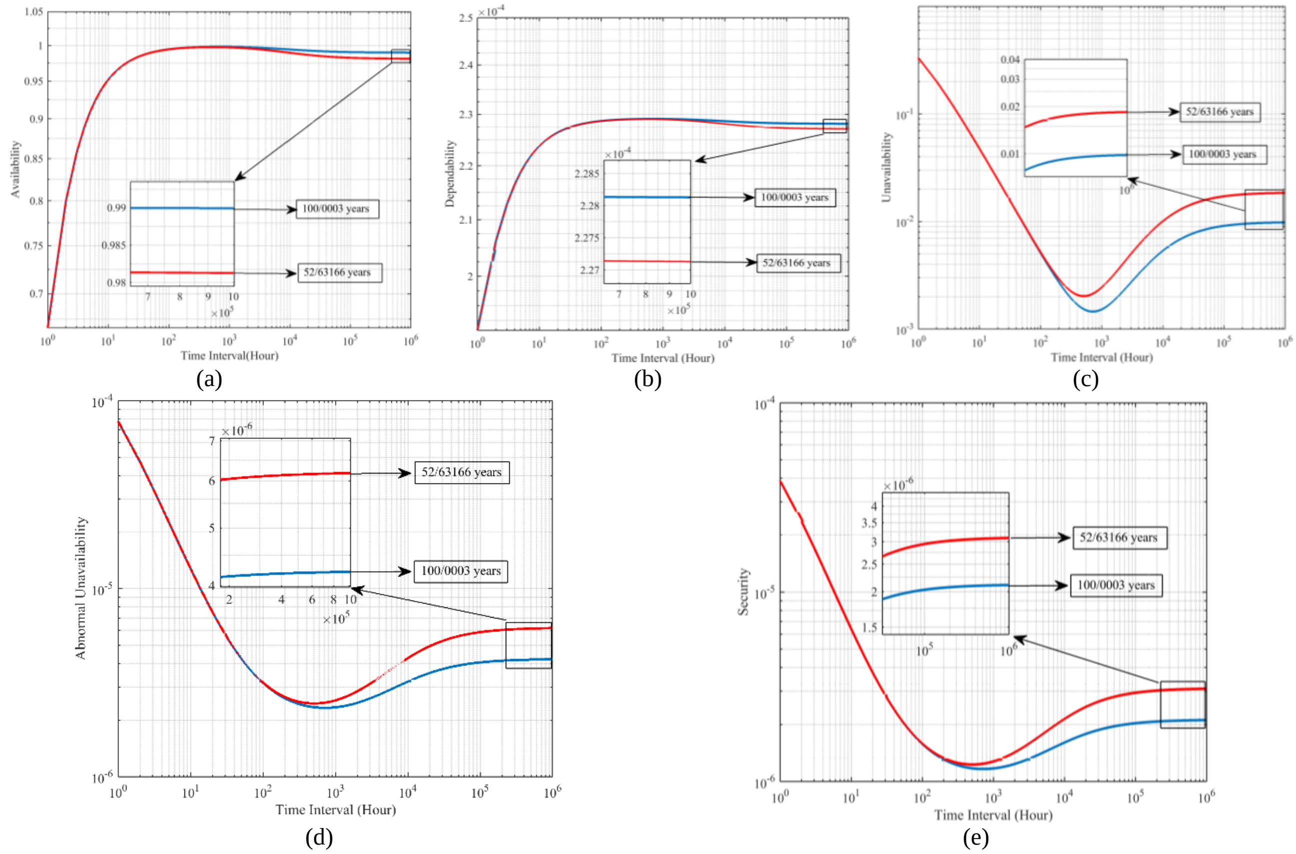

Fig. 4 Reliability indices of the protection system of power transformer without self-checking facility: a) availability, b) dependability, c) unavailability, d) abnormal unavailability, and e) security.

This result shows a major change in the unavailability index of protection system. Corresponding to these changes, the ORTI is reduced from 1048 to 736 hours by the growth of human error rate. It means that the time interval decreased significantly (i.e. 29.77%).

4.3 Determination of the ORTI by Considering the Self-Checking Facility

Table 5 and Fig. 5 present the impact of the human error on the ORTI of the protection system by considering self-checking facility. Based on the obtained results, the dependability of the system increases and its security decreases by the growth of the *SE*. For example, the probability of these indices for the *SE* 50% and 80% change from 0.000229794 and 4.63159×10^{-7} to 0.00022982 and 4.38086×10^{-7}, respectively. As presented in Table 5, for the *MTTF* of 100.0003 years, the ORTTI increases from 1048 to 10^6 for the *SE* that equals 0.99. This means that routine test will not be necessary if the *SE* approaches 100. The dependability and security of the protection system for *MTTF* of 52.63166 years and the *SE* 80% and 90% change from 0.000229803 and 4.54533×10^{-7} to 0.000229821 and 4.37111×10^{-7}, respectively. Moreover, according to Tables 4 and 5, the ORTI increases from 736 hours without self-checking test to 30191 hours with self-checking test with the *SE* 99%.

As shown in Table 5, the ORTI changes from 81519 to 30191 years by decreasing *MTTF* from 71.42871 to 52.63166 years, for the *SE* 99%. In fact, 170% reduction in ORTI made by the reduction of the *MTTF* indicates the high impact of human error on the ORTI by considering self-checking test. For the *SE* 90%, by the reduction of *MTTF* from 71.42871 to 52.63166 years, the ORTI varies from 3501 to 2844. This result indicates 18.7% reduction in ORTI. According to the results, the changes in the ORTI increased from 18.7% to 170% by increasing the *SE* from 90% to 99%. It indicates that the effect of human error on the ORTI increases by the growth of the effectiveness of the self-checking test. In fact, the growth of human error has a significant effect on the variation of the ORTI in modern relays equipped by self-checking facility with high *SE*.

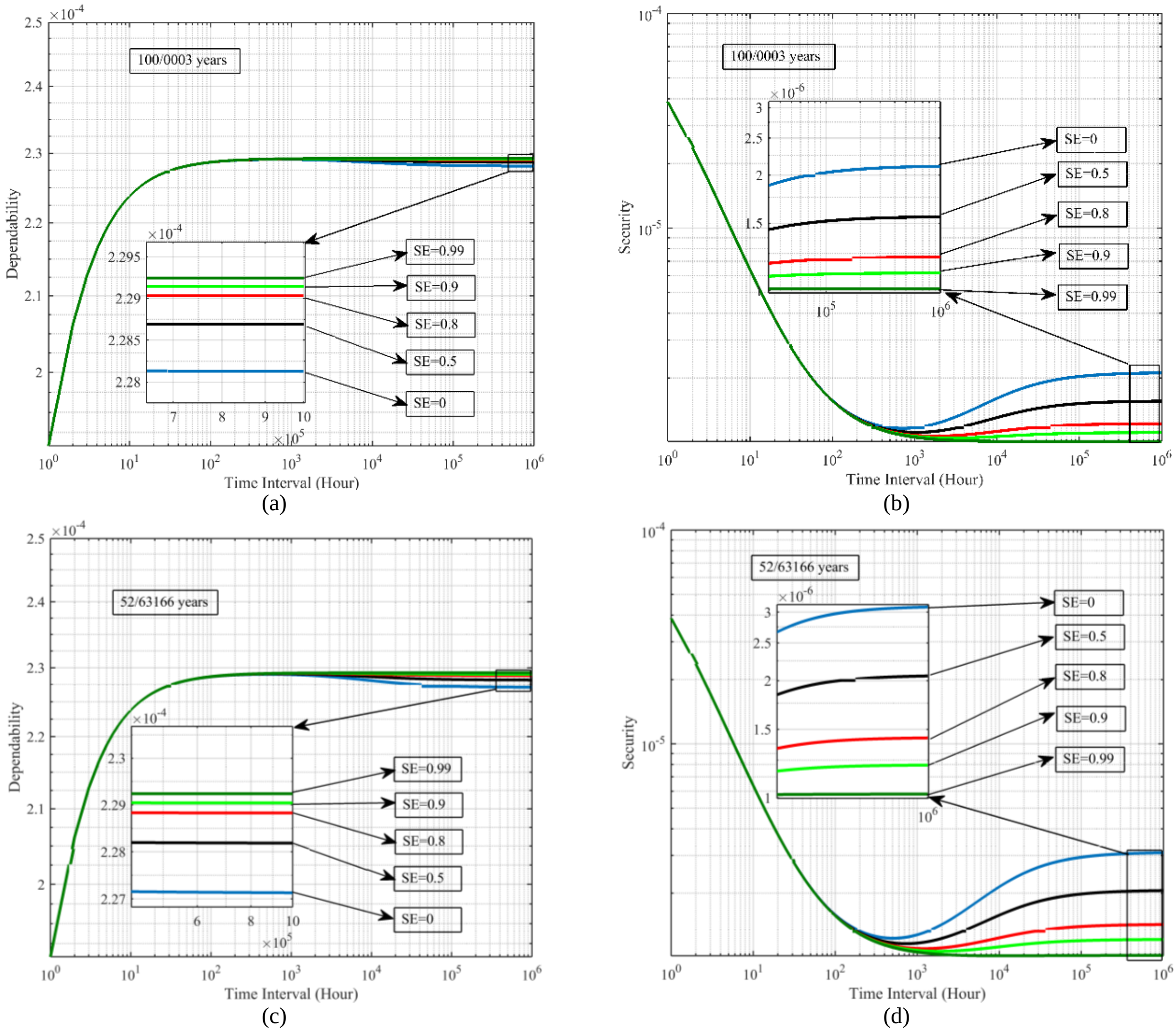

Fig. 5 Dependability and security of the protection system of power transformer with self-checking facility: a and b) *MTTF* 100.003 (year), and c and d) *MTTF* 52.63166 (year).

Table 5 ORTI of the protection system of power transformer with self-checking facility.

MTTF [year]	*SE* [%]	P_I	P_{II}	P_{III}	P_{IV}	P_V	ORTI [hour]
100.0003	50	0.99837232	0.000229794	0.001395133	2.31532×10^{-6}	4.63159×10^{-7}	1559
100.0003	80	0.99892634	0.00022982	0.000841188	2.18996×10^{-6}	4.38086×10^{-7}	2750
100.0003	90	0.99920583	0.000229833	0.000561767	2.12672×10^{-6}	4.25439×10^{-7}	4470
100.0003	99	0.99966693	0.000229855	0.000100764	2.02239×10^{-6}	4.04573×10^{-7}	10^6
71.42871	50	0.99809611	0.000229781	0.001671266	2.37781×10^{-6}	4.75699×10^{-7}	1282
71.42871	80	0.9987514	0.000229812	0.001016125	2.22955×10^{-6}	4.46046×10^{-7}	2216
71.42871	90	0.99908197	0.000229827	0.000685609	2.15475×10^{-6}	4.31086×10^{-7}	3501
71.42871	99	0.99962819	0.000229853	0.000139522	2.03116×10^{-6}	4.06369×10^{-7}	81519
52.63166	50	0.99780196	0.000229767	0.001965318	2.44436×10^{-6}	4.89061×10^{-7}	1078
52.63166	80	0.99856502	0.000229803	0.001202469	2.27172×10^{-6}	4.54533×10^{-7}	1837
52.63166	90	0.99895	0.000229821	0.000817552	2.18461×10^{-6}	4.37111×10^{-7}	2844
52.63166	99	0.99958622	0.000229851	0.000181491	2.04066×10^{-6}	4.08321×10^{-7}	30191

5 Conclusion

In this paper, a Markov model is proposed to investigate the impact of human error on the failure rate and ORTI of the protection system of a power transformer. The model has 17 states. It was assumed that the protection system of power transformer had overcurrent, earth fault, restricted earth fault, and differential relays. The simulation results indicated that *MTTF* of the protection system decreased by increasing human error rate and consequently, the desirable reliability indices and ORTI of the protection system significantly decreased. Moreover, the effect of human error rate on the ORTI increased by the growth of the effectiveness coefficient for self-checking test. Based on the obtained results, the reduction of the human error can play a significant role in increasing the reliability, reducing the ORTI, and reducing the maintenance costs of the system.

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