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Reliability analysis of protection system using neighbouring line dependability failures

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In power system studies, the reliability of protection systems has a considerable effect on the reliability of supply, and hence appropriate reliability models must be incorporated. A majority of studies conducted assuming perfectly reliable protection systems, and hence do not take into account the effects of failure scenarios in their operation.Modelling of the failure modes in protection systems associated with their dependability and security features is essential for comprehensive evaluation of power system reliability. There are relatively fewer works in the literature on power system reliability accounting for the impact of protection system. In this paper, common mode failure operations such as dependability failures of protection of neighbouring lines in a Power System network is considered. In an existing method, only first order and second order failures of transmission lines are considered, whereas, failure modes using higher order Cutsets are not considered. Expressions for reliability analysis are developed and software has been developed using MATLAB. The results for sample systems are obtained and analysed. From the results, it can be concluded that although probability of failure indices are increased as compared to an existing method, the proposed method is more general, realistic and approximate analysis can be carried out for any system having higher order dependable failures.

Keywords: *Reliability, dependent failure, neighbouring line, probability logic diagram*

1.0 INTRODUCTION

The protection unit faulty operations may lead to isolation of healthy line from the network which cause increase in unavailability of the line. Total operational modes of the protection unit are categorized into three groups. They are:

i. Correct operations

ii. Unwanted operations

iii. Missing operations

The dependability based failures can result in large fault clearing times and isolation of additional elements of the electric system. Security based protection system failures can results in isolation of additional elements of the electric system but typically do not result in increased fault clearing time. The causes for the protection unit failures are as follows:

i. Design failures

ii. Installation

iii. Settings

iv. Calibration

v. Switching operations

vi. Instrument transformer failures, etc.

Redundancy of the components present in the protection unit reduces the probability of a

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dependability based failures but it increasesthe probability of a security based protection system failure. Components in protection unit that are applicable for applying redundancy are:

i. Protective relays

ii. Auxiliary tripping relay

iii. Breaker trip coil, etc.

The common mode failures incorporating in reliability analysis is explained in [2]. The effect of the protection system operational modes and failures on theTransmission system is explained in [4]. The statistical data of different causes for protection system operational modes and failuresis given by Kjolle et al. [5] by surveying the existing system operation data. Gjerde et al. [6] provided information about the dependency event in the protection system operations when considering dependability and security based failures. Jiang and Singh [7] provided basic information about different models and concepts to analyze the protection system in the reliability analysis. Venu et al. [8] provided basic information about the fault types of the transmission line because of different operation modes of protection system i.e., isolation of transmission line because of protection system operation modes. Venu et al. [9] provided the information about the involvement of the dependency operation in the reliability analysis of the power system considering protection system reliability.

In this paper, an attempt has been made to consider higher order dependable neighbouring line failures, and expressions are developed. An algorithm has been developed using MATLAB and the results are compared with an existing method for test cases presented in [1] and [3].

2.0 MODELLING OF FAILURE MODES

The isolation of transmission line is considered as the failure of the line. The isolation of transmission line will be done by the circuit breaker and isolators which are the subcomponents of protection unit operates based on the instructions provided by relays when fault occur on the line or manual operations at emergency case. Based on the operations of the protection unit the failure of the system is classified into four faults [9].

i. Fault Type-1 (FT1)

ii. Fault Type-2 (FT2)

iii. Fault Type-3 (FT3)

iv. Fault Type-4 (FT4)

The Fault type-1 is defined as the fault occurring on the transmission line i, where the isolation of line is depend on the protection system performance andin two ways, the line will be isolated based on protection system operations are given as [9]:

i. The line is isolated or fault is cleared by primary protection of line ‘i’.

ii. The line is isolated by neighboring line of line ‘i’.

Any one of the side of two or more lines which are connected to one bus then those lines are said to be neighbouring lines.This event will occur because of protections system of line i that is failed to react or operate.This type of fault on line will affect the neighbouring lines.

The failure rate $\lambda_{FT1(i)}$ and repair time $r_{FT1(i)}$ respectively are given as [9]:

$$\lambda_{FT1(i)} = \lambda_i \, f/yr. \quad \text{....(1)}$$

$$r_{FT1(i)} = r_i \;\; hrs. \quad \text{....(2)}$$

Similarly, for Fault type 2, the failure rate $\lambda_{FT2(i)}$ and repair time $r_{FT1(i)}$ are given as [9]:

$$\lambda_{FT2(i)} = \left(\lambda_{FT2A(i)} + \lambda_{FT2B(i)}\right) f/yr. \quad \text{....(3)}$$

$$r_{FT2(i)} = U_{FT2(i)}/\lambda_{FT2(i)} \quad hrs. \quad \text{....(4)}$$

where, $U_{FT2(i)}$ is the unavailability of line i because of FT2 and it is evaluated as:

$$U_{FT2(i)} = \left(\lambda_{FT2A(i)} * r_{FT2A(i)}\right) + \left(\lambda_{FT2B(i)} * r_{FT2B(i)}\right) hrs./yr. \quad \text{....(5)}$$

Further, for Fault type 3, the failure rate

$\lambda_{FT3(i)}$ and repair time $r_{FT2A(i)}$ are given as [9]:

$$\lambda_{FT3(i)} = (\lambda_j * P_{MOPA(j)}) + (\lambda_k * P_{MOPB(k)}) \quad f/yr. \qquad ....(6)$$

$$r_{FT3(i)} = r_{Br} \ hrs. \qquad ....(7)$$

where, $P_{MOPA(j)}$ and $P_{MOPB(k)}$ are the probability of missing operation of protection unit of line 'i', to the either side i.e., A and B respectively.

Also for Fault type 4, the failure rate $\lambda_{FT4(i)}$ and repair time $\lambda_{FT4(i)}$ are given as [9]:

$$\lambda_{FT4(i)} = ((\lambda_j * P_{CPA(j)}) + (\lambda_k * P_{CPB(k)})) * (P_{UA(i)} + P_{UB(i)} - P_{UA(i)} * P_{UB(i)}) \ f/yr. \qquad ....(8)$$

$$r_{FT4(i)} = r_{Br} \ hrs. \qquad ....(9)$$

where, $P_{CPA(j)}$ is the conditional probability ofprotection unit of line 'j', which is the neighbouring line of 'i' at side Aand '$P_{UA(j)}$' and '$P_{UB(j)}$' are the probability of unwanted operation of protection unit of line 'i' at sides A and Brespectively.

However, the dependability of neighbouring line of a line failure has only been considered. The adjacent line to the neighbouring line and subsequent to its incident lines and so on has not been considered. These multiple failures can be represented using Cutsets and Probability Logic Diagram has been developed in this paper. Therefore, the expressions are developed for Fault type 4 using higher order dependable and security based failures.

Hence, the modified expression for failure rate for Fault type 4 is developed using conditional probability as:

$$\lambda_{FT4(i)} = \left(\sum_{j\varepsilon I} (\lambda_j * P_{CPA(j)})_j \right) * (P_{UA(i)} + P_{UB(i)} - P_{UA(i)} * P_{UB(i)}) \quad f/yr. \qquad ....(10)$$

Further, considering all the various types of faults as mentioned, Probability Logic Diagram has been developed and derived expressions for probability indices. Since all such fault types are mutually exclusive the Probability Logic Diagram (PLD) developed is as shown in Figure 1.

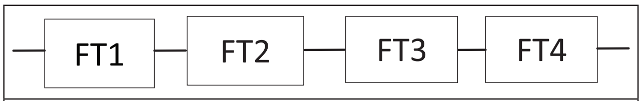

FIG 1. PLD COMBINING OF ALL FAULTS

The equivalent reliability indices i.e., failure rate ($\lambda_{eq(i)}$), repair rate ($r_{eq(i)}$) and unavailability ($U_{eq(i)}$) of line 'i'can be expressed as:

$$\lambda_{eq(i)} = (\lambda_{FT1(i)} + \lambda_{FT2(i)} + \lambda_{FT3(i)} + \lambda_{FT4(i)}) \ f/yr. \qquad ....(11)$$

$$U_{eq(i)} = (U_{FT1(i)} + U_{FT2(i)} + U_{FT3(i)} + U_{FT4(i)}) \quad hrs./yr. \qquad ....(12)$$

$$r_{eq(i)} = U_{eq(i)} / \lambda_{eq(i)} \quad hrs. \qquad ....(13)$$

3.0 MODELLING USING HIGHER ORDER CUTSETS

3.1 Case 2 of Fault type 1:

For higher order Cutset, there is a possibility of having neighbouring lines and for neighbouring lines fault at one line is enough for their isolation from the system because of failure operational modes of protection system i.e., Fault type-1 of one line in neighbouring line set will become Fault type-3 and Fault type-4 of remaining lines in the neighbouring line set of the Cutset.

Adding all Fault types of neighbouring lines individually in the Cutset reliability calculation will lead to involving failures of lines twice and in order to avoid adding the faults twice, the dependability term is incorporated in analysis. In the dependability term the two cases of Fault type-1 are incorporated.

3.2 Fault type 3 as case 1 of Fault type 1:

In Fault type-1, line fault occur on the line and it is isolated, that means it is isolated by its protection unit or by secondary protection unit which is a neighbouring line protectionunit i.e., it is the Fault type-3 of the neighbouring lines. So, it is considered as dependent event and the rate of occurrence of this event is developed as:

$$\lambda_{FT1cs1(i)} = (\lambda_j * \mathrm{P}_{MOPA(j)\ or\ B(i)})\, f/yr. \quad \text{....(14)}$$

The repair rate of this event is same as the switching time of the protection unit because it is the secondary protection operation and it comes to active when primary protection unit is identified and operated manually.

3.3 Fault type 4 as case 2 of Fault type 1:

The Fault type-4 is occurred when fault occur on the neighbouring line and it is cleared by its protection i.e., it is the Fault type-1 of the neighbouring line. So, Fault type-4 of a line is dependent on the Fault type-1 of neighbouring line. The rate of occurrence of this event is developed as:

$$\lambda_{FT1cs2(i)} = ((\lambda_j * \mathrm{P}_{CPA(j)}) * \prod_{j\varepsilon I}(\mathrm{P}_{UA(i)} + \mathrm{P}_{UB(i)} - \mathrm{P}_{UA(i)} * \mathrm{P}_{UB(i)}))\, f/y \quad \text{....(15)}$$

where,'I' is the set of neighbouring lines in the Cutset and C' is the common line for the different set of neighbouring lines in the Cutset. 'i' and 'j' are lines in the neighbouring line set 'I'.The repair rate of this event is same as the switching time of the protection unit because it is the secondary protection operation.

3.4 Dependent event calculation:

The value of the dependent event is the sum of the values of two cases of Fault type-1 each line in the neighbouring line set. It is developed as:

$$\lambda_{eq(i)} = \sum_{j\varepsilon I}(\lambda_{FT1cs1(i)} + \lambda_{FT1cs1(i)})\, f/yr. \quad \text{....(16)}$$

If Cutset contain more neighbouring line then it will be represented as, let i, j, k, l, x and y be the lines in the Cutset and (i, j, k), (k, l) and (x, y) are the neighbouring line sets. Let neighbouring line sets are represented as P, Q and S, where 'k' is the common line for P and Q sets and it is represented as C'. Then the Probability Logic Diagram for dependent term is as shown in Figure 2. The dependent event for each set is calculated and complete PLD is solved by using reliability network reduction technique i.e., series/ parallel event reduction technique.

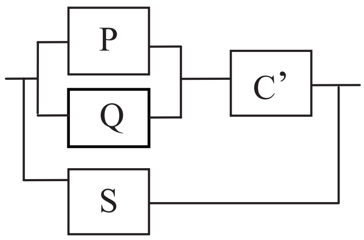

FIG 2. PLD FOR DEPENDENT EVENT

3.5 PLD for Cutset containing dependent event

The Cutset for the elements of i, j, k, l, x and y which contain dependent event 'd' is represented in PLD as shown in Figure 3.

The problem is solved by using basic parallel configuration technique where Fault type-2 only is considered for i, j, k, l, x and y, because the FT1, FT3 and FT4 comesunder dependent event (d) calculation. Based on the above expressions, the performance index Average Energy Not Supplied (AENS) can be expressed as:

AENS = (Average Annual outage time * Load at Load point) MWh./y. ....(17)

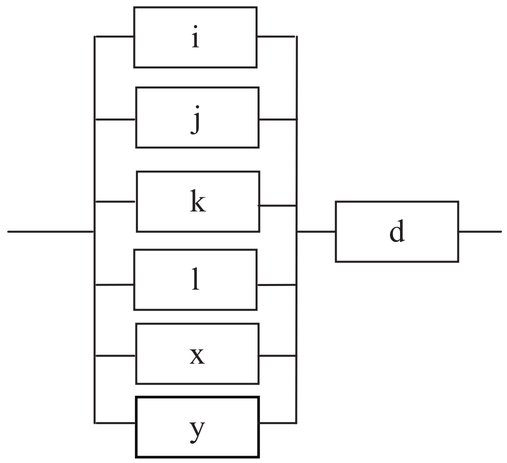

FIG 3. PLD FOR CUTSET CONTAINING DEPENDENT EVENT

Based on the above modelling, an algorithm is presented for evaluation of reliability indices using higher order Cutsets and is presented in next section.

4.0 ALGORITHM

The algorithm for calculating the reliability indices of power system containing dependent event is developed and given stepwise:

Step 1: Read line data, bus data and probability data of each line in the power system.

Step 2: Identify the number of load points (load buses) in the system. Let there be ‘n’ number of load of points.

Step 3: Develop the Path diagram for each load point ‘j’.

Step 4: Identify neighboring lines for every line in the system.

Step 5: Calculate the equivalent failure rate ($\lambda_{eq(i)}$), Mean outage time ($r_{eq(i)}$) and Annual outage time ($U_{eq(i)}$) of each line, where i=1 to total number of lines ‘L’ by combining the dependent and security based failures i.e., missing and unwanted operation of protection unit based on neighboring line sets using Eqns. (1) to (13).

Step 6: Obtain Cutsets for load point ‘j’ and analyze each Cutset:

Develop Probability Logic Diagram (PLD) if neighboring lines present in the Cutset, then add dependent event in the Cutset and calculate basic Probability indices using Eqns. (14) to (17) and go to step 7.

If neighboring lines not present in Cutset, then follow general Cutset procedure for evaluating basic Probability indices.

Step 7: Calculate the equivalent reliability indices for Cutset PLD of load point ‘j’.

Step 8: ‘j = j+1’. If ‘j $\leq$ n’ then go step 6. Otherwise go to step 9.

Step 9: Stop.

4.1 Illustration:

In this paper, IEEE 6 bus system in whichline data is given has been considered [1]. In order to find reliability indices for Load bus by incorporating dependability and security based failures, the MATLAB program is developed and is simulated by considering the 6-BUS system.

TABLE 1
EQUIVALENT LINE RELIABILITY INDICES FOR 6-BUS SYSTEM

Line no.	Failure rate (f/yr)	Repair time (hrs)	Unavailability (hrs/yr)
1	1.8062	8.6436	15.6125
2	5.4258	9.3722	50.8516
3	4.4941	9.1204	40.9883
4	1.5625	7.1201	11.125
5	1.255	8.3746	10.51
6	1.8062	8.6436	15.6125
7	5.4258	9.3722	50.8156
8	1.4941	7.3542	10.9883
9	1.1183	9.1535	10.2367

The equivalent failure rate, equivalent repair time and unavailability for each individual line using Eqns. (11) to (13) by considering dependent and security based failures are in Table 1. The equivalent failure rate, equivalent repair time and Average annual outage time which are obtained using Eqns. (14) to (17) for two methods viz., existing method and proposed method are presented in Table 2. It can be observed from Table 2, that the indices AENS and equivalent Failure rate increased as compared to the existing method and Mean outage time is decreased.

TABLE 2

LOAD POINT-1 RELIABILITY INDICES FOR 6-BUS SYSTEM

Reliability indices	Existing method	Proposed method
Equi. Failure rate (f/year)	1.0023	1.2285
Equi. Repair time (hrs.)	9.886	8.511
Annual outage time (hrs./year)	10.01	10.44
AENS (MWh/year)	200.228	208.9

5.0 CONCLUSIONS

In this paper, dependent and security based failures using higher order Cutsets has beenconsidered, whereas in the existing method, limited order of failure modes only are considered. An algorithm is developed for the proposed method which considers various fault types and explored using higher order Cutsets which includes neighbouring lines.This analysis enables the critical lines to be identified as higher order neighbouring Cutsets, where as in the existing method only a fewer order Cutsets have been considered. Thus, it is concluded that for realistic assessment all Cutsets have to be considered. Further, approximate system reliability analysis can be made for any system using Cutsets which is significant advantage in the predictive assessment.Probability Logic Diagrams are also developed using higher order Cutsets. MATLAB program has been developed and the results for a sample IEEE 6 bus system is simulated and compared with the existing method. The results show that for the same network with the same data considering higher order Cutsets will make the equivalent failure rate to increase, Mean outage time to decrease and Average annual Energy Not Supplied will increase.

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