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Fault Tree Analysis of Failures in Fire Detection System of Grid Connected Photovoltaic System

E. Suresh Kumar, Bijan Sarkar

Abstract— The reliability of the grid connected photovoltaic system is primarily and strongly depends on the reliability of the electrical protection systems, failure of which may lead to fire. So a fire detection system is the crucial component in a grid connected PV system. So its reliability is directed related to the overall reliability of the PV system. A literature review of reliability data of fire detection system was made resulting to rough estimates of some failure frequencies. No theoretical or technical articles on the structure of reliability models of these installations were found. In this paper the classifications of failure severity were made from the system point of view by counting failures of components when possible. Since there are no established fault tree structures available for fire detection system in photovoltaics, these component failure frequencies are intended to be used in the first round of iteration in the fault trees suggested here. The analysis leads to the necessity of the estimation of reliability of fire detection system for the assessment of the reliability of the grid connected photovoltaic power system.

Keywords: Fault tree analysis, Top event, Reliability, Fire detectors, Boolean input.

I. INTRODUCTION

PV systems are unusual in that the energy source cannot be switched off. If there is daylight falling on a PV panel it will produce electricity and it is possible for a relatively small array of only a few panels to deliver a lethal shock. Another important point is that PV panels generate DC voltage, which is not always commonly used by electricians in their normal work. In addition, because of the current limiting properties of PV cells, they are incapable of producing sufficient fault currents to operate over-current protection devices such as fuses. Once established a fault may remain undetected, not only posing a hazard for an extended period, but also wasting valuable energy generated by the PV system.

In many cases simple electrical faults or wiring failures can therefore cause a serious inefficiency in the ability of the system to produce power [1]. In this way undetected faults may also develop into a fire hazard over time. Without fuse protection against such faults, elimination of a fire risk can only be achieved by both good system design and careful installation alongside appropriate electrical inspection and testing. Fire detection and alarm system is an installation, which notifies promptly of fire ignitions as well as the most modern installations on other adverse conditions and trouble decimating the performance of the system.

The Fault tree analysis (FTA) [2] is a top-down approach to failure analysis, starting with a potential undesirable event (accident) called a TOP event, and then determining all the ways it can happen.

The analysis proceeds by determining how the TOP event can be caused by individual or combined lower level failures or events. The causes of the TOP event are “connected” through logic gates. The aim of fault tree analysis is to provide a probabilistic framework that allows a risk-based approach to fire safety. The aim is to systematically generate fire scenarios based on the set up of the photovoltaic system, including the fire safety systems. Each of these scenarios comes with a probability that determines its fire risk. The total fire risk of the grid connected PV system is then given by [3]

$$R=\sum_{i=\sigma}^{n} PiCi$$

- Equation 1

where σ denotes the set of all scenarios, pi is the probability for scenario i, and Ci is a measure of the consequences (or cost) of this scenario (e.g. loss of life). In theory, this sum runs over all possible scenarios. In practice, however, it is impossible to consider all scenarios, and hence one has to preselect. In particular, all scenarios with low probability and low cost would be excluded.

II. QUALITATIVE AND QUANTITATIVE ASSESSMENT

The qualitative assessment is made by investigating the minimal cut sets [4]: The following steps are involved. Order of the cut sets. Ranking based on the type of basic events involved 1. Human error (most critical), 2. Failure of active equipment, 3. Failure of passive equipment.

Rank	Basic event 1	Basic event 2
1	Human error	Human error
2	Human error	Failure of active unit
3	Human error	Failure of passive unit
4	Failure of active unit	Failure of active unit
5	Failure of active unit	Failure of passive unit
6	Failure of passive unit	Failure of passive unit

Let Qo(t) = Pr(The TOP event occurs at time t) qi(t) = Pr(Basic event i occurs at time t), Qj(t) = Pr(Minimal cut set j fails at time t). Let Ei(t) denote that basic event i occurs at time t. Ei(t) may, for example, be that component i is in a failed state at time t. Note that Ei(t) does not mean that component i fails exactly at time t, but that component i is in a failed state at time t. A minimal cut set is said to fail when all the basic events occur at the same time [5].

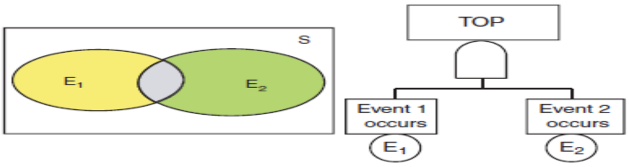

Figure 1 : Venn diagram and fault tree representation of two events.

Let Ei(t) denote that event Ei occurs at time t, and let qi(t) = Pr(Ei(t)) for i = 1, 2.

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When the basic events are independent, the TOP event probability Q0(t) is Q0(t) = Pr(E1(t) \ E2(t)) = Pr(E1(t)) · Pr(E2(t)) = q1(t) · q2(t). When we have a single AND-gate with m basic events, we get

$$Qo(t) = \prod_{j=1}^{m} qj(t)$$

A minimal cut set fails if and only if all the basic events in the set fail at the same time. The probability that cut set j fails at time t is

$$Qj(t) = \prod_{i=1}^{r} qj,i(t)$$

where it is assumed that all the r basic events in the minimal cut set j are independent.

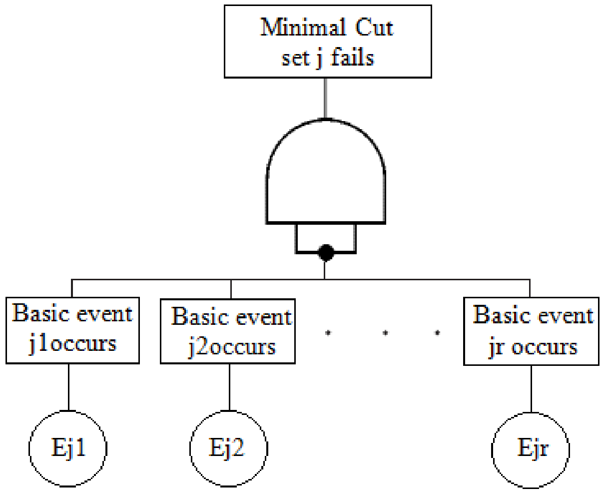

Figure 2 : Minimal cut set representation from basic events.

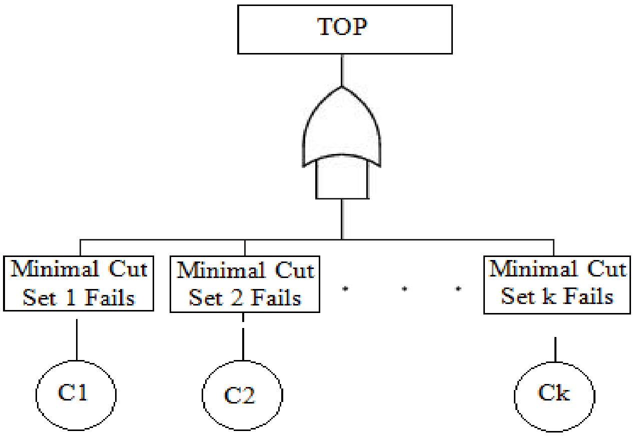

Figure 3 : Minimal cut set failure to TOP event failure.

The TOP event occurs if at least one of the minimal cut sets fails. The TOP event probability is [6]

$$Qo(t) <= 1 - \prod_{j=1}^{k} (1 - Qj(t) \quad \text{- Equation 2}$$

The reason for the inequality sign is that the minimal cut sets are not always independent. The same basic event may be member of several cut sets. Equation 2 is called the Upper Bound Approximation.

Using fault tree analysis predictions for the failure probability or the failure frequency of the system (top event) can be made [7]. Here the top event probability is considered. Having obtained the minimal cut sets the top event logic equation can be expressed as the disjunction (OR) of the NC minimal cut sets, Ci. The system failure probability, Qsys, is then the probability of this disjunction:

$T = C1 + C2 + \dots + C_{Nc}$ - Equation 3

$Qsys = P(T) = P(C1 + C2 + .. + C_{Nc})$ - Equation 4

Basic structure of fire detection and alarm systems is given in Figures 1 to 3. The main components of the system are control unit, initiating devices, manual fire alarm boxes, notification appliances, main and standby power supplies, wiring of the alarm circuits, signalling line to municipal central station, and installation layout charts (Wilson 1997). The oldest systems, where alarm is caused by opening or shunting a alarm circuit, are not shown, because they are no more installed. In more modern installations one or several alarm initiating device circuits are connected to a control unit. One circuit covers a certain part of a building, on which all initiating devices in that area are connected. In local-energy type alarm system initiating devices are galvanically connected to a two-wire circuit,

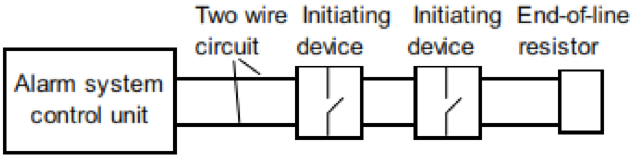

Figure 1: Principal structure and components of a stub line.

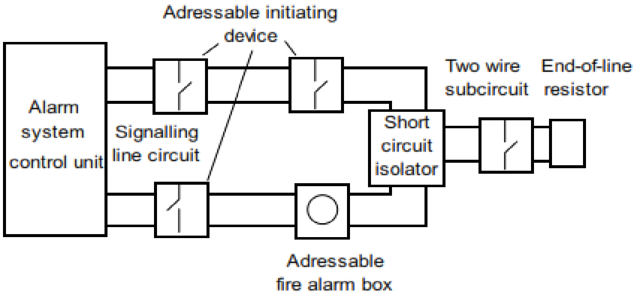

Figure 2: Principal structure and components of a loop line fire detection and alarm system with a stub line sub circuit.

Which has an end-of -line resistor. The circuit operates on non-energized principle. Triggering of an initiating device mechanically or electrically shunts this line causing an alarm.

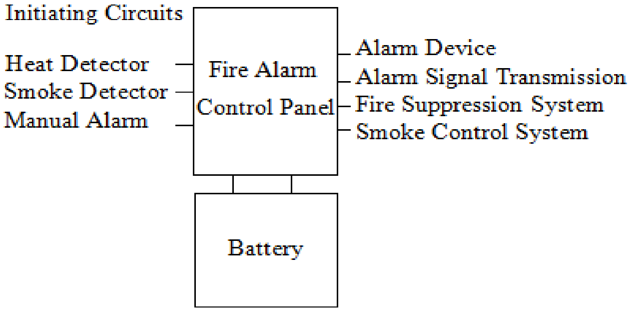

Figure 3: Principal structure of a fire detection and alarming system with alarm transmission, notification devices and control signals to auxiliary fire protection systems.

In systems with signalling line circuits initiating devices are addressable and two-way communication takes place. Control panel electronics polls out periodically at a proper frequency the status of the device: operation, service, trouble, fire. Although the devices may be connected physically to the same electrical circuit, they can be programmed into arbitrary configurations of groups. Installation layout charts are floor plan drawings of the building indicating the location of alarm control panel, access routes, and locations of alarming devices or circuits. These layout charts make possible quick location of fire in the building. Fire alarm system control unit/panel notifies fire ignition ant its location, monitors system condition, supervises actions needed or auxiliary devices, and transmits alarm to the facility/central station. Systems with signalling line circuits have usually a central computer controlled supervisory panel, into which one or multiple fire alarm panels are connected.

III. RELIABILITY MODELLING OF THE SYSTEMS

From the reliability point of view the fire detection system differs from many of the more common systems, because it is distributed in space or rather area wise [8]. If observe a pump: there is a definite place for material intake, and another for output. If the pump cannot move material between these two well defined locations when required, pump fails. A fire alarming system is a multiple entry ’pump’. If one detector does not respond, there is often another possibility through a neighbouring detector, like a pump, which is feeded from several independent inlets. The response through these neighbouring channels is generally more delayed and might be of lower probability than through the detector closest to ignition.

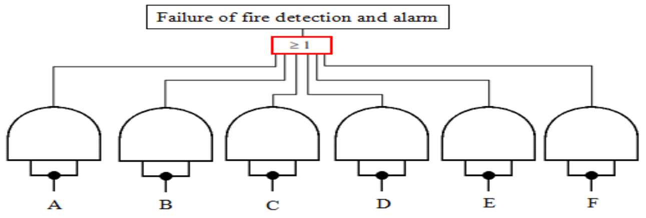

Figure 4 : Fault tree of fire detection and alarming system divided into six subunits by cause of failure.

The Boolean inputs represent the following events. A : Detector failure, B : Failure of alarm system component, C : Signal communication subsystem failure, D : Failure in auxiliary control subsystem, E : Power supply failure, F : False alarm.

Evaluating the performance of fire alarming installation it could have two viewpoints [9]: (i) from the operation of the system, and (ii) from the success of a single alarming mission. Failure of the mission (ii) is at least a partial failure of item (i). In this survey the major viewpoint has been item (ii) to locate critical paths in the success especially as regards performance of single components. In evaluating the performance of the system for the relevance of nuclear safety, the viewpoint must be item (i). In evaluating its performance further modelling is needed to transform a distributed system to a effective simpler system, where local failures of item (ii) are given weights relative to their areas of influence in the total system. This modelling can be made only after we have some preliminary quantitative information from item (ii). In contrast to sprinkler installations (Rönty et al. 2004), which is also a distributed system [10], there are not yet available statistical data, which tells, how many detectors respond to a single fire.

From viewpoint (ii) looking a single fire event in a given location close to an initiating device successful fire detection and alarming requires faultless operation of a number of components coupled in series. Therefore, for assessing the failure of the mission, a ’fault three’ through an OR gate results as given in Figure 4. This tree is for demonstration of the dependencies, and not strictly a fault tree in the mathematical sense, since the number of components in various branches or even within a branch are not the same. Once some numerical values of some component or subsystem performance are available, approximate real fault trees can be built. The same also applies to all other ’fault trees’ presented later in this paper. From left to right in Figure 4 the six subsystems are: (1) detector failure (Det), (2) failure of alarm system component (Comp), (3) signal communication subsystem failure (Comm), (4) failure in auxiliary control subsystems (Control), (5) power supply failures (PS), and (6) failures resulting in false alarms (False).

Each of these six subunits can be divided further down. Guided by statistics available the first guess was to include one or two more levels as indicated in detail in Figures 5 to 12. In fire detection systems the most common component is the initiating device, fire detector. The most common failure is a dirty smoke detector. Dust and other dirt accumulates on smoke detectors requiring cleaning at given intervals. The addressable fire detectors have a built-in calibration, which maintains detector sensitivity despite soiling and dirt.

This modelling of the systems is the first guess and first round in a series of approximations needed. It is mainly intended to represent in a graphical way the complicated groups of failures in the systems. Since there is quite a variation in the electrical and electronic structure of the systems, it is not feasible to try a detailed modelling of the system availability starting from discrete components coupled to each other according to circuit diagrams. Instead, an average way of presentation is attempted, where the smallest subunits are some functional parts of the system. How far in detail this modelling is possible or rather feasible, depends on available statistical data. Borrowing mathematical terms the fault trees presented here are an ansatz in the first round of iteration. Once failure frequencies of the proposed subunits have been determined from statistics, the fault trees has to be redesigned for engineering purposes taken the statistical material available. This type of modelling does not include all the deterministic information in the systems potentially available, but tries to reach the practical level of detail, which is limited by statistical information of the failure causes.

The Boolean inputs represent the following events. A1 : Contaminated in use, B1 : External cause / faulty position, C1 : Damaged in use, D1 : Unknown Cause, E1 : Technical Failure, F1 : Mechanical Failure, G1 : Opened/leaking sprinkler head, H1 : Space damp.

The subunits of detector failure in Figure 5 are (1.1) dirty, (1.2) faulty, and (1.3) wet detector. These are again divided into two to four subunits as given in the fault tree boxes. In the raw material division was made down to this level, if need information was available. Since the number of failure was a few hundreds per system at maximum division to this third level turned out to be too fine a division. Thus here we summaries including the first two levels only. Going further towards viewpoint

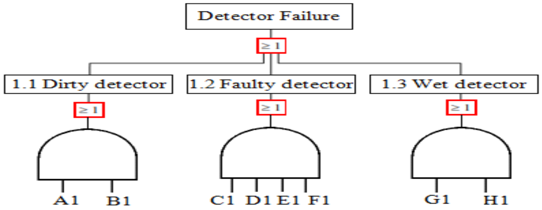

Figure 5 : Fault tree of detector failure.

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(i) detector failure fault tree of Figure 5 should be modified to allow several parallel detectors.

Failures of alarm system 'components' shown in Figure 6 include failures of all components of the system except detectors, which is a separate subunit, and failures of cables, which are included in communication failures of Figure 7. The subunits are (2.1) mechanical failures in control panel, (2.2) electrical or electronic component failures (including programming failures) in control unit, and (2.3) failures in manual initiating devices. Again a third level is indicated in Figure 6 and used in sorting original data, but is not reported for the same reason as given above. Ageing is one contributor to 'component' failures, which is observed especially for manual fire alarm boxes, and various indicating bulbs.

The Boolean inputs represent the following events. A2 : 2.1.1 Mechanical damage, B2 : 2.1.2

Door switch/lock damaged, C2 : 2.2.1 Electronic failure, D2 : 2.2.2 Initiating circuit, E2 : 2.2.3 Alarm notification, F2 : 2.2.4 Indicator light bulb

G2 : 2.3.1 Technical failure, H2 : 2.3.2 Mechanical failure.

In Figure 7 signal communication failures are divided into five subgroups: (3.1) wire/cable failure, (3.2) no/bad connection to a detector, (3.3) announcement forwarding, (3.4) removed circuit, and (3.5) ground short. For the third level the same comments as above. Communication failures in Figure 7 include wire/cable failures, which in old alarm circuits lead easily to critical failures. In addressable systems part of the alarm circuits have been replaced by a network of cables. Therefore, loss of one cable does not necessarily mean a severe failure in the system. For that part the fault tree of Figure 7 is not quite right. It is not changed either, because it is easier to take that phenomenon into account by classifying the effect of the failure, than to change the fault tree.

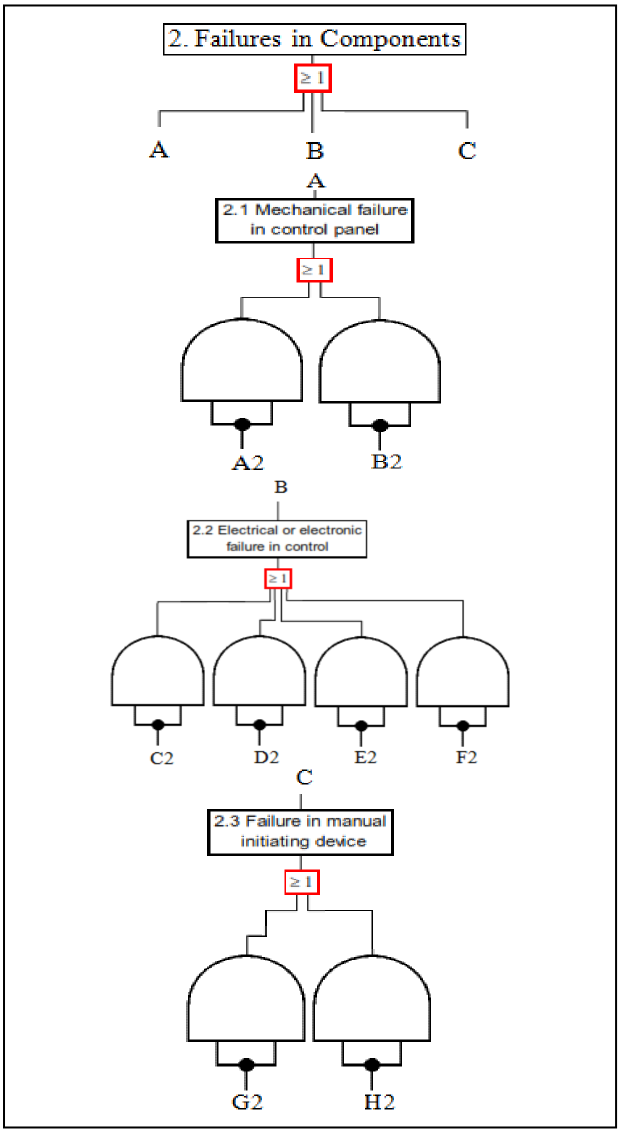

Figure 6 : Fault tree of failures in alarm panel 'components'.

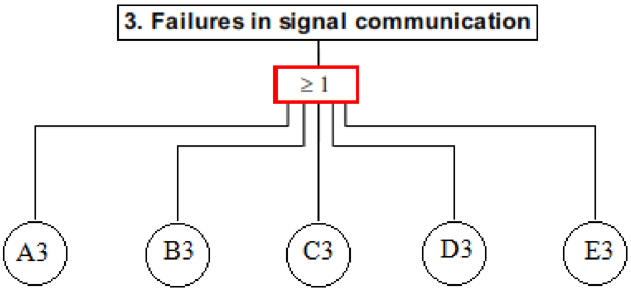

Figure 7 :. Fault tree of failures in signal communication subsystem.

The Boolean inputs in figure 7 represent the following events. A3 : 3.1 Wire/cable failure, B3 : 3.2 No/bad connection to detector, C3 : 3.3 Announcement forwarding, D3 : 3.4 Removed circuit, E3 : 3.5 Ground short. The Boolean inputs in figure 8 represent the following events. P1 : 3.1 Wire/cable failure, Q1 : 3.2 No/bad connection to detector, X1 : 3.3 Announcement forwarding, Y1 : 3.4 Removed circuit, Z1 : 3.5 Ground short. The Boolean inputs in figure 9 represent the following events. P2 : 3.4.1 Cause unknown/ not found, Q2 : 3.4.2 External cause, X2 : 3.5.1Bad grounding, Y2 : 3.5.2 Cause external/ unknown.

Failures in auxiliary control subsystems in Figure 8 are subdivided to five groups: (4.1) failures in computers/coding including all computer code errors throughout the system with the exception of single detectors, (4.2) failures in controls of

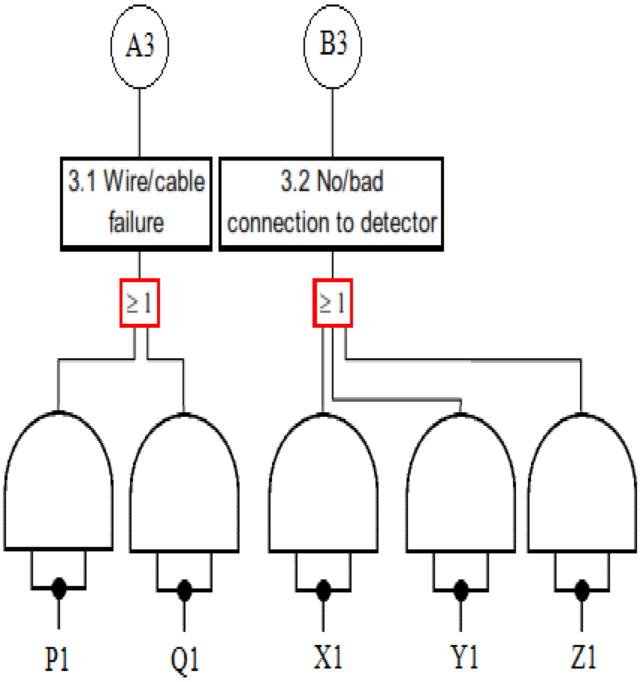

Figure 8 : Fault tree of failures in signal communication subsystem.

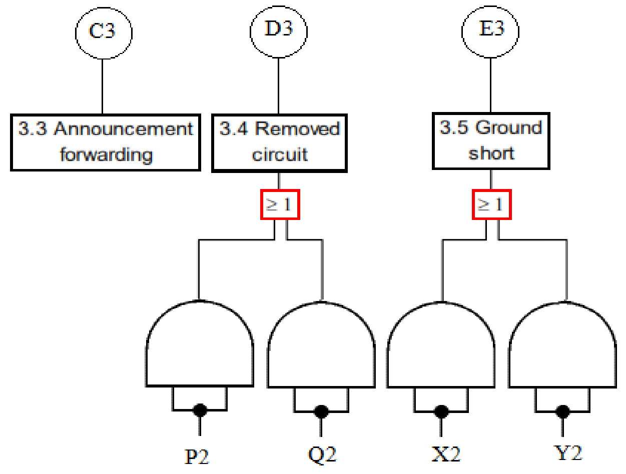

Figure 9 : Fault tree of failures in signal communication subsystem.

fire dampers, (4.3) extinguishing systems, (4.4) pumps, and (4.5) alarming/notification appliances.

The Boolean inputs in figure 9 represent the following events. A4 : Failure in computer/ coding, B4 : Control of fire dampers, C4 : Control in extinguishing systems, D4 : Control of fire pumps, E4 : Control of alarming/ notification appliances.

Failures in power supply are divided into three subgroups in Figure 11: (5.1) failures in mains voltage or circuit current, (5.2) failures in standby power batteries, and (5.3) faulty component/connection.

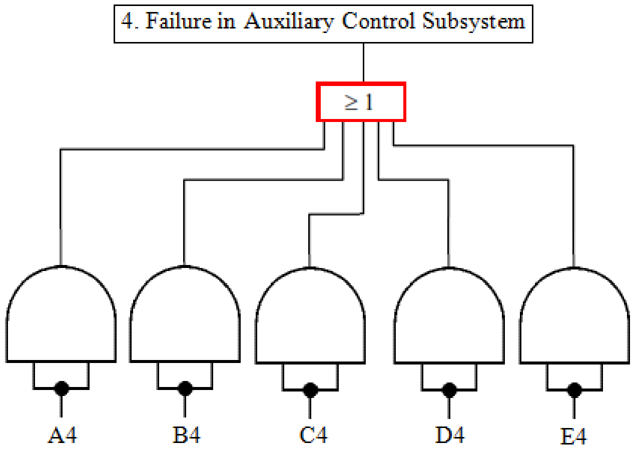

Figure 10 : Fault tree of failures in auxiliary control subsystems.

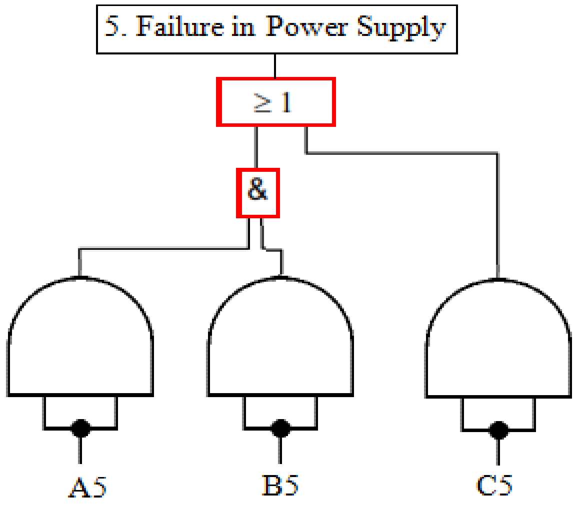

Figure 11 : Fault tree of power supply failure.

The Boolean inputs represent the following events. A5 : 5.1 Failures in mains voltage or circuit current, B5 : 5.2 Failures in standby batteries, C5 : 5.3 Faulty component/connection. The Boolean inputs in figure 12 represent the following events. A6 : 6.1.1 Communication error, B6 : 6.1.2 Control error, C6 : 6.1.3 Testing Error, D6 : 6.2.1 Insufficient/faulty guidance, E6 : 6.2.2 Design error, modification.

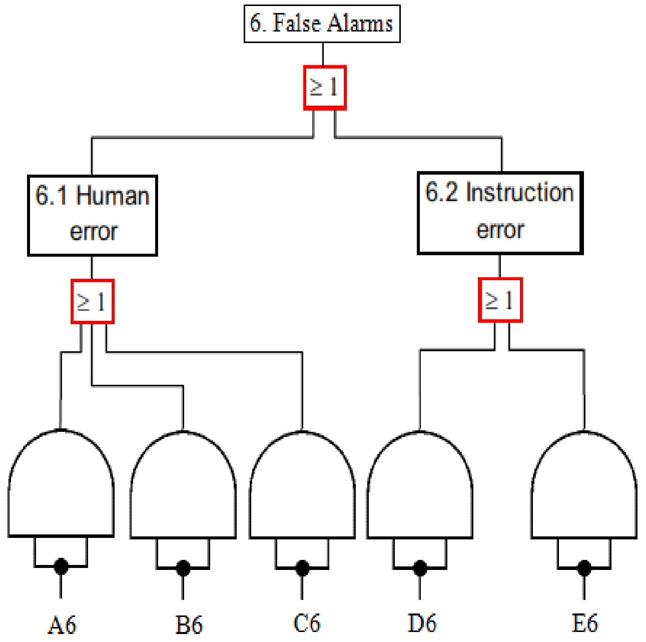

Figure 12 : Fault tree by cause of failures resulting in false alarms.

Failures resulting in false alarms are collected in Figure 12 in two subunits: (6.1) human error, and (6.2) instruction error. Human errors consist of (6.1.1) communication, (6.1.2) control and (6.1.3) testing errors, whereas instruction errors are divided into (6.2.1) insufficient/faulty guidance/data, and (6.2.2) design error or modification.

IV. CONCLUSION AND FUTURE SCOPE

The reliability of the grid connected photovoltaic system is primarily and strongly depends on the reliability of the electrical protection systems, failure of which may lead to fire. So a fire detection system is the crucial component in a grid connected PV system. So its reliability is directed related to the overall reliability of the PV system. The classifications of failure severity were made from the system point of view by counting failures of components when possible. Since there are no established fault tree structures available for fire detection system in photovoltaics, these component failure frequencies are intended to be used in the first round of iteration in the fault trees suggested here. It is possible, that analyses to be carried out later, might require considerable changes to these proposals either due to lacking statistical information from some proposed boxes, or due to internal structure of the system presumed too simple in this paper. Before these analyses become feasible, the point estimates of failure frequencies of the main components/subsystems are needed with error ranges for evaluating the relevance of observations. The study gave a detailed account on fault tree modelling, but not yet sufficiently close the effort in the form of failure frequencies and fault trees, which are left to later studies of the problem.

REFERENCES

[1] Paul K. Kuhn, Cynthia Furse, Paul Smith, (2006) - Locating Hidden Hazards in Electrical Wiring, Symposium on Aged Electrical Systems Research Application October 18-19, 2006, Chicago, Illinois, USA.

[2] Mohammad Sadegh Javadi1, Azim Nobakht2, Ali Meskarbashee (2011) - Fault Tree Analysis Approach in Reliability Assessment of Power System, International journal of multidisciplinary sciences and engineering, vol. 2, no. 6, september 2011.

[3] Casey C. Grant, P.E. (2010) - Fire Fighter Safety and Emergency Response for Solar Power Systems, The Fire Protection Research Foundation, © Copyright Fire Protection Research Foundation, May 2010.

[4] Wang Cheng-gang, Wang Zi-zhen (2010) - Design and Implementation of Safety Expert Information Management System of Coal Mine Based on Fault Tree , Journal of Software, Volume 5, NO. 10, October 2010, Pages : 1114 -1120.

[5] R. Karimi, N. Rasmussen and L. Wolf (May 1980) – Qualitative and quantitative reliability analysis of safety systems, Energy Laboratory Report No. MIT-EL 80-015, Energy Laboratory and Department of Nuclear Engineering Massachusetts Institute of Technology Cambridge, Massachusetts 02139.\

[6] Sanjay Kumar Tyagi, D. Pandey and Reena Tyagi (2010) -Fuzzy set theoretic approach to fault tree analysis, International Journal of Engineering, Science and Technology Vol. 2, No. 5, 2010, pp. 276-283.

[7] John Andrews (2012) - Introduction to Fault Tree Analysis, 2012 Annual RELIABILITY and MAINTAINABILITY Symposium.

[8] Lei Zhang, and Gaofeng Wang (2009) - Design and Implementation of Automatic Fire Alarm System based on Wireless Sensor Networks, ISBN 978-952-5726-02-2 (Print), 978-952-5726-03-9 (CD-ROM) Proceedings of the 2009 International Symposium on Information Processing (ISIP’09) Huangshan, P. R. China, August 21-23, 2009, pp. 410-413.

[9] Merton Bunker (2007) - Fire Alarm Systems Getting It Right The First Time, IMSA Journal Pages : 32-49.

[10] Marsh (2008) - Effectiveness of Fire Safety Systems for Use in Quantitative Risk Assessments, New Zealand Fire Service Commission Research Report Number 89, ISBN Number 978-1-877349-83-6 (on-line), ISBN Number 978-1-877349-82-9 (paperback) © Copyright New Zealand Fire Service Commission.

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