Reliability and Sensitivity Analysis of Motor Protection System Using Fault Tree Method

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***Abstract*-- Maintaining reliability of the electrical motors as large industrial loads in desirable level has special importance because electrical motors with low reliability and in result with inappropriate operation can cause heavy damages in the industrial plants. Appropriate operation of protection system is one of the factors to have desirable reliability of electrical motors in the power system. Components of protection system failure rate has vital role in appropriate operation of power system protection. Therefore, in this study, operation of electrical motor protection system from view of reliability has investigated using fault tree method. Availability, annual downtime and failure rate of motor protection subsystem and system is determined to reliability analysis of the motor protection system. Also, risk reduction worth index of motor protection system components is used for sensitivity analysis.**

***Index Terms*-- Motor protection system, availability, annual downtime, failure rate, risk reduction worth index.**

I. Nomenclature

A_{system}	System availability;
U_{system}	System unavailability;
A_i	Availability of Component i;
U_i	Unavailability of Component i;
A_d	Annual downtime;
T_I	Time period between consecutive tests;
I_i^{RRW}	Risk reduction worth index for component i;
λ	Failure rate;
CT	Current transformer;
VT	Voltage transformer;
DC	Direct power supply source (battery);
W	Wiring;
RTD	Resistance temperature detector;
TACH	Tachometer.

II. Introduction

Reliable electrical motor performance plays vital role to suitable plant operation [1]. Maintaining reliability of electrical motors on desirable level will improve the reliable performance of plant. A study conducted by Electric Power Research Institute (EPRI), has been expressed that electrical motor failures consist of fault in the bearings (41%), in the stator (37%), in the rotor (10%) and in the other parts (12%). Different types of protective systems are installed on electrical motors in order to prevent these failures [2]. Therefore appropriate operation of protection system can significantly reduce electrical motor failures. Maintenance and routine test is necessary to maximize the protection system availability and minimize the protection system unavailability [3]. Several studies have been done on power system protection reliability. In [4] and [5], reliability of transmission line POTT protection system models are evaluated using the fault tree method. In [6], the importance of components according to risk reduction worth index has been performed and reliability indices of protection system for a typical power system have been determined using fault tree method. In this reference, sub-top events have been constructed for transmission line protection, bus protection, breaker failure protection, generator back-up protection and remote trip protection. Top event for typical power system protection failure has been constructed based on these sub-top events and then protection system unavailability is determined. In [7], effect of structure and reliability of system protection scheme (SPS) components have been analyzed on undesired operation rate of protection system and risk index using fault tree method. In [8], generator stator protection reliability has been evaluated using fault tree method and effect of back-up protection system has been investigated on protection system unavailability. In [9], dependability and security of transmission line protection system have been determined using event tree and fault tree methods. Optimum routine test time interval for transmission line protection system [3, 10] and transformer protection system [11] has been determined using Markov method.

With respect to importance of electric motors protection system to reduce electric motor failures, in this paper, electric motor protection system reliability has been investigated considering the components of protection system unavailability index and also, sensitivity analysis has been done based on components of protection system risk reduction worth index.

III. Reliability and Sensitivity Analysis

In this paper, protection system unavailability is calculated using fault tree method for reliability analyzing. Components of the system are either connected in series or parallel. In a system with two components, if these are connected in series (both of the components must be available for correct

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operation of system) (Fig. 1a), they are connected by OR gate with together in fault tree of system (Fig. 1b). Therefore, system availability and unavailability are calculated using (1):

$$A_{system} = A_B \times A_C$$
$$U_{system} = 1 - A_{system} = U_B + U_C - U_B \times U_C \tag{1}$$

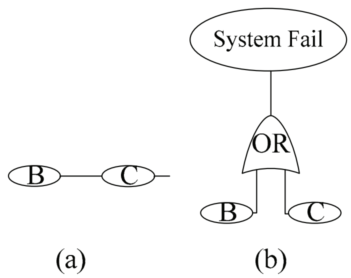

Fig. 1. Fault tree for two series components.

In a system with two components, if these are connected in parallel (both of the components must be unavailable for incorrect operation of system) (Fig. 2a), they are connected by AND gate with together in fault tree of system (Fig. 2b). Therefore, system unavailability is calculated using the following equation:

$$U_{system} = U_B \times U_C$$
$$A_{system} = 1 - U_{system} = A_B + A_C - A_B \times A_C \tag{2}$$

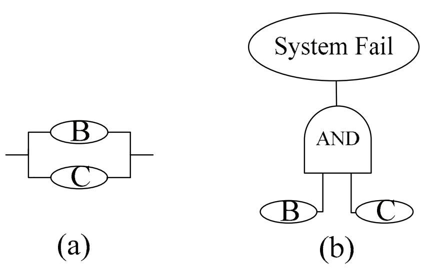

Fig. 2. Fault tree for two parallel components.

The annual downtime can be calculated using (3). Eq. (4) is used to determine failure rate (λ) [6]:

$$A_d = U_{system} \times 8760 \quad (hour/year) \tag{3}$$

$$U_{system} = 1 + \frac{\exp(-\lambda T_I) - 1}{\lambda T_I} \Rightarrow \lambda = F(U_{system}, T_I) \tag{4}$$

Importance of components in increasing of system reliability is considerable. In this paper, risk reduction worth index is used to quantify the component importance in motor protection system that is defined using the following equation [6]:

$$I_i^{RRW} = \frac{U_S\left[U_{base}\right]}{U_S\left[U_{base} \middle| U_i = 0\right]} \tag{5}$$

In Eq. (5), $U_S[U_{base}]$ and $U_S[U_{base}|U_i = 0]$ show system unavailability when component i is not perfect reliable and is perfect reliable, respectively.

IV. Case Study

For reliability analysis of electrical motor protection system, Fig. 3 has been used as electrical motor protection system. According to the Fig. 3, the motor is equipped with different protection types. In Table I, these protection systems have been introduced.

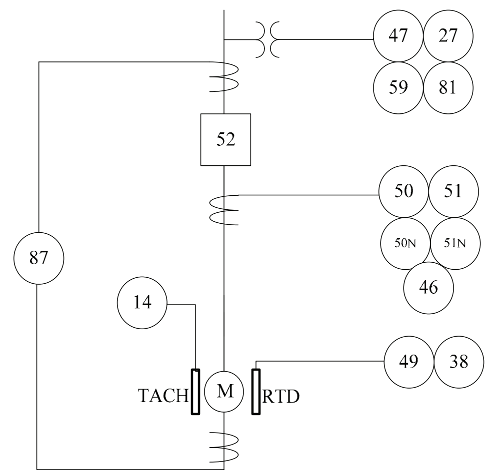

Fig. 3. Schematic of motor protection system

TABLE I
PROTECTION DEVICE NUMBER

14	Under-Speed
27	Under-Voltage
38	Bearing RTD
46	Unbalanced Current
47	Unbalanced Voltage
49	Stator RTD
50	Instantaneous Overcurrent
51	Time delay Overcurrent
50N/51N	Ground Overcurren
52	Breaker
59	Overvoltage
81	Frequency
87	Differential

The fault tree for motor protection system is shown in Fig. 4 that includes five protection subsystems. In the rest of this section these subsystems are explained:

Subsystem 1 is the differential protection system. Subsystem 2 is defined as RTD protection system. In this subsystem, bearing and stator RTD are considered as protection devices. Under-speed relay is as protection device in Subsystem 3 that is shown TACH protection system.

Subsystem 4 consists of under-voltage relay, unbalanced voltage relay, overvoltage relay and frequency relay as protection devices. Subsystem 5 shows the motor over-current protection system that consists of instantaneous over-current relay, time delay over-current relay as back-up protection for instantaneous over-current relay and ground over-current relays.

In constructing of fault tree, it is assumed that failure of each subsystem results in motor protection system failure. In Fig. 4, time delay over-current relay is considered as back-up protection for instantaneous over-current relay.

Based on this assumption, for top event (failure of motor protection system) constructing in the motor protection fault tree, five subsystem should be connected by OR gate. It is noted that each subsystem has another operation logic that is shown in Fig. 4. For example, in subsystem 1, failure of each CTs, wiring and differential relay cause motor differential protection subsystem failure. Therefore, components are connected by OR gate in fault tree of this subsystem.

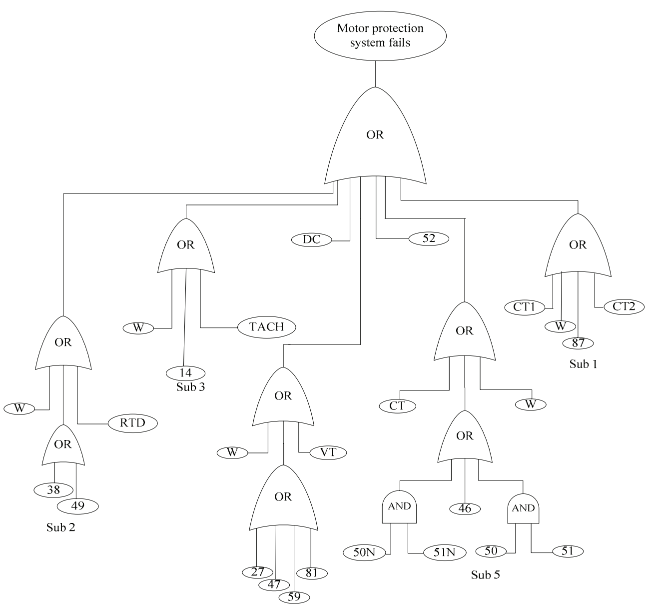

Fig. 4. Fault tree motor protection system.

V. Simulation Results

In this study, motor protection system reliability and sensitivity analysis have been performed based on data presented in Table II [4, 8]. It is noticeable that wiring, RTD, TACH unavailability is assumed 15×10^{-6}, 150×10^{-6} and 150×10^{-6}, respectively.

TABLE II
FAILURE RATES OF COMPONENT

Component	Unavailability
Circuit Breaker	300×10^{-6}
Current Transformer	10×10^{-6}
Voltage Transformer	10×10^{-6}
All Relay	100×10^{-6}
DC power supply source	50×10^{-6}

A. Basic Condition

Tables III and IV show results of reliability and sensitivity analysis, respectively. Time period between consecutive tests are assumed one year to determine motor protection system and subsystems failure rate.

TABLE III
RELIABILITY ANALYSIS FOR MOTOR PROTECTION SYSTEM AND SUBSYSTEMS

System and Subsystems	Availability	A_d (h/yr)	Failure Rate (f/yr)
Motor Protection system	0.9983362	14.57	0.0033120
Sub 1	0.9998650	1.18	2.7001650×10^{-04}
Sub 2	0.9996350	3.2	7.3008720×10^{-04}
Sub 3	0.9997350	2.32	5.3005610×10^{-04}
Sub 4	0.9995751	3.72	8.5010050×10^{-04}
Sub 5	0.9998750	1.09	2.5005550×10^{-04}

TABLE IV
SENSITIVITY ANALYSIS FOR MOTOR PROTECTION SYSTEM AND SUBSYSTEMS

Component	I^{RRW}
Motor protection system	
Circuit Breaker	1.2196158
CT	1.0183319
VT	1.0060368
DC Power	1.0309322
W	1.0471269
RTD	1.0989269
TACH	1.0989269
50,51,50N and 51N	1.0000060
All Relay without 50,51,50N and 51N	1.0638425
Sub 1	
CT	1.1738944
87	3.8570755
W	1.1249871
Sub 2	
RTD	1.6975666
All Relay	1.3772851
W	1.0428470
Sub 3	
TACH	2.3042148
14	1.6059689
W	1.0599886
Sub 4	
VT	1.0240902
All Relay	1.3076280
W	1.0365761
Sub 5	
CT	1.0869325
All Relay without 46	1.00008
46	4.9967266
W	1.1363251

According to Table III, the annual downtime and the failure rate of subsystem 2, 3 and 4 is more than the annual downtime the failure rate of other subsystem. For example, the failure rate of subsystem 4 is 8.5010050×10^{-04} (failures/year) while the failure rate of subsystem 5 is equal to 2.5005550×10^{-04} (failures/year), i.e. the failure rate of subsystem 4 is 70.59% more than the failure rate of subsystem 5 that has the lowest index. Also, the annual downtime of subsystem 4 is 3.4 times the annual downtime of subsystem 5. Therefore, based on these results if the subsystems 2, 3 and 4 are made with better quality than the other subsystems, failure rate and annual downtime of motor protection system will decrease considerably.

Table IV shows importance of other protection system components in motor protection system. As shown in Table IV, risk reduction worth index of circuit is 1.22 times the lowest one that means this component is the most effective component in the failure of motor protection system. Therefore, importance of this subject should be considered in manufacturing of breaker. Also, according to presented results in that Table IV the effect of considering redundancy in components of protection system on reliability indices is significant. For example, If time delay over-current relay is considered as back-up protection for instantaneous over-current relay, risk reduction worth of over-current relay decreases 6% more than the risk reduction worth index of other relays in motor protection system that do not have back-up protection.

B. Effect of Protection System Components Uncertainty on Motor Protection System Reliability

Unavailability of components has been changed from half to twice times of basic condition data to analyze the effect of protection system components uncertainty on motor protection system reliability indices and risk reduction worth index. Also, time period between consecutive tests is assumed one year. For example, results of uncertainty analysis on breaker, differential relay, RTD and direct power supply have been presented in Table V.

TABLE V
UNCERTINATY ANALYSIS

Index	Breaker Unavailability		
	150×10^{-6}	300×10^{-6}	600×10^{-6}
Availability	0.9984860	0.9983362	0.9980367
A_d (h/yr)	13.26	14.57	17.20
Failure Rate (f/yr)	0.0030310	0.0033120	0.0039318
I^{RRW}	1.1098079	1.2196158	1.4392316

Index	Differential Relay Unavailability	
	50×10^{-6}	200×10^{-6}
Availability	0.9983862	0.9982364
A_d (h/yr)	14.13	15.44
Failure Rate (f/yr)	0.0032311	0.0035313
I^{RRW}	1.0319212	1.1276850

Index	RTD Unavailability	
	75×10^{-6}	300×10^{-6}
Availability	0.9984111	0.9981865
A_d (h/yr)	13.9	15.88
Failure Rate (f/yr)	0.0031811	0.0036314
I^{RRW}	1.0494634	1.1978537

Index	DC Unavailability	
	25×10^{-6}	100×10^{-6}
Availability	0.9983612	0.9982863
A_d (h/yr)	14.35	15.01
Failure Rate (f/yr)	0.0032812	0.0034313
I^{RRW}	1.0154661	1.0618644

The presented results in Table V show that the risk reduction worth index, annual downtime and failure rate of motor protection system will increase by increasing protection system components unavailability. For example, by increasing breaker unavailability from 300×10^{-6} to 600×10^{-6}, motor protection system failure and risk reduction worth index increase 18.71% and 18.01%, respectively and annual downtime becomes 1.18 times. Also, motor protection system failure and risk reduction worth index decrease 8.48% and 9%, respectively and annual downtime was be 0.91 times by decreasing breaker unavailability from 300×10^{-6} to 150×10^{-6}.

VI. CONCLUSIONS

In this paper, reliability and risk reduction worth analysis have been performed for motor protection system. Also, effect of protection system components uncertainty has been investigated on motor protection system reliability indices and risk reduction worth index. Results show that circuit breaker is the most effective component among motor protection system components to improve reliability indices. For example, by increasing circuit breaker unavailability from 150×10^{-6} to 600×10^{-6}, motor protection system failure rate and risk reduction worth index increase 29.72% and 29.64%, respectively and annual downtime becomes 1.3 times that these results are significant. Also, redundancy causes decreasing risk reduction worth index.

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VIII. Biographies

Javad Sadeh (M'08) was born in Mashhad, Iran in 1968. He received the B.Sc. and M.Sc. with honor both in Electrical Engineering from Ferdowsi University of Mashhad, Mashhad, Iran in 1990 and 1994, respectively and obtained his Ph.D. in Electrical Engineering from Sharif University of Technology, Tehran, Iran with the collaboration of the electrical engineering laboratory of the Institute National Polytechnique de Grenoble (INPG), France in 2001. He is currently as associate professor in the Department of Electrical Engineering at the Ferdowsi University of Mashhad, Mashhad, Iran. His research interests are power system protection, dynamics and operation.

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