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Research paper

Onsite power system reliability assessment for nuclear power plants

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Abstract

The onsite power system of the Nuclear Power Plants (NPPs) provides electrical energy necessary to bring the plant to a controlled state following anticipated operational occurrences or accident conditions and to maintain it in a controlled state, or a safe state. The onsite power system reliability is essential for reliable and safe operation of the NPPs. The onsite power system reliability for Advanced Power Reactor (APR1400), European pressurized water reactor (EPR) and Advanced Passive (AP1000) are assessed using Fault Tree (FT) analysis technique. The reliability of the onsite power system is evaluated based on the unreliability of the power supplied to safety buses. The overall onsite power systems reliabilities for each design are assessed and compared to each other. Components importance measures are calculated for each plant to identify the most important electrical components in the power system from the nuclear safety point of view.

Keywords: *Fault Tree; Nuclear Power Plants; Onsite Power System; Reliability.*

1. Introduction

The Nuclear Power Plant (NPP) is equipped with an uninterrupted and reliable source of electrical energy so as to maintain the successful cooling of the fuel. In normal operation, the preferred source of electrical energy is Alternating Current (AC) electrical energy from the generator bus through unit transformers. During the startup, shutdown or maintenance of the NPP, the offsite power system is the preferred source of electrical energy. In case of the grid is unavailable, there are backup diesel generators, which provide energy until normal conditions in the power system are restored. The onsite standby power system powered by the onsite Emergency Diesel Generators (EDGs) which supplies power to selected loads in the event of loss of normal, and preferred AC power supplies. The onsite Direct Current (DC) and Uninterruptable Power Supply (UPS) systems provide a reliable source for the safety loads required for the plant monitoring, control and other essential functions needed for the plant shutdown [1]. The reliability of onsite power is enhanced by sufficient independence, redundancy and testability of batteries, diesel generators, and gas turbines. The onsite electric distribution systems also designed to perform safety and other functions even if a single failure occurs [2].

In [3] the author discussed the reliability evaluation of auxiliary power supply and its effect on High Voltage Direct Current (HVDC) link using Fault Tree (FT) analysis. These analyses investigate system design and identify the system's critical components that help improve the design and increase the reliability. A. Volkanovski et al. presented a statistical analysis of the Loss of Offsite Power (LOOP) listed in four assessed databases, the number of LOOP events in respective year in the period studied and operation modes are assessed [4, 5]. A case study of the power station is considered for performing the FT analysis and the results are presented in [6]. The methodology adopted in the investigation is to generate FT for each load point of the power system. In [7] FT technique based on generalized fuzzy numbers to a distribution possibility of reliability indices for power systems is illustrated. All the failure probabilities are characterized by generalized trapezoidal fuzzy number. A real case study for the US Surry NPP which was touched down by a tornado in 2011 causing the electrical switchyard damage and LOOP is executed in [8]. A method for assessing LOOP initiating event (IE) probability are reviewed and improved. The probability is evaluated and the current plant performance and power system are matched to the plant performance and power system performance from years ago. In [9] M. S. Javadi presented surveys on the FT Analysis in modelling the reliability assessment of an engineering system using Boolean algebra. This approach can be implemented for calculation the reliability indices, regardless of the complexity of the modelling of large scale system. A. Volkanovski et al. developed a new technique for the evaluation of power system reliability. The method combines the FT analysis and the power flow model utilizing a DC model [10], [11].

In this paper, the reliability of the onsite power system is evaluated for Advanced Power Reactor (APR1400), European pressurized water reactor (EPR) and Advanced Passive (AP1000) using FT analysis technique. The reliability of the onsite power system is evaluated based on the unreliability of the power supplied to safety buses. The importance measures presented identify the most important components in the power system from the aspect of nuclear safety.

2. Fault tree analysis

The FT analysis is a standard method for the assessment and improvement of reliability and safety. The FT analysis is defined as: “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 beginning of the FT analysis, is normally a state that is critical from a safety or reliability point of view and is identified as the top event. Consequently, a top event is, therefore, an undesired event, which is further investigated with the FT analysis [11 - 13].

The logical gates of the FT incorporate the primary events to the top event. The primary events are the events that are not further developed, e.g., the basic events (BEs) and the house events. The BEs are the ultimate parts of the FT, which represent the undesired events and their failure modes, e.g., the component failures, the lost actuation signals, the human errors, the unavailabilities due to test and maintenance activities, the common cause failure (CCF) contributions and software errors. CCF events are a group of dependent events where at the same time there are two or more components exist at failure condition as a result of a shared root cause. An example is a case where two parallel power transmission lines connected to the same tower, or two transmission lines share the same right of way [14 – 16].

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 (MCSs). MCSs are combinations of the smallest group of BE that lead to the top event if occur simultaneously [17], [18].

The onsite power system reliability is defined from its complement, i.e., unreliability as follows [11]:

$$R_{PS} = 1 - U_{PS} \tag{1}$$

Where:

R_{PS}: the power system reliability.

U_{PS}: the power system unreliability.

The onsite power system unreliability can be assessed from the top event probability of the respective FT analysis. In general, the equations for representing the MCSs as the result of the qualitative FT analysis are joined into the following equation [11].

$$P_{MCSi} = \prod_{j=1}^{J} B_j \tag{2}$$

Where:

P_{MCSi}: the probability of occurrence of MCS i

B_j: the BE j.

J: number of BEs in a particular MCS.

The quantitative FT analysis represents a calculation of the top event probability, equal to the failure probability of power supplied to the respective load. The calculation of the top event probability (using rare event approximation) as [11]:

$$P_{TOP} = U_{PS} = \sum_{i=1}^{I} P_{MCS_i} \tag{3}$$

Where:

P_{TOP}: the top event probability of the FT.

I: number of MCSs.

Electrical components can be sorted according to their influence on the electrical grid reliability. In general, the importance of a component within a system depends on the position of the component in the system, on the reliability of the component, and the reliability of the system. Three importance measures are introduced. The first one is called Fussell-Vesely Importance (FV) and provides the BE fractional contribution to the system unreliability. The second one of the importance measures is the Risk Achievement Worth (RAW) and represents the change of the system unreliability when the contributor’s failure probability is set 1. The third one is the Risk Reduction Worth (RRW) and represents the change of the system unreliability when the contributor’s failure probability is set 0 [19].

$$FV_i = \frac{P_{TOP_i}}{P_{TOP}} \tag{4}$$

$$RAW_i = \frac{P_{TOP}(P_i=1)}{P_{TOP}} \tag{5}$$

$$RRW_i = \frac{P_{TOP}}{P_{TOP}\ (P_i=0)} \tag{6}$$

Where:

FV_i: the Fussel–Vesely importance for BE i.

P_{TOPi}: the top event probability for all cut sets containing the BE i.

RAW_i: the risk achievement worth for BE i.

P_{TOP} ($P_i = 1$): the top event probability when failure probability of BE i is set to 1.

RRW_i: the risk reduction worth for BE i.

P_{TOP} ($P_i = 0$): the top event probability when failure probability of BE i is set to 0.

3. Case study

The method described will be applied on three different types of NPPs: the three types are chosen from the 3^+ generation NPPs that being recently operated or being constructed around the world. Generation III+ designs offer significant improvements in safety and economics with Enhanced passive or inherent safety features.

The first NPP is the APR1400 which is designed by the Korea electric power corporation with rated thermal output of 4000 MWth and a corresponding electrical output of 1455 MWe. In May 2002, APR1400 grants certification by the Korean Institute of nuclear safety. The APR1400 includes a variety of engineering enhancements and operating experience to improve safety, economics and reliability [20 - 21].

The second NPP is the EPR developed by AREVA with 4590 MWth, and 1750 MWe. EPR has an "evolutionary" design, so as to draw maximum benefit from the accumulated experience in designing and operating NPPs till now. It has double containment and a four redundant and separate active safety systems with a core catcher below the pressure vessel [22].

The third NPP is the Westinghouse AP1000 with 3400 MWth and 1200 MWe. The AP1000 is designed to achieve a record of high safety and performance. It is conservatively based on a verified technology, but with a dependence on safety features that based on natural forces. The natural driving forces such as gravity flow, pressurized gas, natural circulation flow and convection are used by safety systems. The safety systems do not use active components (e.g. fans, pumps or diesel generators) and are designed to work without safety support systems (e.g. AC power, service water, component cooling water). The number and complexity of operator actions required to run the safety systems are minimized; the approach is to eliminate the need for operator action rather than automate it [23].

In this paper, the assessment is performed on Class 1E onsite power system only, so only this system will be described. The onsite power system for each design is illustrated in the following section.

3.1. APR1400 onsite power system

The onsite power system of APR1400 involves the Class 1E and the non-Class 1E power systems. The Class 1E power system supply safety loads necessary to safely shut down the reactor, remove the residual heat and to prevent release of radioactive materials, for abnormal and accident conditions [24], [25].

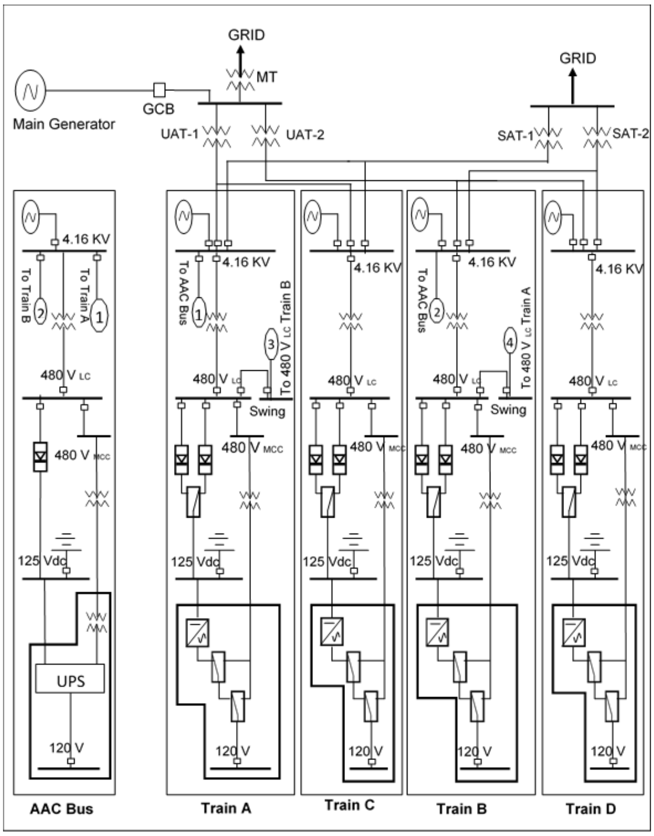

Fig. 1: Class 1E Trains for APR1400 Onsite Power System.

The Class 1E onsite power system has four redundant subsystems (A, B, C, and D trains) with an EDG for each train. The Class 1E power system involves 4.16 kV buses, 480 V load centers (LCs) buses, 480 V Motor Control Centers (MCCs) buses, 125 Vdc buses, and 120 V Instrumentation and control (I&C) buses. The configuration of Class 1E onsite power system for APR1400 is shown in Fig. 1.

The Class 1E 4.16 kV buses are connected to offsite power sources through the two unit auxiliary transformers (UATs) and with two standby auxiliary transformers (SATs) in case of UATs are unavailable. Each Class 1E 4.16 kV bus is also supplied by an EDG (9100 KW, 4.16 KV) during LOOP event. In case of loss of both the offsite and all EDGs, two trains for Class 1E 4.16 kV buses (train A or train B) are connected also to the non-Class 1E Alternate AC (AAC) bus (8688 KW, 4.16 KV) for a Station Blackout (SBO) event [26].

The 480 V Class 1E LCs and MCCs buses are provided with potential and current transformers and relays. The Class 1E 480 V LCs buses are fed from Class 1E 4.16 kV buses through load center transformers. The Class 1E 480 V MCC buses are linked to the Class 1E LCs buses.

The Class 1E 125 Vdc power system provides the plant safety system DC loads with a reliable power. Each DC power subsystem contains a battery (2800 AH for trains A, B and 8800 AH for train C, D), two battery chargers (normal and standby), distribution panels and a DC control center.

The Class 1E 120 V I&C bus has four separate and independent 120 V buses. Each Class 1E 120 V I&C bus has an inverter, distribution panel, regulating transformer, two transfer switches (manual and automatic) and distribution panels [26].

3.2. EPR onsite power system

The onsite power system of EPR involves both the Class 1E and the non-Class 1E power systems. The Class 1E power system supply safety system loads that are necessary to shut down the reactor safely, maintain it in shutdown condition, remove the residual heat and stored heat and to prevent release of radioactive materials, under accident conditions.

The Class 1E onsite power system has four redundant divisions with an EDG for each division. The Class 1E power system consists of 6.9 kV buses, 480 V LCs buses, 250 Vdc buses 480 V UPS buses and 24 Vdc buses. The configuration of Class 1E onsite power system for EPR is shown in Fig. 2.

The Class 1E 6.9 kV buses are linked to offsite power sources through the two emergency auxiliary transformers (EATs). Each Class 1E 6.9 kV bus is also powered by an EDG (9500 KW, 6.9 KV) during LOOP event. In case of loss of both the offsite and the onsite power supply and all EDGs, two additional diesel generators (connected to Division 1 and 4 with rating 4500 KW, 6.9 KV). The two additional diesel generators are diversified in regards to the EDGs and provide an alternate AC sources for coping with postulated SBO events.

The 480 V Class 1E LCs buses are provided with potential and current transformers and relays are fed from Class 1E 6.9 kV buses through load center transformers. The 480 V UPS Class 1E bus is fed form 480 V bus and 250 Vdc bus through an inverter.

The Class 1E 250 Vdc power system provides the plant safety system DC loads with a reliable power. Each DC power subsystem has one (2 hour, 5700 AH) battery, two battery chargers (normal and standby). In addition to the four (2 hour) rated UPS systems, two supplemental (12 hour, 2400 AH) rated UPS systems are provided, one each for divisions 1 and 4. These supplemental UPS systems are provided for severe accident mitigation and increase the coping time for restoration of AC power. The Class 1E 24 Vdc buses are supplied from two deferent sources, 480 V UPS bus AC/DC converter and 250 Vdc bus through DC/DC converter.

3.3. AP1000 onsite power system

The AP1000 onsite power system includes both the AC power system and the DC power system. The AC power is a non-Class 1E system. The DC power system involves two independent systems, Class 1E and non-Class 1E. The Class 1E onsite power system function is to provide reliable electric power to the plant safety equipment for normal plant operation, start-up, normal shutdown, accident mitigation, and emergency shutdown.

The AP1000 electrical distribution system has four redundant trains (A, B, C, and D trains). Each train includes 6.9 kV buses, 480 V MCC buses, 250 Vdc buses and 120 V buses. Offsite power has no safety-related purpose due to the passive safety features integrated in the AP1000 design. Therefore, no redundant offsite power supplies are required. The design provides a reliable offsite power system that reduces challenges to the passive safety system. The configuration of Class 1E onsite power system for AP1000 is shown in Fig. 3.

The non-Class 1E 6.9 KV bus is linked to the offsite power sources through UATs. In case the power is unavailable from the UATs, the power source is moved automatically to the reserve auxiliary transformers (RATs). In the event of a loss of offsite power, two non-Class 1E onsite standby diesel generators (SDGs) (5700 KW, 6.9 KV) supply power to selected loads in the event of loss of the normal, preferred, and maintenance power sources. There are only two 6.9 KV buses shared between the four redundant trains.

The 480 MCC V bus provide power for various loads such as lighting systems and heaters. The 480 MCC V bus also provide AC power to the Class 1E battery chargers for the Class 1E 250 Vdc power system. The 480 MCC V bus also connected to an ancillary AC generator (ADG) (80 KW, 480 V) to the Class 1E voltage regulating transformers (train B and C only). This supplies the Class 1E post-accident monitoring systems and the control room lighting and ventilation.

The Class 1E 250 Vdc power system includes four independent trains of 24 hours battery systems. Trains B and C have two battery banks, one of these battery banks is designed to provide power to the selected safety loads for at least 24 hours (2400 AH), and the other battery bank is designed to provide power to another smaller group of selected safety loads for at least 72 hours (1800 AH) in case of the loss of all AC power.

The Class 1E 120 V instrument bus is fed from two different sources. The normal power to the Class 1E bus comes from the respective Class 1E 250 Vdc bus, and the backup power comes from the main AC power system through Class 1E 480/120V voltage regulating transformers.

4. Results

FT is constructed for all onsite power system safety buses for APR1400, EPR and AP1000 NPPs. unreliability for power supplied for each bus is assessed as the top event probability for the respective FT. The construction and analysis of the FT is done using Systems Analysis Programs for Hands-on Integrated Reliability Evaluations (SAPHIRE-8) software. SAPHIRE is an integrated probabilistic safety assessment software tool that gives a user the ability to create and analyze FTs using a personal computer. Using SAPHIRE-8 on a PC, a user can perform a FT for any complex system, facility, or process, regarding NPPs. Component failure rates are captured from [27].

4.1. Results for APR1400

The FT is constructed for all onsite power system safety buses, due to existing symmetry, only trains A and C for the onsite power system of APR1400 are analyzed. 4.16 kV bus, 480 V LC bus, 480 MCC bus, 480 SWING bus, 125 Vdc bus and 120 V bus for train A and C are analyzed. There are 46 components, 5 CCFs, and 1 IE are modelled for train A. There are 42 components, 5 CCFs and 1 IE are modelled for train C.

Table 1 shows the calculated unreliability for train A and C buses and the total onsite power system. The buses unreliability for train A is smaller than the unreliability for train C, this decrease due to the additional SBO diesel generator which connected to train A.

Table 2 shows components with the largest FV importance for the APR1400 onsite power system. Failure of 4.16 KV bus, failure of battery, failure of 125 Vdc bus, fail to start SBO generator and fail to load and run EDG, have the largest FV values.

Table 3 shows components with the largest RAW importance for the APR1400 onsite power system. Failure of battery Circuit Breaker (CB), failure of 125 Vdc bus, failure of battery, failure of all 4.16 KV bus CBs due to CCF and failure of 4.16 KV bus, have the largest RAW values.

Table 4 shows components with the largest RRW importance for the APR1400 onsite power system. Failure of 4.16 KV bus, failure of battery, failure of 125 Vdc bus, fail to start SBO generator, and fail to load and run EDG, have the largest RRW values.

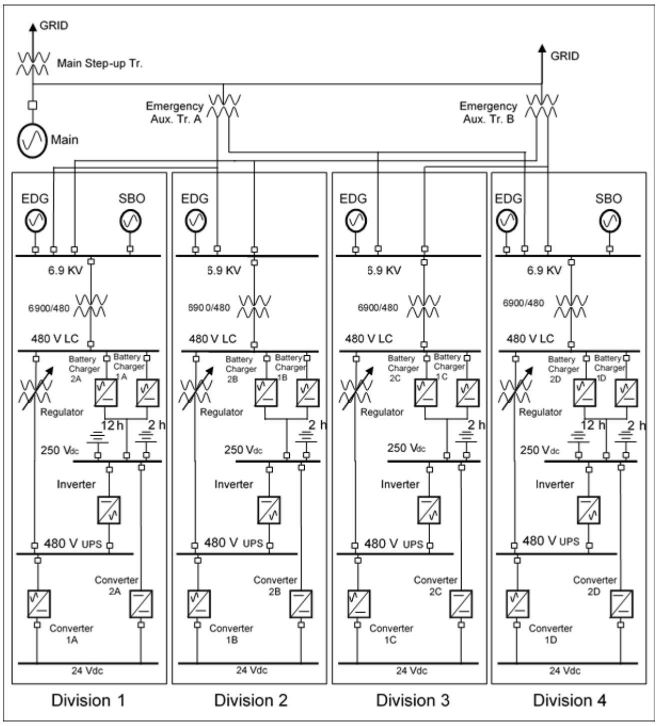

Fig. 2: Class 1E Divisions for EPR Onsite Power System.

Table 1: The Calculated Unreliability for APR1400 Train A and C Buses

Bus	Train (A) unreliability	Train (C) unreliability
4.16 KV	1.186E-02	1.857E-02
480 V LC	4.753E-02	5.315E-02
480 MCC	5.05E-02	5.611E-02
480 SWING	8.41E-03	N.A.
125 Vdc	2.20E-03	2.10E-03
120 V	1.39E-02	1.409E-02
Total onsite power system	2.26E-05	

Table 2: FV Importance for the APR1400 Onsite Power System

Name	FV	Description
BUS_4160V_FOP	7.047E-01	Fail to Operate 4.16 KV Bus
BT_FOP	6.483E-01	Fail to Provide Output of Battery
BUS_125VDC_FOP	2.527E-01	Fail to Operate 125 VDC Bus
SBO_FTS	2.025E-01	Station Blackout SBO fail to start
EDG_FTLR	1.333E-01	Fail to Load and Run of Diesel Generator (<1h)

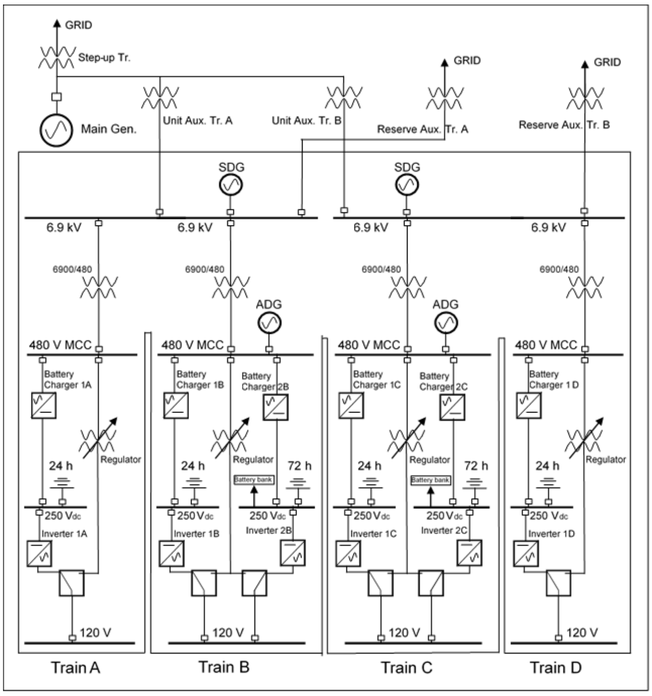

Fig. 3: Class 1E Trains for AP1000 Onsite Power System.

Table 3: RAW Importance for the APR1400 Onsite Power System

Name	RAW	Description
CB_BT_FOP	1.328E+02	Open Spuriously of DC Power Circuit Breaker
BUS_125VDC_FOP	1.327E+02	Fail to Operate 125 VDC Bus
BT_FOP	1.323E+02	Fail to Provide Output of Battery
CCF_CB_4160V_FOP-AB	8.493E+01	Fail to operate all 4.16 KV CBs due to CCF
BUS_4160V_FOP	8.423E+01	Fail to Operate 4.16 KV Bus

Table: 4: RRW Importance for the APR1400 Onsite Power System

Name	RRW	Description
BUS_4160V_FOP	3.386E+00	Fail to Operate 4.16 KV Bus
BT_FOP	2.843E+00	Fail to Provide Output of Battery
BUS_125VDC_FOP	1.338E+00	Fail to Operate 125 VDC Bus
SBO_FTS	1.254E+00	Station Blackout SBO fail to start
EDG_FTLR	1.154E+00	Fail to Load and Run of Diesel Generator (<1h)

4.2. Results for EPR

The FT is constructed for all onsite power system safety buses, due to existing symmetry, only divisions 1 and 2 for the onsite power system of EPR are analyzed. 6.9 kV bus, 480 V LC bus, 250 Vdc bus, 480 V UPS bus and 24 Vdc bus for divisions 1 and 2 are analyzed. There are 49 components, 3 CCFs, and 1 IE are modelled for division 1. There are 45 components, 2 CCFs and 1 IE are modelled for division 2.

Table 5 shows the calculated unreliability for divisions 1 and 2 buses and the total onsite power system. The buses unreliability for division 1 is smaller than the unreliability for division 2, this decrease due to the additional SBO diesel generator and 12 hour battery which connected to division 1.

Table 6 shows the largest FV components for the EPR onsite power system. Failure of battery, failure of 250 Vdc bus, failure of 6.9 KV bus, failure of 480 LC V bus and failure of battery CB, have the largest FV values.

Table 7 shows the largest RAW components for the EPR onsite power system. Failure of battery, failure of 250 Vdc bus, failure of 6.9 KV bus, failure of battery CB and failure of all 6.9 KV bus CBs due to CCF, have the largest RAW values.

Table 8 shows the largest RRW components for the EPR onsite power system. Failure of battery, failure of 250 Vdc bus, failure of 6.9 KV bus, failure of 480 LC V bus and failure of 6.9 KV bus CB, have the largest FV values.

Table 5: The Calculated Unreliability for EPR Divisions 1 and 2 Buses

Bus	Division 1 unreliability	Division 2 unreliability
6.9 KV Bus	1.16E-02	2.18E-02
480 V LC Bus	4.73E-02	5.71E-02
250 Vdc Bus	1.91E-03	2.25E-03
480 V UPS Bus	1.28E-02	1.32E-02
24 Vdc Bus	6.04E-03	6.56E-03
Total onsite power system	2.39E-06	

Table 6: FV Importance for the EPR Onsite Power System

Name	FV	Description
BT_FOP	6.982E-1	Fail to Provide Output of 2 H Battery
BUS_250VDC_FOP	1.980E-1	Fail to Operate of Electrical 250 V DC Bus
BUS_6900V_FOP	6.102E-1	Fail to Operate of Electrical 6.9 KV AC Bus
BUS_480VLC_FOP	2.205E-1	Fail to Operate of Electrical 480 V AC Bus
CB_BT_FOP	1.039E-1	Open Spuriously of 2 H Battery Circuit Breaker

Table 7: RAW Importance for the EPR Onsite Power System

Name	RAW	Description
BT_FOP	1.476E+2	Fail to Provide Output of 2 H Battery
BUS_250VDC_FOP	1.481E+2	Fail to Operate of Electrical 250 V DC Bus
BUS_6900V_FOP	1.322E+2	Fail to Operate of Electrical 6.9 KV AC Bus
CB_BT_FOP	1.482E+2	Open Spuriously of 2 H Battery Circuit Breaker
CCF_CB_6.9KV_FOP	1.328E+2	Failure to operate all 6.9 KV CBs due to CCF

Table: 8: RRW Importance for the EPR Onsite Power System

Name	RRW	Description
BT_FOP	5.317E+0	Fail to Provide Output of 2 H Battery
BUS_250VDC_FOP	1.369E+0	Fail to Operate of Electrical 250 V DC Bus
BUS_6900V_FOP	4.061E+0	Fail to Operate of Electrical 6.9 KV AC Bus
BUS_480VLC_FOP	1.537E+0	Fail to Operate of Electrical 480 V AC Bus
CB_6900V_FOP	1.049E+0	Open Spuriously of 6.9 KV Circuit Breaker

4.3. Results for AP1000

The FT is constructed for all onsite power system safety buses, due to existing symmetry, only trains A and B for the onsite power system of AP1000 are analyzed. 6.9 kV bus, 480 V MCC bus, 250 Vdc (24 h), 250 Vdc (72 h) bus and 120 V bus for train A and B are analyzed. There are 39 components, 3 CCFs, and 1 IE are modelled for train A. There are 24 components, 2 CCFs and 1 IE are modelled for train B.

Table 9 shows the calculated unreliability for train A and B buses and the total onsite power system. The buses unreliability for train B is smaller than the unreliability for train A, this decrease due to the additional ADG and the 72 hour battery bus which connected to train B.

Table 10 shows the largest FV components for the AP1000 onsite power system. Failure of 24 hour battery, failure of 250 Vdc bus, failure of 6.9 KV bus, fail to load and run SDG and fail to run SDG, have the largest FV values.

Table 11 shows the largest RAW components for the AP1000 onsite power system. Failure of 24 hour battery, failure of 250 Vdc bus, failure of 6.9 KV bus, failure of 6.9 KV bus CB and failure of 24 hour battery CB, have the largest RAW values.

Table 12 shows the largest RRW components for the AP1000 onsite power system. Failure of 24 hour battery, failure of 250

Vdc bus, failure of 6.9 KV bus, failure of 24 hour battery CB and fail to run SDG, have the largest FV values. The onsite power system reliabilities for AP1000, EPR and AP100 are illustrated in Table 13.

Table 9: The Calculated Unreliability for AP1000 Train A and C Buses

Bus	Train A unreliability	Train B unreliability
6.9 KV Bus	2.18E-02	2.18E-02
480 V MCC Bus	5.71E-02	1.39E-02
250 Vdc Bus (24 h)	2.38E-03	2.14E-03
250 Vdc Bus (72 h)	N.A.	1.91E-03
120 V Bus	1.06E-02	8.45E-03
Total onsite power system	8.98E-05	

Table: 10: FV Importance for the AP1000 Onsite Power System

Name	FV	Description
BT24_FOP	7.00E-1	Fail to Provide Output of 24 H Battery
BUS_250VDC_FOP	1.96E-1	Fail to Operate of Electrical 250 V DC Bus
BUS_6900V_FOP	3.32E-1	Fail to Operate of Electrical 6.9 KV AC Bus
SDG_FTLR	2.96E-1	Fail to Load and Run of Diesel Generator (<1h)
SDG_FTR	1.41E-1	Fail to Run of Diesel Generator (>1h)

Table: 11: RAW Importance for the AP1000 Onsite Power System

Name	RAW	Description
BT24_FOP	1.465E+2	Fail to Provide Output of 24 H Battery
BUS_250VDC_FOP	1.469E+2	Fail to Operate of Electrical 250 V DC Bus
BUS_6900V_FOP	5.461E+1	Fail to Operate of Electrical 6.9 KV AC Bus
CB_6900V_FOP	1.000E+0	Open Spuriously of 6.9 KV Circuit Breaker
CB_BT24_FOP	1.470E+2	Open Spuriously of 24 H Battery Circuit Breaker

Table: 12: RRW Importance for the AP1000 Onsite Power System

Name	RRW	Description
BT24_FOP	5.354E+0	Fail to Provide Output of 24 H Battery
BUS_250VDC_FOP	1.353E+0	Fail to Operate of Electrical 250 V DC Bus
BUS_6900V_FOP	1.692E+0	Fail to Operate of Electrical 6.9 KV AC Bus
CB_BT24_FOP	1.126E+0	Open Spuriously of 24 H Battery Circuit Breaker
SDG_FTLR	1.494E+0	Fail to Load and Run of Diesel Generator (<1h)

Table 13: Onsite Power System Reliability

System	Reliability
APR1400 onsite power system	0.9999774
EPR onsite power system	0.99999761
AP1000 onsite power system	0.9999102

Regarding each bus the AP1000 has the lowest buses unreliability for DC buses and UPS AC buses due to the main dependence on passive safety systems that uses natural phenomena (e.g. gravity and natural circulations), also the battery system has longer capacity to supply loads for 27 hours. On the other hand EPR has the lowest unreliability for high voltage and low voltage AC buses due to the reliance on safety systems that depend mainly on electrical power. APR1400 uses a combination of active and passive safety systems. For the overall onsite power system reliability EPR has the highest system reliability and AP1000 has the lowest.

5. Conclusion

The onsite power systems for APR1400, EPR and AP1000 were assessed using the FT analysis technique. The reliability of onsite power systems were evaluated based on the unreliability of the power supplied to safety buses. The unreliability for all safety buses for the selected NPPs were obtained, and the overall onsite power systems reliabilities were assessed and compared to each other. The results showed that EPR has the highest onsite power system reliability and AP1000 has the lowest. The calculated importance measures identify the highest important elements of the power system from the aspect of nuclear safety. The proposed method is efficient in assessing and comparing deferent designs for NPPs onsite power systems.

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