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ORIGINAL ARTICLE

Power system: a reliability assessment using FTA

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Abstract The Fault Tree Analysis (FTA) serves as a powerful tool for system risk analysis and reliability assessment. FTA is a top-down approach to failure analysis, starting with a potential undesirable event and then determining Base event (BE). The undesired state of the system is represented by the Top Event (TE). TE and BE are integrated through electronic logic gates (AND gate, OR gate). The fault tree is a tool to identify and assess the combinations of the undesired events in the control of system operation and its environment that can lead to the undesired state of the system. It is recognized worldwide as an important tool for evaluating safety and reliability in system design, development and operation. In this work, an efficient methodology is utilized to find out reliability assessment of critical and/or complex system. The main features and application of this technique for a power system are discussed. Minimal cut sets are developed by means of Boolean equation method. For main substation all CCF are considered at an average temperature of 35 °C. The objective of this work is to develop a method for power system reliability using the FTA approach. The methodology adopted in this investigation is to generate fault trees for each load point of the power system. This fault trees are related to disruption of energy delivery from generators to the specific load points. Quantitative evaluation of the fault trees represents a standpoint for assessment of reliability of power delivery and enables identification of the most important elements in the power system. The power system reliability is assessed and the main contributors to power system reliability are identified, both qualitatively and quantitatively.

Keywords Reliability · Fault tree analysis · Basic event · Top event · Minimal cut sets

1 Introduction

The power systems are usually large, complex and in many ways, it seems to be nonlinear systems. It includes subsystems and components such as generators, switching substations, power lines and loads. Further, Switching substations consist of buses, transformers, circuit breakers, relays and disconnect switches. Switching substations are important elements of power systems. A generator and/or a load can be connected to the switching substation. Switching substations are connected with power lines, through the power is transferred from generators and other switching substations to loads. Failure of the power systems are mainly due to line or substation failure. The substation failure is because of the substation component failures. Failure of components or subsystems can result in a failure of power delivery to specific loads or in certain cases in a full blackout of the power system. The need for analysis of power system reliability emerges from the aspect of the consequent terrorist threats on major infrastructures including the power systems. The power system is usually divided into generation, transmission and distribution functional zones.

The important methods used for power system reliability analysis are: (i) the stochastic process approach (Massim et al. 2005); (ii) the Monte-Carlo simulation technique

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(Massim et al. 2005); (iii) the Universal moment generating function (UMGF) approach (Y. Massim et al. 2006); (iv) multi-parameter gamma distribution (Singh and Chintaluri 1995); and (v) FTA (Matijevics and Jozsa 1995). The aim of this work is to find out the power system reliability using the FTA, one of the recent techniques adopted for this field. FTA is one of the most common techniques used for risk assessment and system reliability calculations and is commonly used in the process industries. In this paper fault tree technique is used to determine the reliability of the power system. In the fault tree the TE is divided into number of BEs. By knowing the probability of failure of the BEs, the probability of failure of the TE can be easily calculated.

2 Power system reliability

Reliability is the probability of a device or system performing its function adequately, for the period of time intended, under the operating conditions existing. The reliability of an electric supply system can be defined as the degree of assurance in providing the customers with continuous service of satisfactory quality (voltages and frequency within prescribed bounds). The fault tree is a tool to identify and assess the combinations of the undesired events in the context of system operations and its environments which can lead to the undesired state of the system (Vesely et al. 2002). The undesired state of the system is represented by a TE for this analysis. The failure probability of power delivery to *i*th load (Q_{GDi}) is calculated through the TE probability of the respective fault tree and the values of weighted failure probabilities of power delivery to loads are considered to get the overall measure of the power system reliability as (Volkanovski et al. 2009):

$$R_{ps} = 1 - \sum_{i=1}^{NL} \left(Q_{GDi} \frac{Ki}{K} \right) = 1 - Q_{PS} \tag{1}$$

where, R_{ps} is power system reliability; Q_{ps}, power system unreliability; Q_{GDi}, failure probability of power delivery to *ith* load (TE probability of the respective fault tree); *NL*, number of loads in the system; K_i, capacity of *ith* load; *K*, total capacity of the system; (*Ki*/*K*), weighting factor for *ith* load, *K* is given by: (Volkanovski et al. 2009).

$$K = \sum_{i=1}^{NL} (K_i) \tag{2}$$

The FTA is performed separately for each of the loads in the power system and the power system reliability is calculated.

3 Fault tree analysis

FTA is a top down approach to failure analysis (Vesely et al. 1981) and it is a basic method used in probabilistic risk assessment. It was first used by Bell Telephone Laboratories in connection with the safety analysis of the Minuteman missile launch control system in 1962 and this technique is improved by Boeing Company. The classic fault tree is mathematically represented by a set of Boolean equations. FTA is based on Boolean algebraic and probabilistic basis that relates probability calculations to Boolean logic functions. FTA is starting with a potential undesired event (accident) called a TE, and determining how the TE can be caused by individual or combined failures of BEs by connecting through logic gates (logic AND and logic OR gates) these symbols arrived from electronic logic diagrams (Javadi et al. 2011). The BEs are the ultimate parts of the fault tree, which represent the undesired events, e.g. the component or system failures. FTA attempts to model and analyze failure processes of engineering and biological systems (Alvehag 2008). This method is used for qualitative and quantitative analysis of the failures modes of critical systems. A fault tree is tailored to a particular failure of interest and it models only that part of the system which influences the probability of that particular failure. The failure of interest is called the TE. The TE is a box containing a description of the failure event of interest. The selected TE is usually described in terms of what event occurred. The fault tree breaks down the TE into lower-level events.

FTA procedure (Yang et al. 2009):

1. Select a top event for analysis.
2. Identify faults which could lead to the top event.
3. For each fault, list as many causes as possible in boxes below the related fault.
4. Draw the diagram of the fault tree.
5. Continue identifying causes for each fault until reach a root cause (reactive FTA), or one that can do something about (proactive FTA).
6. Consider countermeasures.

Simple rules to construct and analyze fault trees are (CCPS 2008):

1. Use an OR gate to express a failure caused by any of several possible lower level failures. The failure probability of the subsystem represented by an OR gate is the sum of the component failure probabilities.
2. Use an AND gate to express a failure caused only when all (usually two) lower level failures occur. The failure probability of a subsystem represented by an AND gate is the product of the component failure probabilities.

4 Minimal cut sets

A minimal cut set is a smallest combination of primary events or BEs, causing the TE. All the primary events must occur to cause the TE (Vesely et al. 2002). Each minimal cut set is a casual-combination, i.e. a combination of primary events. The set of minimal cut set directly link the TE to the primary events. The complete set of minimal cut set provides the complete set of causes of the TE. The failure probability is determined by using the equation (3). Hence, for calculating the failure probability it is essential to find the minimal cut sets of the given fault tree. The minimal cut sets can be calculated by the following two methods,

1. Matrix method and
2. Boolean equation method

The qualitative FTA (process of Boolean reduction of a set of equations) identifies the minimal cut sets, which are combinations of the smallest number of BEs, which, if occur simultaneously, may lead to the TE. The quantitative FTA represents a calculation of the TE probability equal to the failure probability of the corresponding load (Zhenjie Li et al. 2010). The TE probability Q_{GD} is given by (Volkanovski et al. 2009):

$$Q_{GD} = \sum_{i=1}^{n} (Q_{MCSi}) \quad (3)$$

where, Q_{CSi} is the probability of minimal cut set of *ith* load and is given by:

$$Q_{MCSi} = \prod_{j=1}^{m} Q_{Bj} \quad (4)$$

where, m is the number of BEs in minimal cut set i; Q_{MCSi} is probability of minimum cut set i; Q_{Bj-}, probability of the BE B_j describing failure of the component.

5 Discussion about power system reliability

The power systems are large, complex and in most of the cases usually seem to be nonlinear. Failure of the components or subsystems can result in the failure of power delivery to specific loads or in certain cases in a full blackout of the power system. For the case study, the Electric power system (refer Fig. 1.) available at National Institute of Technology, Tiruchirappalli, Tamil Nadu, India—620015 is considered for the analysis. The power system consists of A main substation directly connected to generator 1 (G1) and generator 2 (G2), power lines and four load stations. These loads are connected to the generators through circuit breakers (CB) and disconnect switches (DS). For main substation the Common Cause of Failures (CCF) are considered at an average ambient temperature (T_{amb-}) 35 °C in this analysis. The CCFs are failures of multiple equipment items occurring from a single cause that is common to all of them. The failure of multiple lines due to the severe weather conditions or earthquakes in a specified region can be considered as the CCFs. The fault tree structure corresponds to the configuration of the system and includes all possible flow paths of disruption of the power supply from generators to loads.

In order to start with the FTA, the corresponding fault tree should be built first for each connected to each load. Fig. 2 shows the fault tree structure corresponds to the configuration of the system and includes all possible flow paths of disruption of the power supply from generators to load 1. Normally open and closed states of DS and CB are assumed and modeled in the fault tree. The probability of failure of each component is given in Table 1. The substation generators and load capacities are mentioned in Table 2.

In the present case study, Fails to close (active state) and fails to remain closed (passive state) conditions are considered as two failure probabilities for building the fault

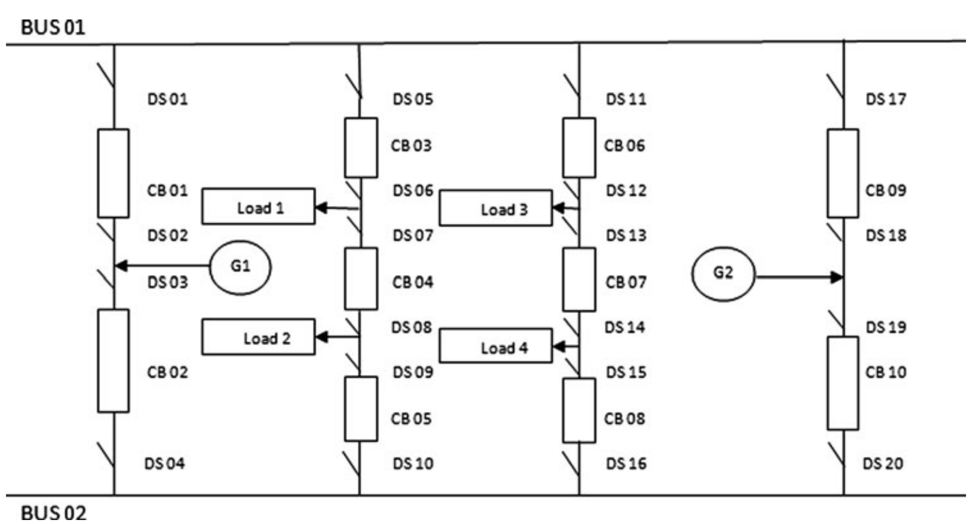


Fig. 1 Schematic representation of the main substation

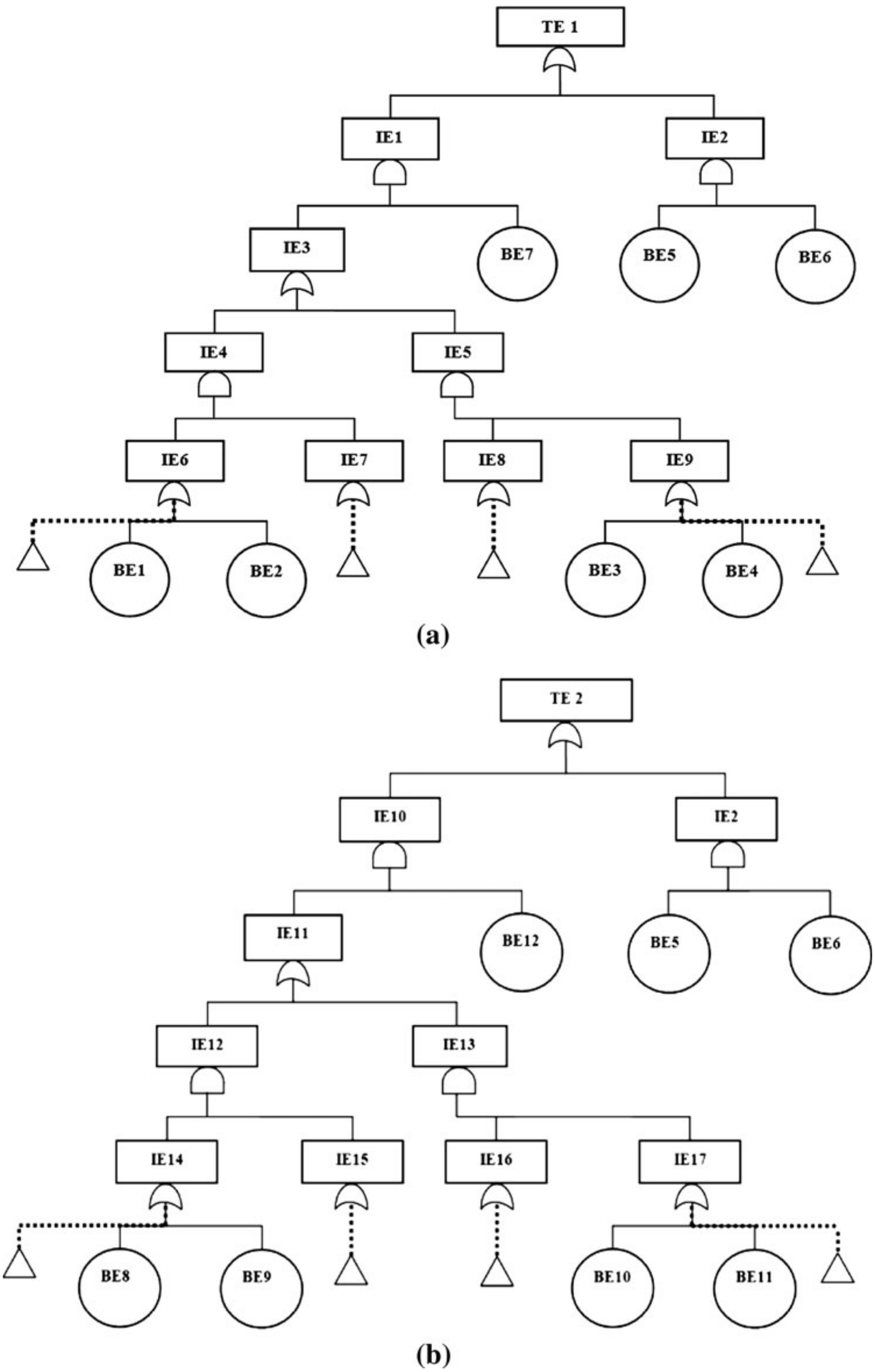


Fig. 2 Fault tree for **a** load failure 1 **b** load failure 2 **c** load failure 3 and **d** load failure 4

trees and reliability calculation of power failure to load. Fault tree for load 1, load 2, load 3 and load 4 failures are described in Fig. 2. In order to find out minimal cut set probability of failure at load 1, load 2, load 3 and load 4, *Boolean Equation Method* is adopted.

$$\mathrm{TE1} = \mathrm{IE1} + \mathrm{IE2}$$

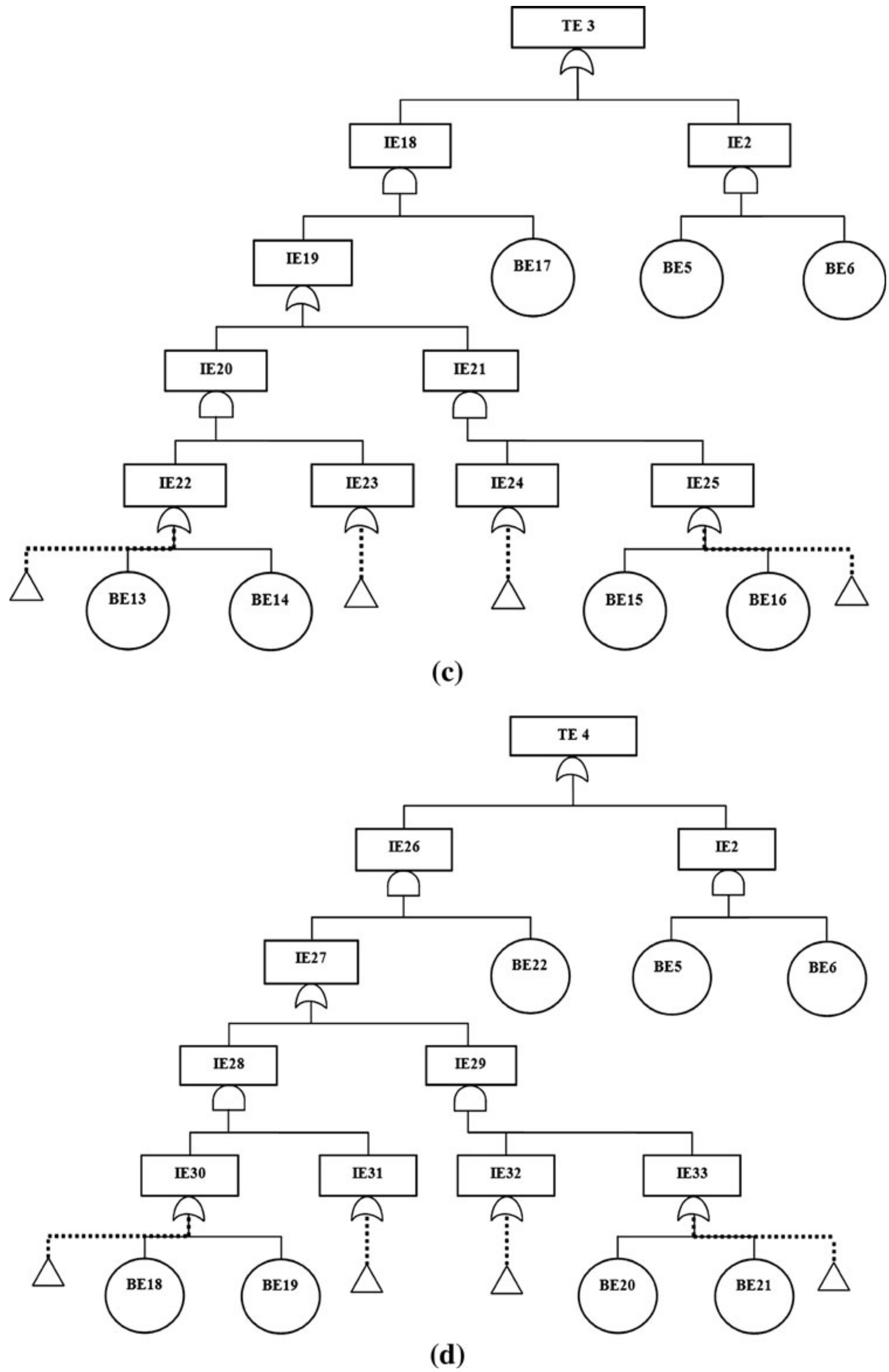
$$\mathrm{TE1} = (\mathrm{IE3} * \mathrm{BE7}) + \mathrm{IE2} \quad \text{(a)}$$

$$\mathrm{IE3} = \mathrm{IE4} + \mathrm{IE5}$$

$$\mathrm{IE3} = (\mathrm{IE6} * \mathrm{IE7}) + (\mathrm{IE8} * \mathrm{IE9})$$

$$\mathrm{IE3} = [(\mathrm{BE1} + \mathrm{BE2} + \mathrm{BE3} + \mathrm{BE4}) * \mathrm{IE7}] + (\mathrm{IE8} * \mathrm{IE9})$$

Fig. 2 continued



$$\mathrm{IE3} = \left[(\mathrm{BE1} + \mathrm{BE2} + \mathrm{BE3} + \mathrm{BE4}) * (\mathrm{BE1} + \mathrm{BE2} + \mathrm{BE3} + \mathrm{BE4})\right] + (\mathrm{IE8} * \mathrm{IE9})$$

Applying idempotence rules [Sinnamon and Andrews 1997] to the above equation:

$$\mathrm{IE3} = (\mathrm{BE1} + \mathrm{BE2} + \mathrm{BE3} + \mathrm{BE4}) + \left[(\mathrm{BE1} + \mathrm{BE2} + \mathrm{BE3} + \mathrm{BE4})\right] * (\mathrm{BE1} + \mathrm{BE2} + \mathrm{BE3} + \mathrm{BE4})$$

$$\mathrm{IE3} = (\mathrm{BE1} + \mathrm{BE2} + \mathrm{BE3} + \mathrm{BE4}) + (\mathrm{BE1} + \mathrm{BE2} + \mathrm{BE3} + \mathrm{BE4})$$

Table 1 Component failure probability

Component	Failure probability
Circuit breaker (fails to close)	8.14E−05
Circuit breaker (fails to remain closed)	6.16E−06
Disconnect switch (fails to close)	4.09E−06
Disconnect switch (fails to remain closed)	6.16E−07
Line failure	2E−1
Generator G1 (250KVA)	1.2E−01
Generator G2 (200KVA)	1.0E−01

Table 2 Component and its capacity

Component	Capacity (KVA)
Load 1	125
Load 2	100
Load 3	75
Load 4	100
Generator G1	250
Generator G2	200

$$IE3 = (BE1 + BE2 + BE3 + BE4) \quad (b)$$

$$IE2 = (BE5 * BE6) \quad (c)$$

Substituting the values of equation (b) and (c) in (a)

$$TE1 = [(BE1 + BE2 + BE3 + BE4) * BE7] + (BE5 * BE6)$$

$$TE1 = (BE1 * BE7) + (BE2 * BE7) + (BE3 * BE7) + (BE4 * BE7) + (BE5 * BE6) \quad (d)$$

where, TE represents the TE, IE represents intermediate events, BE represents the BEs. From above expression, the products are correspond to the cut sets of the fault tree, here there are 5 cut sets of order two, i.e. {1,7}, {2,7}, {3,7}, {4,7} and {5,6}. Similarly by applying *Boolean Equation Method* to fault tree load 2 failure (refer Fig. 2.b), load 3 failure (refer Fig. 2.c) and load 4 failure (refer Fig. 2.d), equation (e) (f) and (g) are obtained respectively. Each expressions contains five cut sets of order two, i.e. [{8,7}, {9,7}, {10,7}, {11,7}, {5,6}], [{13,7}, {14,7}, {15,7}, {16,7}, {5,6}] and [{18,7}, {19,7}, {20,7}, {21,7}, {5,6}].

$$TE2 = (BE8 * BE7) + (BE9 * BE7) + (BE10 * BE7) + (BE11 * BE7) + (BE5 * BE6) \quad (e)$$

$$TE3 = (BE13 * BE7) + (BE14 * BE7) + (BE15 * BE7) + (BE16 * BE7) + (BE5 * BE6) \quad (f)$$

$$TE4 = (BE18 * BE7) + (BE19 * BE7) + (BE20 * BE7) + (BE21 * BE7) + (BE5 * BE6) \quad (g)$$

5.1 Failure probability and system reliability:

5.1.1 Failure probability

Probability of each minimal cut set (Q_{MCSi}) is calculated using the relation of simultaneous occurrence of independent events. The equation (4) is used to find out the probability of each minimal cut set. For load 1, *i* vary from 1 to 5.

Therefore,

$$Q_{GD1} = \sum_{i=1}^{5} (Q_{MCSi})$$

$$Q_{MSC1} = BE1 * BE7$$

$$Q_{MSC1} = 6.16E - 7 * 2E - 1 = 1.232E - 7$$

$$Q_{MSC2} = BE2 * BE7$$

$$Q_{MSC2} = 6.16E - 6 * 2E - 1 = 1.232E - 6$$

$$Q_{MSC3} = BE3 * BE7$$

$$Q_{MSC3} = 4.09E - 6 * 2E - 1 = 8.18E - 7$$

$$Q_{MSC4} = BE4 * BE7$$

$$Q_{MSC4} = 8.14E - 5 * 2E - 1 = 1.628E - 5$$

$$Q_{MSC5} = BE5 * BE6$$

$$Q_{MSC5} = 1.2E - 1 * 1E - 1 = 1.2E - 2$$

So the Failure probability of power delivery to load 1,

$$Q_{GD1} = Q_{MSC1} + Q_{MSC2} + Q_{MSC3} + Q_{MSC4} + Q_{MSC5} = 1.20184532E - 2$$

Since all the BEs are having same probability of failure to deliver the load. Q_{GD2}, Q_{GD3} and Q_{GD4} are equal and are calculated as 1.20184532E−2.

$[(Ki)/K]$, the Weighing factor for each of the load is calculated as follows

Weighing factor for load1 = 125/450 = 2.7778E−1
Weighing factor for load2 = 100/450 = 2.2222E−1
Weighing factor for load3 = 75/450 = 1.6667E−1
Weighing factor for load4 = 100/450 = 2.2222E−1

5.1.2 System reliability

The power system reliability is calculated by using the equation (1).

Therefore the reliability of the power system,

$$R_{ps} = 1 - \sum_{i=1}^{4}\left(Q_{GDi} * \frac{\mathrm{Ki}}{\mathrm{K}}\right) = 0.98931$$

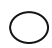
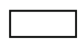
6 Results and discussion

A case study of power station available at National Institute of technology, Trichy is considered for performing the FTA and the results are presented in this work, which consists of a substation, two generators, power lines and four load points. For substation all CCF are considered at an average temperature of 35 °C. The methodology adopted in this investigation is to generate fault trees for each load point of the power system. This fault trees are related to disruption of energy delivery from generators to the specific load points. Probabilities of failures of DS and CB close to open and remains close to open conditions in the lines are included in the calculation of system reliability. In order to find out smallest combination of primary events or BEs causing the TE, Boolean equation method is applied. The Boolean equation seems to provide an alternative technique to efficiently analyze fault trees. For this particular case, there are five minimal cut sets, each with order of two (maximum of two BEs in each minimal cut sets) is obtained. The Minimal Cut Sets give all the unique combinations of component failures on system failure. The results are analyzed in both qualitative and quantitative manner. Qualitative analysis involves obtaining the various combinations of events and quantitative analysis involves calculating the probability of failure of TE as well finding out reliability of system. Both quantitative and qualitative results help in focusing attention on those sections of a power system which contributes the most to the unreliability of power delivery to specific load. Total reliability of power system is found to be **0.98931**, which is directly depends on the failure probabilities of BE. The presented method can be helpful for the reliability design of the nuclear plants, high capacity plants, traffic, gas storage yards and other critical infrastructures which have similar topology as the power system.

7 Conclusion

An efficient methodology is used to find out reliability assessment of critical and/or complex system. A method for assessment of power system reliability is developed using FTA. The result depends on the failure probabilities of the components and on the flow lines in the power system. By keeping the fault trees simple and employing simplifying assumptions such as the rare event approximation, fault trees can easily be analyzed with hand calculations. FTA is critical steps in ensuring limited resources are best applied. Even though the unavailability's of individual components are approximate, FTA gives useful order of magnitude results.

Appendix Nomenclature and abbreviations

Symbol	Event
Q_{GDi},	The failure probability of power delivery to *ith* load
R_{ps},	Power system reliability
Q_{ps},	Power system unreliability
K_i,	Capacity of *ith* load
K	Total capacity of the system
R_{ps}	Reliability of the power system
	AND gate
	OR gate
	Basic event
	Top & intermediate event
	Transfer gate
DS	Disconnect switch
CB	Circuit breakers
NL,	Number of loads in the system
TE1, TE2, TE3 and TE4	Power failure to load 1, load 2, load 3 and load 4 respectively.
IE1, IE 10, IE18 and	Failure to deliver energy from generators and lines to load 1, load 2, load 3 and load 4 respectively.
IE26	Failure of energy delivery from generators to lines
IE3, IE11, IE19 and IE27	Failure of generators to load 1, load 2, load 3 and load 4 due to substation component failure respectively.
IE4, IE12, IE20 and IE28	Failure of energy delivery from generator 1 (G1) to load1, load 2, load 3 and load 4 respectively.
IE5, IE13, IE21 and IE29	Failure of energy delivery from generator 2 (G2) to load, load 2, load 3 and load 4 respectively.
IE6, IE14, IE22 and IE30	Failure of energy deliver from G1 to load 1, load 2, load 3 and load 4 through Bus 01 respectively.
IE7, IE15, IE23 and IE31	Failure of energy deliver from G1 to load 1, load2, load 3 and load 4 through Bus 02 respectively.
IE8, IE16, IE24 and IE32	Failure of energy deliver from G2 to load1, load2, load 3 and load 4 through Bus 01 respectively.

Appendix continued

Symbol	Event
IE9, IE17, IE25 and IE33	Failure of energy deliver from G2 to load1, load 2, load 3 and load 4 through Bus 02 respectively.
BE1, BE8, BE13 and BE18	DS06, DS08, DS12 and DS14 fails to remain closed respectively.
BE2, BE9, BE14 and BE 19	CB03, CB04, CB06 and CB07 fails to remain closed respectively.
BE3, BE10, BE15 and BE 20	DS07, DS09, DS13 and DS15 fail to close respectively.
BE4, BE11, BE16 and BE 21	CB04, CB08, CB07 and CB05 fail to close respectively.
BE7, BE12, BE17 and BE22	Failure of lines to load 1, load 2, load 3 and load 4 respectively.
BE5	Failure of generator 1
BE6	Failure of generator 2

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