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Loss of Offsite Power Probability Assessment using Fault Tree Analysis

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Abstract—The loss of offsite power (LOOP) probability is assessed using fault tree (FT) analysis. The method combines alternating current (AC) load flow analysis with FT technique. The probability of LOOP initiating event is assessed based on the unreliability of the power delivered to the house load of the nuclear power plant (NPP). Based on the quantitative and qualitative analysis of the constructed FT, the probability of the LOOP initiating event is assessed. The FT results include the importance measures which enable identification of the most important elements of the power system from the aspect of nuclear safety. The effect of modifications on the power system unreliability is evaluated. The verification of the method was performed on the IEEE test system.

Index Terms— LOOP, FT, NPP, power system unreliability.

1 Introduction

NPP safety and the power system reliability are mutually interdependent parameters. The safe operation of the NPP results in delivering a large amount of electrical energy to the power system and contributes to its stable operation. On the other side, the power system delivers the electrical energy to the house load of the NPP, which is especially important during the shutdown and the startup of the NPP. The LOOP initiating event occurs when all electrical power to the plant from electrical grid is lost. In spite of the fact that NPP is equipped with diesel generators in such emergency case, the safety of the NPP is decreased at the LOOP [1, 2]. The evaluation of the overall system unreliability is very complicated as it is necessary to include detailed modeling of both generation and transmission facilities and their auxiliary elements. A failure of components or subsystems can result in a failure of power delivered to specific loads or in certain cases in a full blackout of the power system. The goal of this paper is to assess the probability of the LOOP initiating event based on the unreliability of the power delivered to the house load of the NPP using FT analysis technique.

2 ReviewOfPreviousWork

Most of the approaches for the assessment of power system reliability use approximation or simplification of the problem in order to degrade the problem on a solvable level. Reliability assessment of auxiliary power supply and its impact on high voltage direct current (HVDC) link is performed by using FT analysis [3]. Statistical analysis of the LOOP registered in four reviewed databases is presented. The number of LOOP events in each year in the analyzed period and mode of operation are assessed [4, 5]. A case study of power station is considered for performing the FT analysis and the results are presented. The methodology adopted in the investigation is to generate FT for each load point of the power system [6]. FT technique based on generalized fuzzy numbers to a possibility distribution of reliability indices for power systems is described. All the failure probabilities are represented by generalized trapezoidal fuzzy number [7]. A real case study for the US Surry NPP which was touched down by tornado in 2011 causing the electrical switch yard destruction and LOOP is performed. A method for assessing initiating event LOOP probability are reviewed and improved. The probability is assessed and the current plant status and power system are compared to the plant status and power system status from years ago [8]. A survey on FT analysis in modeled using reliability assessment of an engineering system using Boolean algebra [9]. A new method for assessment of power system reliability is developed. The method integrates the FT analysis and the power flow model using direct current (DC) model [10-11].

3 Fault Tree Analysis

The FT analysis is a standard method for the assessment and improvement of reliability and safety [12-16]. It has been and it is applied in various sectors, such as nuclear industry. The FT analysis is an analytical technique, where an undesired state of the system is specified and then the system is analyzed in the context of its environment and operation to find all realistic ways in which the undesired event can occur. The undesired state of the system, which is identified at the top of the FT, is usually a state that is critical from a safety or reliability standpoint and is identified as the top event. Top event is therefore an undesired event, which is further analyzed with the FT analysis. The FT analysis is a term that combines the graphical model, which is called FT model, the qualitative analysis and the quantitative analysis (which includes the probabilistic failure data and the associated results).

The logical gates of the FT integrate the primary events to the top event. The primary events are the events that are not further developed, e.g., the basic events (BE). BE are the ultimate parts of the FT, which represent the undesired events and their failure modes, e.g., the component failures, the human errors, the unavailability because of the test and maintenance activities and the common cause failure (CCF) contribu-

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tions [17-19].

FT is represented mathematically by a set of Boolean equations. The qualitative analysis (in the process of Boolean reduction of a set of equations) identifies the minimal cut sets (MCS), which are combinations of the smallest number of BE, which, if occur simultaneously, lead to the top event.

The quantitative FT analysis represents a calculation of the top event probability, equal to the failure probability of power delivered to the corresponding load. The calculation of the top event probability (using rare event approximation) as:

$$Q_{GDi} = \sum_{i=1}^{n} Q_{MCSi} \qquad (1)$$

Where Q_{GDi} unreliability of the power delivered to the i-th load (top event probability of the respective FT). Probability of each MCS is calculated using the relation of simultaneous occurrence of independent events:

$$Q_{MCSi} = \prod_{i=1}^{m} Q_{B\,i} \qquad (2)$$

Where Q_{MCSi} is probability of minimal cut set i, m number of basic events in minimal cut set i, Q_{Bj} probability of the basic event *Bj* describing failure of the component (i.e. failure probability of component *Bj*).

The importance measures are divided in two groups. The first group consists of the measure that is called Fussell-Vesely Importance (FV) and gives fractional contribution of the BE to the system unreliability, the second group of the importance measures depicts the change of the system unreliability when the contributor's failure probability is set to 0 or 1. These importance measures are named Risk Increase Ratio (RIR) and Risk Reduction Ratio (RRR) [20]. The three important measures are defined as:

$$FV_K = 1 - \frac{U_{GDi}\,(U_k=0)}{U_{GDi}} \qquad (3)$$

$$RIR_K = \frac{U_{GDi}\,(U_k=1)}{U_{GDi}} \qquad (4)$$

$$RRR_K = \frac{U_{GDi}}{U_{GDi}(U_k=0)} \qquad (5)$$

Where:

FV_k :Fussell-Vesely importance for component k.

RIR_k : Risk Increase Ratio for component k.

RRR_k : Risk Reduction Ratio for component k.

$U_{GDi}(U_k= 0)$: Unreliability of the power delivered to the i-th load when unreliability of the component k is set to 0.

$U_{GDi}(U_k = 1)$: Unreliability of the power delivered to the i-th load when unreliability of the component k is set to 1.

4FAULT TREE CONSTRUCTION

In order to start with the FT analysis, the corresponding FT should be built first for each substation, which is connected to a load. Complexity of the substation depends on its configuration, number of generators, lines and loads connected into it.The FT structure corresponds to the configuration of the system and includes all possible flow paths of interruption of the power supply from generators to loads.

The next step in construction of the corresponding FT is identification of all the possible energy flow paths from the adjacency matrix of the corresponding power system. The six nodes system shown on Fig. 1, is presented as an example for the description of the method.

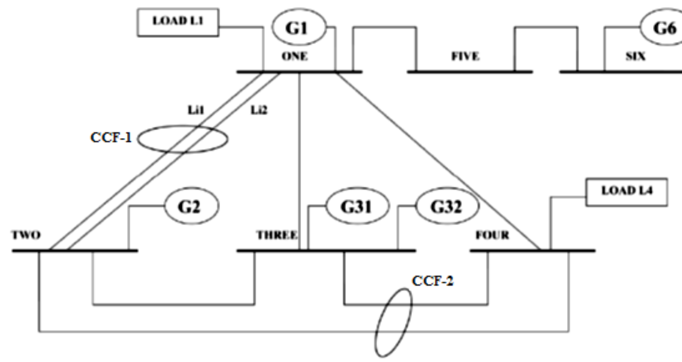

Fig. 1 Example of power system with 6 buses

The system consists of six substations, five generators in substations 1, 2, 3 and 6 and two loads in substations 1 and 4. There are multiple generators (two in substation three) and multiple lines (marked Li1 and Li2) between substations 1 and 2. The lines for which CCF are accounted are marked on Fig. 1, CCF-1 of lines due to the common tower and CCF-2 of lines that are assumed to be on a common right-of way for part of their length.

The adjacency matrix A of a simple graph is a matrix with the rows and columns labeled by graph vertices, with a 1 or 0 in position (v_i, v_j) according to whether graph vertices v_i and v_j are adjacent or not. The adjacency matrix A of an example system is given on Fig. 2.

$$\boldsymbol{A}=\begin{bmatrix} 0 & 1 & 1 & 1 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

Fig. 2 adjacency matrix A of an example system.

The next step is the identification of power flow paths between the load and other substations in system using the rooted tree. A rooted tree is a tree in which a labeled node is singled out. The rooted tree for substation 1 is given on Fig. 3-(a).

The identified flow paths of energy delivered between substations are tested for consistency as follows:

1. If there is overloaded line in the flow path, then that flow path is rejected.
2. If there is substation with a violated voltage in the flow path, then that flow path is rejected.

Test of overloaded lines in a flow path and voltages in the subs-

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tations is performed using AC load flow model, using load flow method all active and passive power flow in the lines and voltage magnitude and angle for each bus in the system in defined. In case of line overloaded above the thermal limits or any voltage magnitude exceed the limits (i.e. ± 5 % of rated value), then this branch or bus in not accepted in the FT construction.

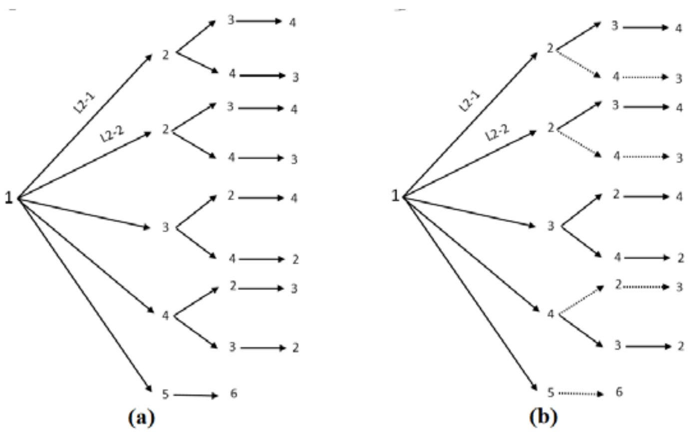

Fig. 3 (a and b) the rooted tree for substation 1.

Let the line 2-4 is overloaded for specific flow path corresponding to power delivered from substation 2 to substation 1 and the line 4-2 is overloaded for specific flow path corresponding to power delivered from substation 4 to substation 1, also voltage in substation 5 is lower than nominal in case of the failure of generator 6. In that case, only flow paths marked with the dark solid lines are accepted for FT construction. All other flow paths are discarded due to overload of the line or violated voltage, these lines are marked with dashed lines in Fig. 3-(b).

Flow paths accepted in previous test of consistency, are used in next step for the FT construction. Part of the FT for the load L1 of the example system, is created using the modular FT as shown in Fig. 4.

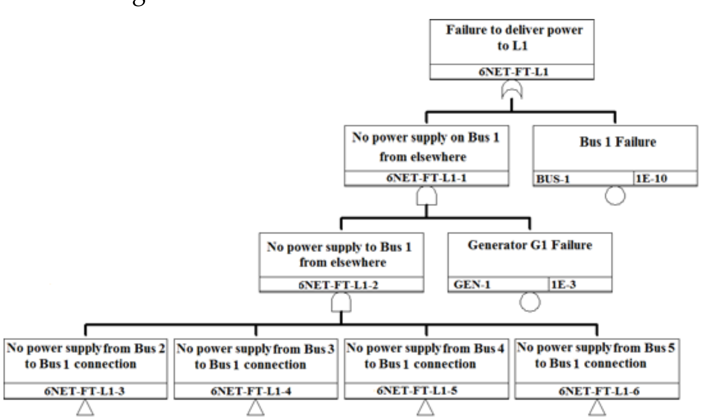

Fig. 4 part of the fault tree built for load L1.

5RESULTS

The verification of the method was performed on the IEEE One Area RTS-96 (Institute of Electrical and Electronics Engineers - Reliability Test System), consisting of 24 substations (17 substations directly connected to loads and 7 substations directly connected to generators), 32 generators and 38 power lines. For 14 lines, CCF are considered [21]. The IEEE reliability test system is specially designed to be used for different static and dynamic analyses and to compare the results obtained by different methods. Diagram of the IEEE One Area RTS-96 is given in Fig. 5.

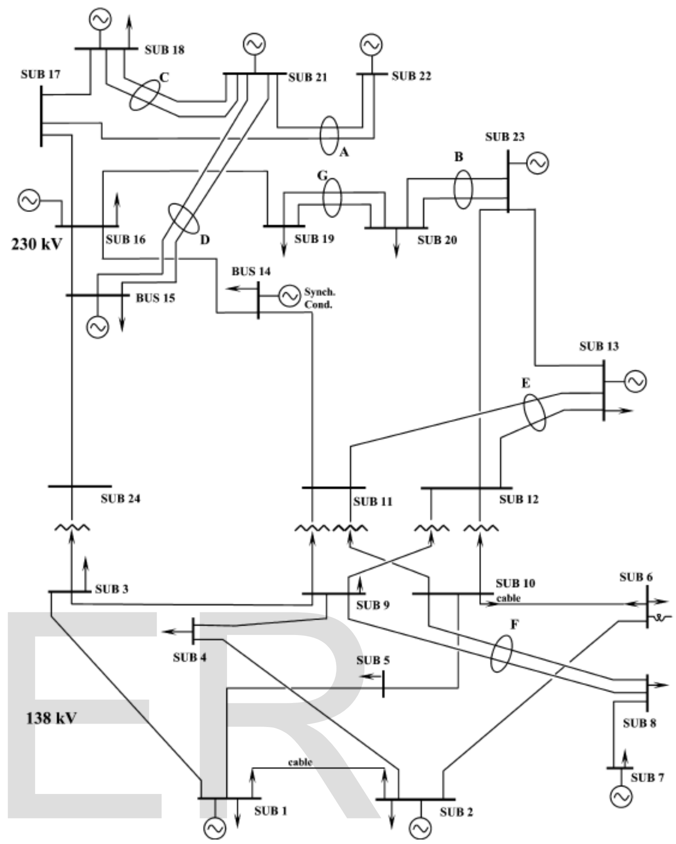

Fig. 5 IEEE one area RTS-96

The NPPs in the IEEE One Area RTS-96 are situated in the substations 21 and 18 allowing testing of the applicability of the method for estimation of the LOOP initiating event probability for the corresponding NPP. The load of size 20 MW was added in the substations 21 and18 in order to account house loads of the NPPs in the analysis. The available data for component reliability are used in the analysis [22].

The following results are obtained for the selected loads (loads 21 and 18):

- FT model and top event probability,
- Unreliability (i.e. LOOP initiating event probability),
- FV importance for all elements of the system,
- RIR for all elements of the system,
- RRR for all elements of the system and
- Unreliability comparison of several configurations with different modifications of the system.

In FT construction it is assumed that NPP generators (substation 21 and 18) can't run in house load operation mode (i.e. they can't supply their own load only). FT analysis is done using Systems Analysis Programs for Hands-on Integrated Reliability Evaluations (SAPHIRE-8) software [20].

The quantitative and qualitative results of the FT analysis are presented in the following tables:

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TABLE 1
IDENTIFIED MCS FOR POWER DELIVERED TO THE LOAD IN THE SUBSTATION 21.

#	Prob. /year	Cut Set
total	2.199E-7	Displaying 10 of 10 Cut Sets.
1	1.302E-8	GEN-15-6,GEN-16,GEN-18,GEN-21,LINE-21-22
2	9.216E-9	GEN-14,GEN-15-6,GEN-16,GEN-18,GEN-21,GEN-22-1
3	9.216E-9	GEN-14,GEN-15-6,GEN-16,GEN-18,GEN-21,GEN-22-5
4	9.216E-9	GEN-14,GEN-15-6,GEN-16,GEN-18,GEN-21,GEN-22-4
5	9.216E-9	GEN-14,GEN-15-6,GEN-16,GEN-18,GEN-21,GEN-22-3
6	9.216E-9	GEN-14,GEN-15-6,GEN-16,GEN-18,GEN-21,GEN-22-2
7	6.509E-9	GEN-15-1,GEN-16,GEN-18,GEN-21,LINE-21-22
8	6.509E-9	GEN-15-2,GEN-16,GEN-18,GEN-21,LINE-21-22
9	6.509E-9	GEN-15-3,GEN-16,GEN-18,GEN-21,LINE-21-22
10	6.509E-9	GEN-15-4,GEN-16,GEN-18,GEN-21,LINE-21-22

TABLE 2
IDENTIFIED MCS FOR POWER DELIVERED TO THE LOAD IN THE SUBSTATION 18

#	Prob. /year	Cut Set
total	6.505E-4	Displaying 10 of 10 Cut Sets.
1	5.760E-4	GEN-16,GEN-18,GEN-21
2	5.268E-5	CCF-LINE-18-21,GEN-18
3	9.763E-6	GEN-18,GEN-21,LINE-22-17
4	6.322E-6	GEN-18,GEN-21,LINE-17-16
5	5.789E-6	GEN-18,GEN-21,LINE-17-18
6	4.514E-9	SUB-18
7	1.397E-9	CCF-LINE-21-15,GEN-16,GEN-18,LINE-21-22
8	9.251E-10	GEN-16,GEN-18,LINE-21-18A,LINE-21-18B
9	7.949E-10	GEN-15-6,GEN-16,GEN-18,GEN-22-1,LINE-15-16
10	7.949E-10	GEN-15-6,GEN-16,GEN-18,GEN-22-2,LINE-15-16

Table (1) and (2) shows the ten most important MCS identified from the FT built for the loads in the substation 21 and 18 respectively, BE (GEN-21) corresponds to the failure of the generator in the substation 21, BE (GEN-15-6) corresponds to the generator 6 failure in substation 15, BE (GEN-18) corresponds to the failure of the generator in the substation 18, BE (SUB-18) corresponds to the failure of the substation 18. Line failures are identified with the BE (LINE-21-22) corresponding to the failure of the line between substation 21 and substation 22, BE (CCF-LINE-18-21) corresponds to the CCF of the lines between substation 18 and 21.

The top event for load 21 is 2.199E-7/year which corresponds to the probability of LOOP for that load. Similarly LOOP probability for load 18 is 6.505E-4/ year. The LOOP probability for load 18 is higher because it has less connections to the grid (thee transmission lines) compared to five transmission lines for load 21.

TABLE 3
BASIC EVENTS WITH THE LARGEST IMPORTANT MEASURES FOR LOAD 21

Name	FV	RIR	RRR	Description
GEN-21	9.789E-01	8.179E+00	4.738E+01	Gen. 21 Failure
LINE-21-22	2.093E-01	3.712E+02	1.265E+00	Line 21-22 failure
LINE-22-17	1.377E-02	2.129E+01	1.014E+00	Line 22-17 Failure
SUB-21	2.052E-02	4.547E+06	1.021E+00	SUB 21 Failure

TABLE 4
BASIC EVENTS WITH THE LARGEST IMPORTANT MEASURES FOR LOAD 18

Name	FV	RIR	RRR	Description
GEN-16	8.855E-01	2.225E+01	8.725E+00	Gen. 16 Failure
GEN-18	1.000E+00	8.329E+00	1.441E+05	Gen. 18 Failure
GEN-21	9.190E-01	7.738E+00	1.234E+01	Gen. 21 Failure
LINE-22-17	1.501E-02	2.311E+01	1.015E+00	Line 22-17 Failure

The largest important measures for loads 21 and 18 is given in tables (3) and (4) respectively. Table (3) shows that substation 21 has the largest FV, RIR and generator 21 has the largest RRR. Table (4) shows that line between substations 22 and 17 has the largest FV and RIR, and substation 18 has the largest RRR.

Several configurations of the IEEE test system are analyzed. The following table shows the effect of modification on the unreliability of power delivered to the selected loads, table (5) and Fig. (6) show the basic and different configurations added to the model. The modifications are as follows:
Case 1: adding a new generator (155 MW) at substation 17.
Case 2: adding new load (100 MW, 20 MVAR) at substation 17.
Case 3: adding new load (150 MW, 20 MVAR) at substation 22.
Case 4: adding a single line between substation 22 and substation 23.

TABLE 5
SUMMARIZED RESULTS FOR THE IEEE-RTS SYSTEM

Case Description	load 21 Prob./year	load 18 Prob./year
Basic configuration	2.20E-07	6.51E-04
Adding new generator at SUB 17	1.33E-08	8.22E-05
Adding new load at SUB 17	2.24E-07	6.51E-04
Adding new load at SUB 22	7.50E-06	6.51E-04
Adding new line between SUB 22 and SUB 23	7.78E-08	6.51E-04

Table (5) and Fig. (6 and 7) shows different unreliability for different configuration of the test system. The best configuration is adding a new generator at substation 17 which decrease significantly the LOOP probability for NPP at substations 21 and 18. On the other hand adding a new load at substation 22 increaseLOOP probability for NPP at substations 21.

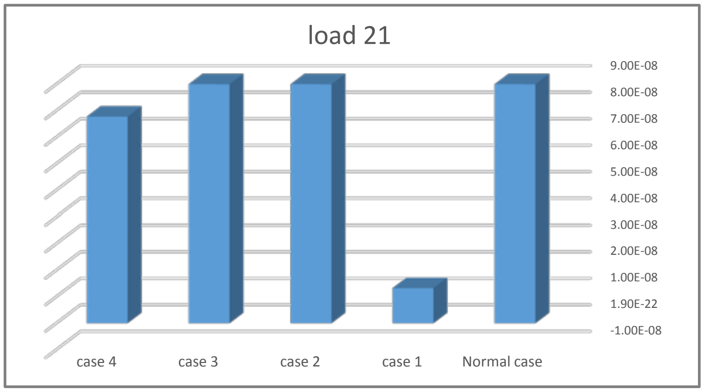

Fig. 6 Summarized results for the IEEE one area RTS-96 system (load 21).

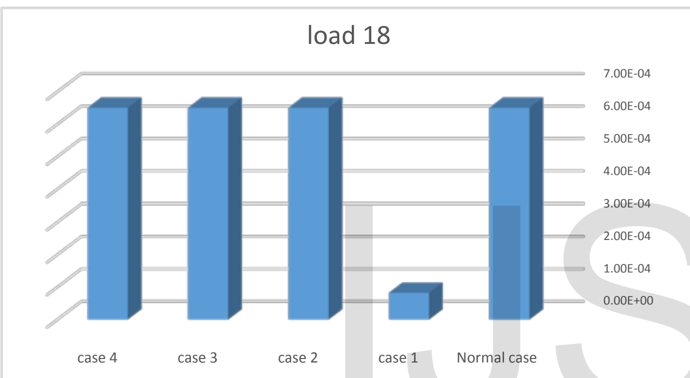

Fig. 7 Summarized results for the IEEE one area RTS-96 system (load 18).

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6 Conclusion

FT technique and AC load flow analysis are used to assess the probability of the LOOP initiating event based on the unreliability of the power delivered to the house load of the NPP. The results are qualitative and quantitative and they depend on the failure probabilities of the components, load flow and topology of the power system. The obtained results include identified MCS, unreliability of the power delivered to the corresponding loads and the importance measures of components corresponding to selected loads. results of both quantitative and qualitative help in focusing attention on those sections of a power system that contribute the most to the unreliability of power delivered to the house load of the NPP. The method is applied on IEEE one area RTS-96 test system. Several configurations of the test system and the effect of modification on the unreliability of the system are analyzed.

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