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MODELLING AGEING AT THE LEVEL OF ELECTRICAL SYSTEMS FROM CERNAVODA NPP

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Abstract. *The effects of age-related degradation of plant components, systems and structures are necessary to be assessed in order to assure the continuous safe operation of nuclear power plants. The ageing process is an ongoing process, its evolution depends on many factors (physical properties of materials, operating conditions, period of operation, loads), and can lead to reduced efficiency of the component if it's left unmitigated. The Probabilistic Safety Analysis (PSA) is an efficient system analysis method which can be used to assess the risk of operation of an aged plant. The paper will present the benefits of using PSA in evaluation of impacts of ageing effects, as the changes induced by the ageing effects incorporation in the analysis results, for electrical power systems of Cernavoda NPP.*

Keywords: ageing effects, PSA, electrical power systems

1. Introduction

The degradation of the functional capability of components, systems and structures can be determined in time by a number of factors as follows: typical stressors for operating environment (irradiation, primary and secondary chemistry, vibration loads), service wear (accumulation of fatigue damage due to plant operational cycling, wear of rotating equipments), excessive testing of equipment or improper installation, application or maintenance. The ageing process is an ongoing process, and can lead to reduced efficiency of the component. If the phenomenon is left unchecked and unmitigated, the ageing could increase the risk associated with the facility operation [1].

As no facility can be considered immune to the ageing effects, the ageing phenomena represent a significant factor of concern, because of the tendency for safety level of the aged facility to be diminished as the time is passing.

Assuming that during the component life period there is no preventive or corrective maintenance, the component failure rate will follow the bath-tube curve.

The service life of any equipment, generally comprises three main phases, characterized by specific failure rates, as in the figure 1: [1], [2]

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- period of “infant mortality” – failure rate values drop with increased operating time or number of demands;
- period of maturity, characterized by a relatively constant failure rate and during which mortality is random, accidental and sudden. This is the normal period of operation for equipment; its design must be such that this period lasts longer than or at least as long as the mission assigned to the equipment;
- ageing period, during which the failure rate of equipment will increase with time or demand.

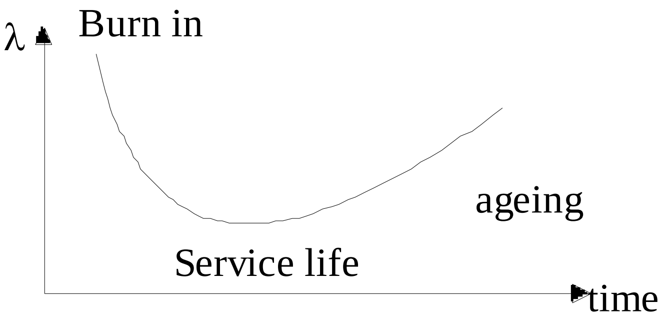


Fig. 1. Evolution of component failure rate.

The maintenance activity has as goal to prevent or to delay the occurrence of the third period in failure rate evolution. The ageing studies based on the failure occurrences examine the failure modes and failure time in order to observe and highlight if a failure rate for a particular failure mode has an increasing value, fact which indicates that the components population reach the third part of the bath-curve.

Explicit consideration of the risk effects of ageing is an important feature of ageing risk assessment evaluation.

As results of performing an ageing analysis for component, the following can be obtained:

- ✓ stress factors (operational and environment conditions) which affects the components performance, as they are ageing;
- ✓ the effects induced by ageing phenomena on components performance;
- ✓ ageing management methods available for mitigation of ageing effects.

By explicitly considering the risk effects of ageing, ageing contributors can be prioritized according to their risk importance, ageing management activities can thereby be focused on important areas and the ageing management strategies can thus be made cost effective.

2. Probabilistic safety analysis considerations

One of the main applications of Probabilistic Safety Analysis (PSA) studies is related to identification of major issues related to plant safety.

The PSA study has as main strengths the following:

- provides insights into plant design, performance and environmental impact, including the identification of dominant risk contributors and the comparison of options for reducing risk;
- offers a consistent and integrated framework in the safety assessment field;
- supports the idea that the risk associated to nuclear power plant is not an unwarranted one, because the estimates can be compared with other hazards (non-nuclear), to which public is exposed;
- enables a much wider array of accident scenarios to be managed in one coherent analysis;
- commonly employ realistic models of the likelihood of accidents, their phenomenology and their consequences;
- gives a picture of the safety or risk profile of a plant that is more comprehensive and balanced than other approaches to reactor safety analysis.

Level 1 PSA uses as modelling techniques the event trees and fault tree modelling techniques, in order to quantify the accident sequences leading to various core damage states and to evaluate the failure probability for components and plant systems.

Fault trees technique is used for modelling the systems reliability as a function of component reliability.

The method is a deductive one, and details the modalities in which an event could happen, by:

- assuming the system state;
- determining the component state contribution to this state.

PSA study is an efficient system analysis method which can be used to assess the risk of operation of an aged facility.

Regarding the reliability models, the incorporation of ageing in PSA means possible modification on the model, as follows: [2], [7]

- modeling ageing for active components means inclusion of additional gates and basic events in the F/T;

- modeling ageing for passive components means additional gates and basic events and changes in F/T structure;
- in case of initiating events, the ageing incorporation implies changing of parameter or additional gates and basic events in the F/T;
- for CCF events, we have to modify parameters, F/T structure or introduce additional gates and basic event.

The component failure rate express the probability of a component failure per unit time given no previous failure. Standard PSA model assumes a constant value for component failure rate, but in case when age dependence is considered, the change in component failure rate as a function of component age must be considered. For ageing phenomena, this dependence causes the failure rate of a component (or a set of components) to increase in time as the component wears out. A risk model such as PSA can be used to identify what failure rates are risk sensitive and can cause significant variations in the risk if they vary. These risk-sensitive failure rates need to be estimated as accurately as possible. With regard to plant applications, these risk-sensitive failure rates need to have strict quality control and qualification.

The ageing assessments with application of PSA models permit: [7]

- to evaluate the component ageing impact to the unavailability of the safety systems;
- to extrapolate the system unavailability curves to the end of plant lifetime;
- to evaluate an increasing of core damage frequency due to ageing of safety important components and structures;
- to propose the optimal periodical test and preventive maintenance intervals for active and passive components;
- to evaluate the effectiveness of surveillance program (periodical tests, in-service inspections);
- to prioritize/ rank components for ageing management;
- to develop recommendation for mitigation actions in ageing management.

3. Case study

The electric power system of Cernavoda plant comprises main power output transformer, unit and service transformers and a switchyard. This system steps up the generator output to match the electric utility's grid requirements for transmission to the load centres and it also supplies the power needed to the station services.

The electrical systems were chosen for the study because there are a lot of cables and for these types of equipment there is no planned preventive or corrective maintenance, and they are originally designed to reach the end of plant life with an adequate safety margin.

During normal station operation the station services power is supplied by both the unit transformers and the system service transformers. Either transformer can provide the total service load in the event of a failure of one supply. The transformers are fed from the output system to the turbine generator.

System service transformers supply half of the plant services power requirements under normal operating conditions and are able to provide the total service load when necessary.

These transformers are fed from the switchyard and supplies all plant loads during the start-up of the plant, or when the turbine generator is unavailable.

Both the unit service and station service transformers are designed to automatically maintain voltage in the station services.

The station services power supplies are classified in order of their levels of reliability requirement, into classes that range from uninterruptible power to that which can be interrupted with limited and acceptable consequences.

3.1. Class IV electrical power supply (CLIV)

Class IV is an a.c. power supply system which provides electrical power to the process, control, instrumentation and lighting loads through the plant.

The system supplies the equipment which can tolerate long interruption in feeding, without affecting the personnel or the plant safety.

The safety function of CLASS IV system is the guarantee of one available and sufficient power supply in order that: [3]

- in advanced exploitation situation, the design limits defined as acceptable for the nuclear fuel and the design conditions for the reactor cooling agent pressurized premises will not been exceeded;
- in case of accidents defined before, the reactor core cooling will be assured, and the containment integrity as well as the other vital functions will be maintained.

The electrical power supply system is divided into two subsystems, ODD and EVEN, each one sized for 100% load capacity, completely physical separated.

The system is supplied either the unit or the service transformers from the external grid and the 24kV generator system.

For CANDU reactors, the station services in normal plant operating conditions are shared equally between these two supplies.

The station services can also be supplied entirely by T/G or by grid, in abnormal plant operating conditions.

The initiating event “Loss of CLIV” can be caused by failures which appear in both supply ways:

- either by perturbation in the grid causing the turbine stop due to the fact that the turbine is not capable to take-over the external supply grid;
- either in grid supply, due to turbine stopping or generator, if the grid is not capable to take-over the station supply.

Assumptions: [3]

- before the accident it was considered that the supply sources are available, the bus being supplied by either of the sources, depending only by the position of supplying circuit breaker (by its closing if it was in opening position or by its remaining closed if it was closed;
- all the circuit breakers between buses and loads to all voltage level were considered in normal position (closed);
- all the failures of cables between buses and circuit breakers to any voltage level were included in the ‘bus failure’ event;
- “short circuit” events of components from loads line, situated after power-down voltage transformers weren’t modelled;
- it was considered that the supply circuit breaker cannot be repaired without de-energizing the corresponding bus;
- the component failures from bus supply line which is in operation were considered as monitored and those from the stand-by line were considered unrepairable;
- there were not considered events associated with commission human error;
- the events with occurring frequency lower then 1.E-7 ev/an were considered as being unbelievable events, and they were not taken into consideration;
- it was allocated a generic value of 1.E-4 for all the events without available data.

3.2. Emergency Power System (EPS)

The EPS provides an alternate power source for equipment essential to the safe shutdown and cooldown of the reactor, following loss of normal station supplies as a consequence of a seismic event or other common mode events.

The system has as special safety function the mitigation of main electrical power systems loss.

The system and its buildings are seismically qualified to be operational after an earthquake.

The EPS system is comprised of two 1000 kV Diesel Generators supplying an “ODD/EVEN” distribution system located in the Secondary Control Building, housed in separate fire resistant rooms, which are self-contained and completely independent of the station normal services. There is adequate redundancy provided in both the generating distribution equipment and the loads. The Emergency Power System is 100% redundant.

Assumptions: [3]

- the unavailability caused by the corrective maintenance wasn’t taken into account;
- the operator recovery error was credited for the manual valves (left in wrong position initially);
- the test and maintenance activities for DG fuel line were considered as being performed in the same time with test of corresponding DG;
- there were not considered events associated with commission human error;
- the events with occurring frequency lower then 1.E-7 ev/an were considered as being unbelievable events, and they were not taken into consideration;
- it was allocated a generic value of 1.E-4 for all the events without available data;

The following top events were evaluated: [3]

PL1465 – Loss of power supply on PL1465 from 52900 DG1;

Failure Criteria: – DG1 fails to start or to run;

– line between DG1 and PL1465 unavailable;

– PL1465 unavailable;

PL1466 – Loss of power supply on PL1466 from 52900 DG2;

Failure Criteria: – DG2 fails to start or to run;

– line between DG2 and PL1466 unavailable;

– PL1466 unavailable.

3.3. Class III electrical power supply (CLIII)

Alternating current supplies to equipments that are necessary for the safe shutdown of the reactor and turbine are obtained from the CLASS III power supply with a standby diesel generators system back-up. These loads can tolerate short interruptions in their power supplies. This class of power supply comprises:

– two medium voltage buses supplied from the secondary windings of the two transformers on the class IV primary buses. These buses supply power to the loads with safety functions and protection of equipments (pumps in the service water system, emergency core cooling system, shutdown cooling system, heat transport system, feed lines, steam generator auxiliary feed line and the air compressors and chillers).

– a number of low voltage buses.

Stand-by power for the Class III loads is supplied by two diesel generator sets, housed in separate rooms with fire resistant walls. Each diesel generator can supply the total safe shutdown load of the unit. The Class III shutdown loads system is duplicated, one complete system being fed from each diesel generator. In the event of failure of Class IV power, diesel generator will start automatically. Each generator automatically energizes half of the shutdown load through a load sequencing scheme.

Assumptions: [3]

- all the circuit breakers which supply loads were considered in closed position;
- only one of the bus supply circuit breakers can be closed at one time, to prevent parallel operation for supply sources;
- all the failures which appear after the step-down transformers 6/0.4KV were not considered in the modelling;
- only fast transfer was credited;
- the supply circuit cannot be repaired without de-energizing the bus;
- there were not considered events associated with commission human error;
- it was allocated a generic value of 1.E–4 for all the events without available data;

- the events with occurring frequency lower then 1.E–7 ev/an were considered as being unbelievable events, and they were not taken into consideration.

3.4. Modelling considerations

The effects of ageing were modelled in PSA study on the component level, and the corresponding unavailabilities were calculated using the reliability law, where the failure rate is expressed as a function of time (the component age).

The unavailability of component can be expressed as:

$$U(t) = q_0 + 1 - \exp [- \int \lambda (t') \, \mathrm{d} \, t'] \qquad (1)$$

where:

t' - component age,

q_0 - failure probability for component at time t=0, which doesn’t depend on the component age.

To quantify the effects of age-related degradation on active components, the linear aging model (ref: NUREG/ CR-6415) was used. In this model, the failure rate of a component λ (t) is expressed as a sum of two independent failure rates, one associated with random failure, λ_0, (failure rate without ageing) and the other associated with failures due to aging α- the accelerating ageing rate, or the linear ageing rate for a component, which shows the rate on which the failure rate increases: [7]

$$\lambda(t) = \lambda_0 + \alpha t \qquad (2)$$

t – component age, expressed in time, or any measure of age, with the replacement or renew of component.

The linear failure rate can be simply viewed as a straight line fit to the wear-out portion of the standard bathtub curve.

The linear ageing model is very easy to use, by this constituting an attractive model for reliability assessment of ageing. In preliminary evaluations, are necessary less detailed data and generic data can be used.

The assumptions used by the linear aging model are:

- the component failure rate is proportional to the amount of deterioration;
- both the occurrence time and the severity of deterioration are considered to be random;
- the occurrence of deterioration is described by a stationary Poisson process.

The linear ageing model is suitable for modelling ageing mechanisms which cause a cumulative degradation in the component so as to continually increase its failure rate, and it can serve as a first order linear approximation, even where the degradation buildup is not linear or independent of the previously-accumulated damage.

In the process of components failure rates allocation the generic date were used, because due to the fact that the Cernavoda collection system started few years ago, the collected data are not very numerous

The amount of failure rate available and the information on the degree of component degradation (usually obtained by surveillance and condition monitoring), are limited.

As a result of the limitations above mentioned, in performing the analysis we use some assumptions:

- it was assumed that the failure rates of components follows the traditional bath-tub curve;
- to quantify the effects of age-related degradation, we use the linear aging model for all the components;it was assumed the same ageing rate for all the components.

The basic event was labelled using a computer code similar to CAFTA, EDFT, which was developed in INR Pitesti. The code is designed for:

- editing of INPUT files in text format;
- reliability data allocation for basic events;
- fault trees qualitative and quantitative analyses;
- fault trees drawings.

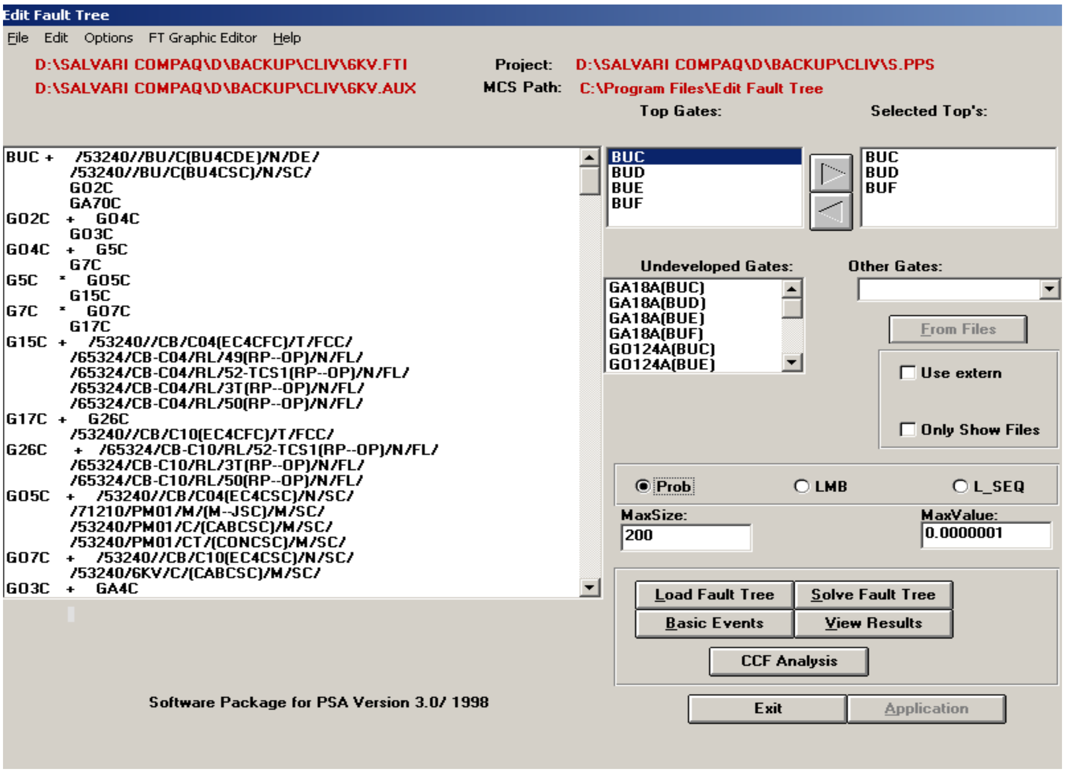
The qualitative and quantitative assessments were also performed using EDFT code. Reliability data used in the analysis were extracted from:

- Point Lepreau Component Reliability Data [4];
- IAEA Component Reliability Data for use in PSA [5];
- Ontario Hydro Data Base [6].

For the component ageing rates were used generic values [7].

The study focuses on the evaluation of ageing impact on system safety level rather than making an initial assessment or analysis of aging, including the identification of aging causes, mechanism, and effects.

The safety importance was studied at system level with qualitative and quantitative fault tree analysis.



D:\SALVARI COMPAQ\D\BACKUP\CLIV\6KV.FTI

D:\SALVARI COMPAQ\D\BACKUP\CLIV\6KV.AUX

Project: D:\SALVARI COMPAQ\D\BACKUP\CLIV\S.PPS

MCS Path: C:\Program Files\Edit Fault Tree

```
BUC +   /53240//BU/C(BU4CDE)/N/DE/
        /53240//BU/C(BU4CSC)/N/SC/
        G02C
        GA70C
G02C  +   G04C
        G03C
G04C  +   G5C
        G7C
G5C   *   G05C
        G15C
G7C   *   G07C
        G17C
G15C  +   /53240//CB/C04(EC4CFC)/T/FCC/
        /65324/CB-C04/RL/49(RP--OP)/N/FL/
        /65324/CB-C04/RL/52-TCS1(RP--OP)/N/FL/
        /65324/CB-C04/RL/3T(RP--OP)/N/FL/
        /65324/CB-C04/RL/50(RP--OP)/N/FL/
G17C  +   G26C
        /53240//CB/C10(EC4CFC)/T/FCC/
G26C    +  /65324/CB-C10/RL/52-TCS1(RP--OP)/N/FL/
        /65324/CB-C10/RL/3T(RP--OP)/N/FL/
        /65324/CB-C10/RL/50(RP--OP)/N/FL/
G05C  +   /53240//CB/C04(EC4CSC)/N/SC/
        /71210/PM01/M/(M--JSC)/M/SC/
        /53240/PM01/C/(CABCSC)/M/SC/
        /53240/PM01/CT/(CONCSC)/M/SC/
G07C  +   /53240//CB/C10(EC4CSC)/N/SC/
        /53240/6KV/C/(CABCSC)/M/SC/
G03C  +   GA4C
```

Top Gates: BUC, BUD, BUE, BUF

Selected Top's: BUC, BUD, BUF

Undeveloped Gates: GA18A(BUC), GA18A(BUD), GA18A(BUE), GA18A(BUF), G0124A(BUC), G0124A(BUE)

☐ Use extern

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MaxSize: 200

MaxValue: 0.0000001

Software Package for PSA Version 3.0/ 1998

Fig. 2. EDFT window.

4. Results

As results, the values of unavailability and major contributors for electrical systems of Cernavoda NPP, with and without incorporation of ageing effects, were obtained.

Only the first ten contributors, or those with more then 1% contribution to the achievement of undesired event were considered.

Class IV results

In the first case it was obtained for system unavailability a value of 7.04E–05.

In case of ageing effects incorporation it was obtained an increase value for the system unavailability (2.54E–03). The major contributors to 10 kV bus Class IV system unavailability before and after the incorporation of ageing effects are presented below.

Due to existing simetry, the analogy of the buses results is possible, so the results were presented only for one bus.

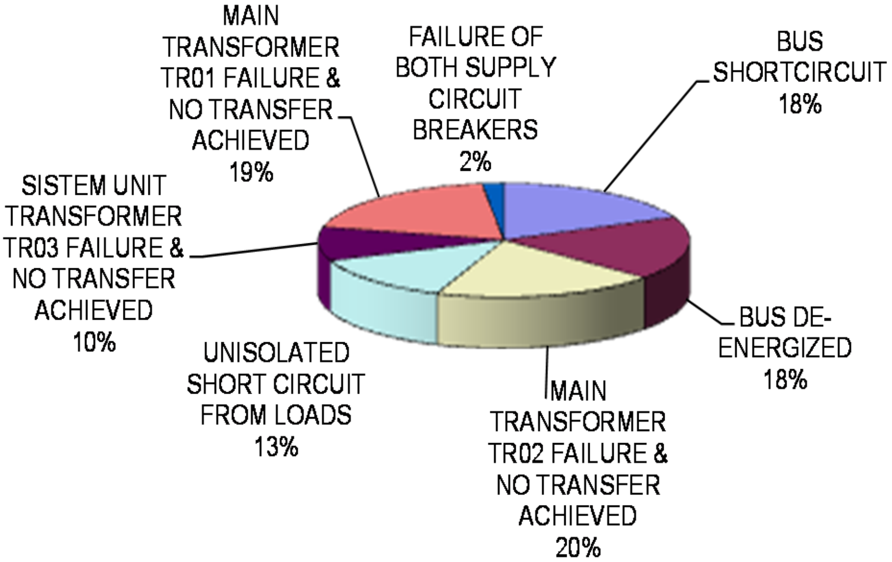

Fig. 3. Class IV contributors without taking into account the ageing effects.

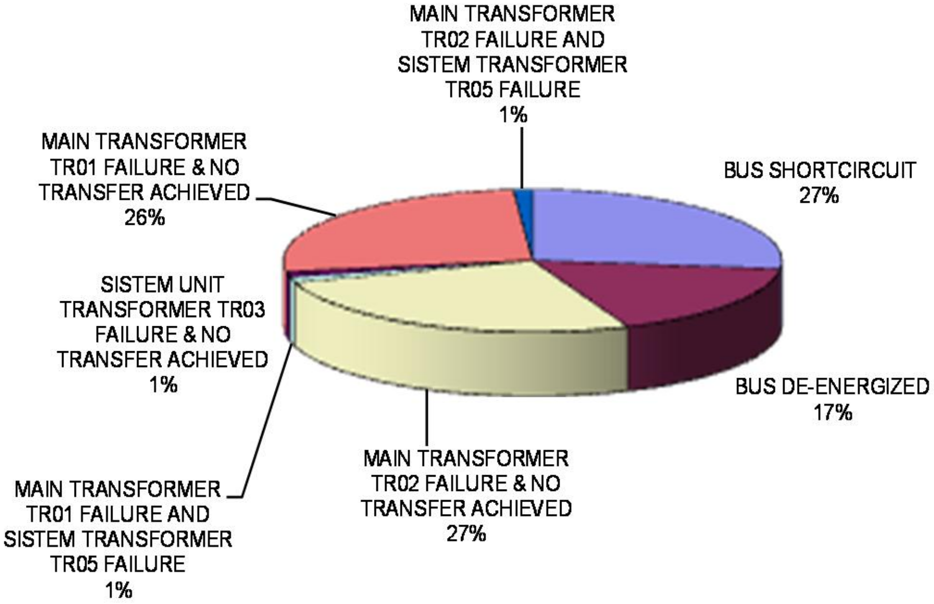

Fig. 4. Class IV contributors after incorporation of ageing effects

For 380V buses, we obtain a value of 5.1639E−05 without considering the ageing, and a value of 3.531E−04 for system unavailability after implementation in the model of the ageing effects.

Below are presented contributors for one 380V bus.

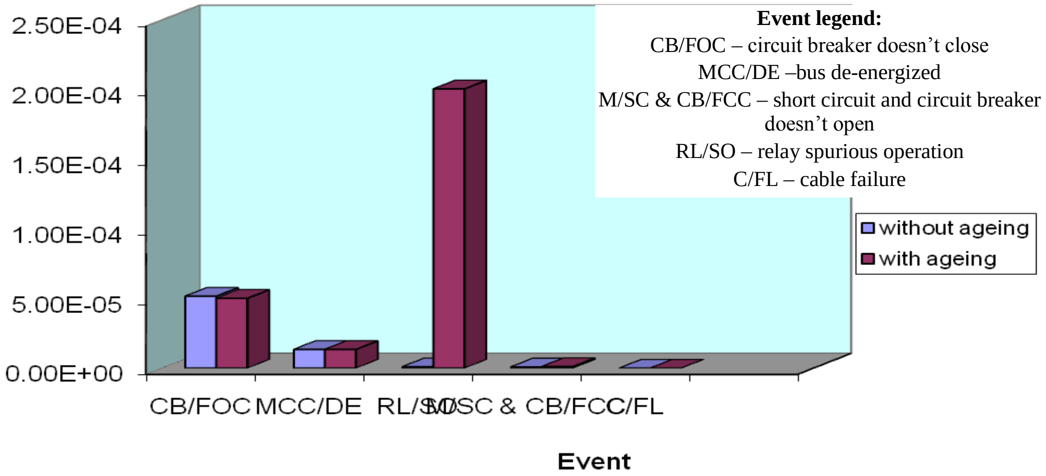

Fig. 5. 380V MCC CLIV contributors.

EPS results

The major contributors to EPS system unavailability before and after the incorporation of ageing effects are presented below (due to symmetry, below we present only the contributors of one EPS panel).

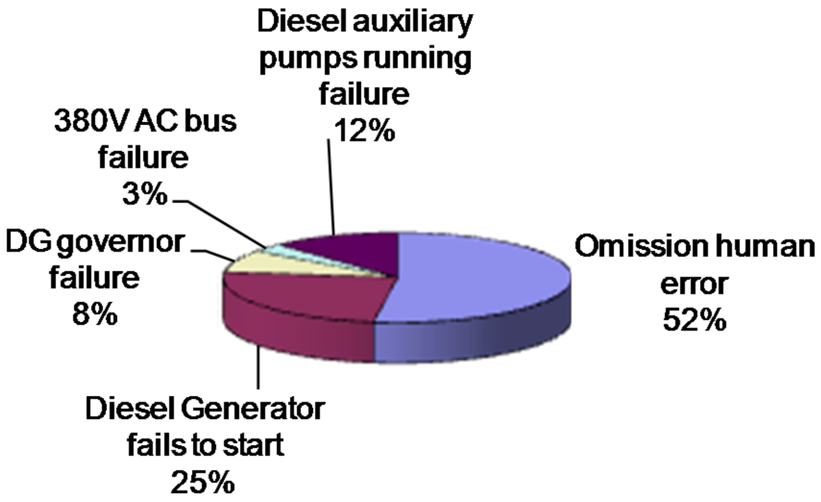

Fig. 6. EPS contributors without modeling ageing

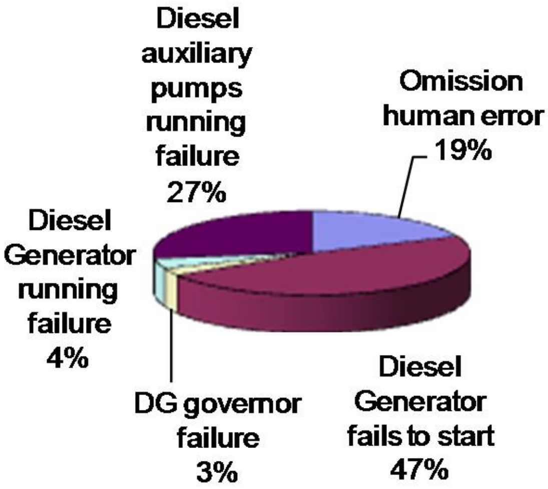

Fig. 7. EPS contributors after incorporation of ageing effects

Without the ageing effects incorporation it was obtained for system unavailability a value of 5.339 E–02.

In case of ageing effects incorporation it was obtained an increase value for the system unavailability (0.144).

Class III results

For Diesel Generators, without considering the ageing effects in the model it was obtained for system unavailability a value of 0.0205.

In case of ageing effects incorporation in the model, it was obtained 0.1328 for unavailability. The contributors are presented below (only for one DG):

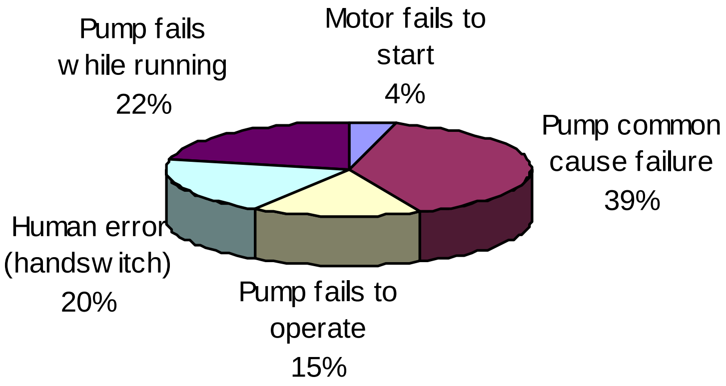

Fig. 8. DG contributors without considering ageing effects.

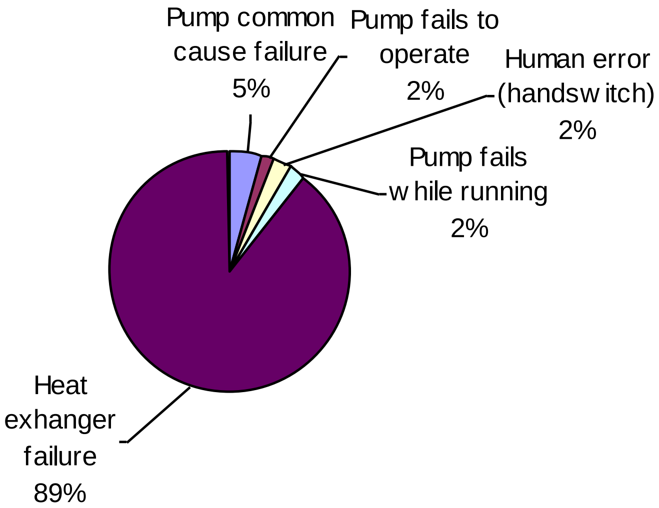

Fig. 9. DG contributors after ageing effects incorporation.

After implementation of ageing effects in fault tree developed for Diesel generators, the human errors are no longer major contributors to the unavailability of Diesel Generators system, as opposed to the failure associated to heat exchangers, which are becoming important only after modelling of ageing effects.

The major contributors to Class III system unavailability before and after the incorporation of ageing effects are presented below.

Due to existing symmetry, the results were presented only for one bus.

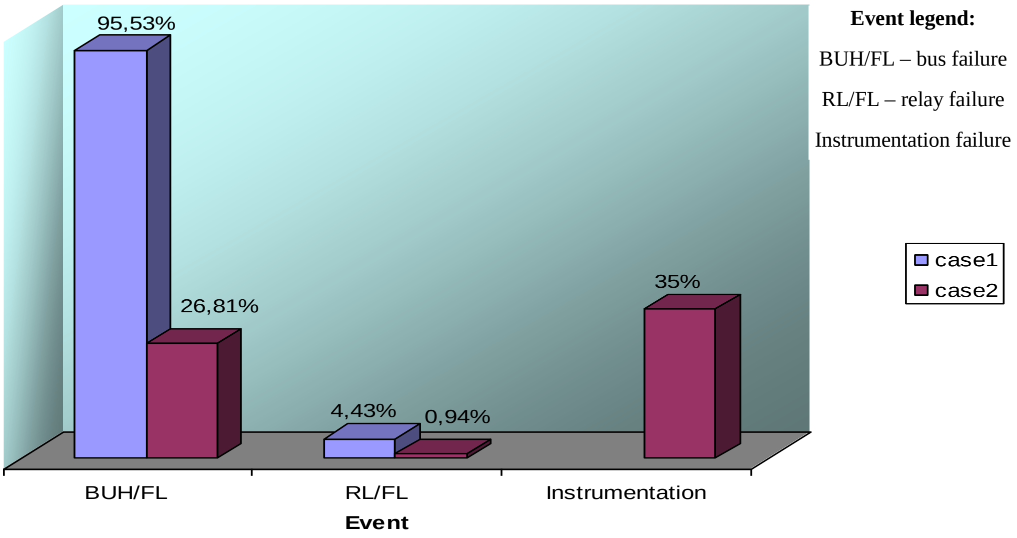

Fig. 10. CLASS III unavailability contributors.

Without the ageing effects incorporation in the model it was obtained for Class III system unavailability a value of 2.99E–05.

In case of ageing effects incorporation it was obtained an increase value for the system unavailability (3.5E–03).

Conclusions

This paper promotes the idea that PSA study can be used to evaluate the significance of ageing phenomenon. After performing the analysis, the following specific conclusion can be drawn:

- ✓ the values for system unavailability are increasing, after the incorporation of ageing effects;
- ✓ as the components age, contributions associated to aged major contributors are changing, some of the contributors can no longer be significantly major (case of human errors), or will became significantly major contributors only after the implementation of ageing effects (case of relays, heat exchangers);
- ✓ before the truncation of minimal cut-sets, it should be checked if the set related to age effects has or not the potential for being significant contributor (after incorporation of ageing affects in the model, some insignificant contributors can become significant).

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