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Reliability model for switchgear failure analysis applied to ageing

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Abstract: The failure analysis for each component is the biggest problem for maintenance task for switchgears. It should consider the redundant mechanical and electrical systems, in circuit breakers for the analysis. In recently researches, they are often described innumerable system failure modes, according to the methodology applied: RCM plus, RCM 2, among others. Nevertheless, in these methodologies, the specific effects are independently considered (for example the IEEE standard) has proposed 11 failures modes, furthermore CIGRE has proposed 4 evolutionary failures modes however The effects are independent for the failure mode, there is no interaction between them. On the other hand, this research proposes a new perspective with combinations between them and the degradation sequence for ageing process. A proficient method is used to recognize main failure modes, according to IEC 62271–100 (2011) and IEC 62271-1 (2007), later, in the space of arbitrary components, it accomplishes system reliability analysis to calculate the system failure probability, due to reliability analysis, this research proposes a new proposal to complement the IEC standards. To establish the main failure and to propose in decreasing in order their influence. This new proposal to model the searching technique uses the Weibull and gamma distribution. Finally, the authors have done a case study with the new proposal, to prove the reliability goal for contending failure modes under the faster circumstances than traditional methods. In the section 1, the main aspect for the failure analysis in switchgear is described, in the section 2 a system reliability is analyzed with the failure modes criteria: A classical approach and a reliability scope in the analysis. In the section 3 a new proposal is described for a framework, it considers the failure mode analysis and reliability studies, later, in the section 4, the case study is developed with thirty-four hydraulic switchgear and 3201 site acceptance test for preventive maintenance and a section 5, for a discussion about the new proposal in the international standards.

1. Introduction

In the last years, many papers have studied the failure probabilities, many of them about a single equipment or the behavior in the grid. So far, the reliability study has been done for a particular event, it designated by a particular "limit state function" [1], in the space of arbitrary components. In the literature, the scheme reliability forecast was considered based on dissimilar norms and pertinent, at diverse granularity of data [2]: "One technical solution is of the theory of power system reliability" [3], he has represented quantitatively assessing influences produced by element uncertainties, for example: Unpredicted power plant disconnection.

However, this method is appropriate for taking stochastic parameters. Many papers have been developed on its framework, due to

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evaluate reliability performances for power system analysis, for example: Non-conventional generation and his influence in the smart grids [4]. In the complexity prediction of the failures, the critical arrangement and incorporation of complex engineering procedures [1], with the statistical test have an important value for data integrity.

Both the expertise (hardware and software) in addition to in the incorporation of the systems, their data requirement should be verified. About the data, it includes the reliability, availability, maintainability. Besides, the safety process has an important factor in the systems and their associated components [5], the most important concept is the reliability, for the failure analysis [6].

Reliability could be regarded as the probability of effective operation or system performance, associated to their components with the lowest risk, if it has considered the loss or sudden failure. Scheming for reliability needs for a particular assessment of the failure effects, intrinsic systems and components [1]. Reliability forecast in this circumstances can be defined in its simplest form as "estimation of the probability of successful system performance or operation" [10]. Complementary, the reliability evaluation could be conceptualized as "estimation of the probability that an item of equipment will perform its intended function for a specified interval under stated conditions", as well as, "purpose of the occurrence with which elements failures happen over a specified period of time [7]. Availability considers the equipment maintainability, that is to say: How fast you can change the pieces and turn on the asset for the operation. If an equipment has the availability property, it needs an assessment of the effects of a sudden failure or performance of the integrated systems, and the critical requirements necessary to restore operation or performance to design expectations [26]. Maintainability is a fundamental feature of maintenance task, it considers the downtime for the analysis. If the equipment considered the maintainability design, it needs an assessment of the accessibility, that is to say, if it is easy to replace a component of the inherent systems, besides it considers its associated equipment in the event of a failure, as well as of integrated systems shutdown throughout planned task [7].

Safety should be classified as following:

- Relating to personal protection.
- Relating to equipment protection.
- Relating to environmental protection.

Safety in this situation should be described as "not involving risk", that is to say, the risk is called: "The chance of loss or disaster" [7].

Predictive maintenance (PdM) has introduced the potential defects and it has evaluated the future status of system health. The method mentioned above are just for one component in the system, it not consider the condition of the blocking function between the mechanisms between its mechanisms. Nevertheless, because of the growing "complexity and variety of systems" [8], it should be paid attention to PdM for multi-component systems [8] It is not considers in the currently standards and practices for the maintenance and assessment for the power system, with a focus in the circuit breakers. In the last papers about multi-component schemes [8], all the maintenance policies define element degradation with a relation of hazard rate (HR) failure rate (FR). Maintenance activities have considered tasks, if a system situation breaks more than one prescribed thresholds. On the other hand, the problem typically develops "how to optimize these thresholds or other parameters" [8], the focus with this perspective is the cost optimization. However, during the actual operation of a system, many factors will reduce the credibility of a maintenance scheme. It is very necessary to adjust maintenance actions dynamically according data such as on-line operating information and external environment factors [8].

Circuit breaker can interrupt fault current. The circuit breaker has the following class as following:

- "Continuous rating" [3].
- "Interruption rating" [3].
- "Insulating medium, and tank potential [3].

Continuous rating is the incessant current that could flow over the equipment without overheating (typically from 1.2kA to 5kA). Besides, the interruption rating is the main quantity of current caused by a failure, it could be interrupted (40 kA or 63 kA). In most equipment, the insulation is the oil and sulfur hexafluoride (SF6) gas; on the other hand, some years ago the common insulator was the vacuum. In South America, most switchgear or circuit breakers "have a grounded tank—referred to as a dead tank—enclosing" [9] the switchgear contacts. In Asia, most switchgear "have the tank at line potential—referred to as a live tank" [9].

The gamma weaknesses support with discovering the unobserved covariates and, thus, they improve the model's precision. It can define the circuit breaker reliability features, together with the starting point hazard rate or Health index and reliability R(t). Due to these weaknesses, the Weibull distribution has completed this procedure, with a rigorous statistics procedure for verifying the results. The main contribution is complement the actual standards for the calculations with Weibull and Site acceptance test results to ensure the reliability of the equipment. In that way, is easy to the companies the interpretation of the reliability analysis and to ensure the interactions of all the failures modes when an event caused an outage.

Currently, the power transmission system in Peru has a weak performance and high maintenance costs, considering the technological surveillance of the operation status of electricity transmission companies worldwide.

- The main problem is the limited knowledge in the diagnosis of equipment, it can be used to ensure the reliability of the equipment and the system, and therefore, if the management continues with the current model, the city reliability level and companies will not permit a future smart grid.
- The second important point is the government policies and the system model for the concession of the transmission of electric

power, which is based on a system planning based on the growth of cities and industries, with the increase in short-circuit and stability of the electricity system energy. However, the reliability of the system is not evaluated, it should consider the equipment is old, with a radial design and degraded, therefore, the Peruvian electric system does not have an integral model that allows to evaluate the renewals of energy transmission concession electrical.

With this novel framework and model, many companies will consider the failure mode analysis and reliability studies, besides; the case study is a guide to develop the model proposed with thirty-four hydraulic switchgear for preventive maintenance. These outputs allow the improvement of reliability through an appropriate decision-making, improving the reliability and performance of the electric power transmission system. The calculation of the Health Index (HI) (inverse of the deterioration index) allows studying the degradation and its modes of failure and its remaining life (Vr) allows calculating the failure probability time and planning equipment replacements or major maintenance.

2. System reliability using failures modes

The objective is to establish a theoretical framework, methodology and tools. It can diagnose system reliability using failures modes in circuit breakers.

2.1. Methodology

This research assumes a universal reliability study using both Bayesian semi-parametric and traditional degradation method. The objective is to demonstrate the degradation with the technical data; it could be exhibited and investigated to compliantly regulate reliability to provision PM strategy for circuit breakers, based on a general data-driven framework. On the other hand, GO Methodology has an important effectiveness as a method for system reliability study. There are some papers with a successfully applications; in the last years it has been used in the study for nuclear plants [10], with an emphasis in its components, key performance indicators and in some utilities for overhead lines, according to the author Xiuhong J. et al. [10].

2.2. Reliability approach

The evaluation is an extensive term, it contains all the methods used to regulate a creation design status or active capability. This evaluation could include detailed analysis, a distributed parameters model, simulation according to the different scenarios, and test.

2.3. Classical approach

Some techniques and methods cited by “organizations or companies for reliability prediction and life evaluation” [11]. One of the most important for this approach is from USA, a military handbooks called “Mil-HDBK-217” it has been used for prediction in electronic devices, it associated to maintainability [11]. Nevertheless, it has not intended to predict field reliability with more than one component, if it considers all the framework, it has not done precise good job [12]. In the field failure engineering and the association among them: Time vs currently stress level; it has not been considered in the handbook [13]. It does not denote to the failure mode, machinery of the devices. For example, some companies as General Motors (GM), communication companies as Intel and airplane constructors as Boeing “prefer to predict reliability in favor of the methods based on the product's failure modes and failure mechanisms” [14].

In the currently international standards, an example is the IEEE 1413, it offers a context for the reliability forecast process for electronic devices and components, it takes into account the software for production and hardware for establish new frontiers all levels [15].

Nevertheless, the forecast techniques need to complete the reliability assessment [16]. Still, these techniques and methods “are usually intended for devices and are not so applicable to a whole machine or electrical system” [5]. It has been proposed in the IEC 662271 [6,17].

For circuit breakers, the maintenances are the followings: Preventive and Corrective [10]. As the Fig. 1, the preventive maintenance (PM): Conditional and systematic [18]. The first one has proactive activities and based conditions and risk according deterioration index [19]. The systematic has predictive, cyclic substitution and overhaul [20]. The PM reliability assessment is a technique used for evaluating the future performance of the system, that is to say, forecast. It includes the use of algorithms and models associated to physical and mathematical behavior to simulate the behavior of the system in response to various outages that can occur in a system. Based on the response of the system to a fault, various customer and system wide indices can be computed [21]. PM and reliability evaluation methods could be integrated in two groups: Analytical techniques and modulation/simulation techniques [22]. Although, analytical assessment of reliability forms, it has been implemented for assessment programs, on the other hand the modulation techniques take into account the procedure of the Monte Carlo methods, it is more multifaceted and computationally intensive [23] for the results. If it considered all the results of each approach, just one has some rewards over the other and “hence useful to study both of them in a complimentary manner” [24].

For corrective, the classic approach has planned repair and unplanned repair. In the first one, it has remaining life parameters with health index using “Failure modes and effects analysis” called FMEA [25]. This methodology is the simplest techniques of calculating reliability, it studied by Billinton R & Wang P [2]. With the purpose of calculate the reliability of the system, individually

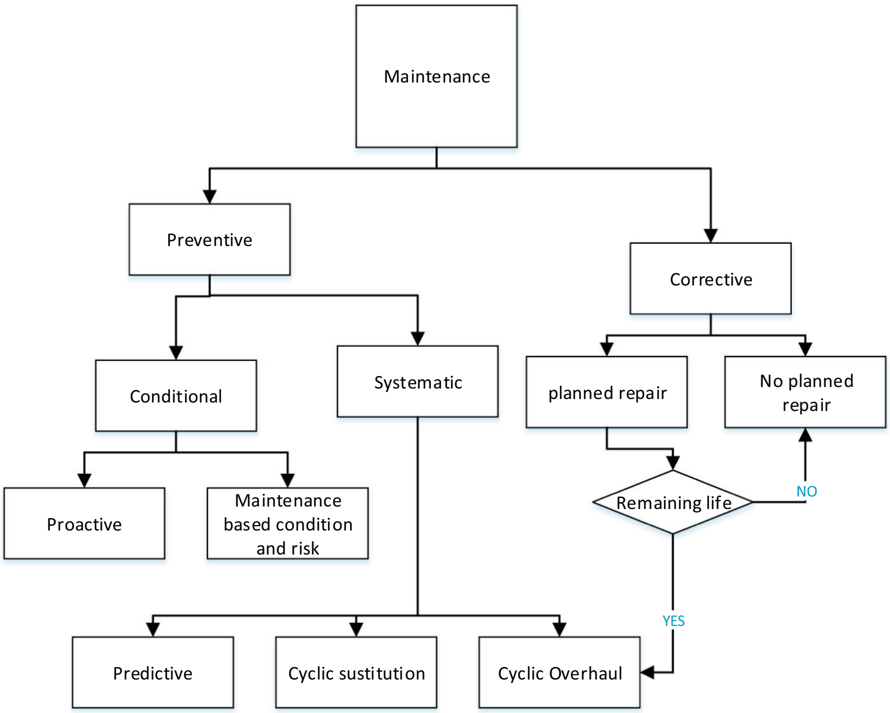

Fig. 1. Types of circuit breakers' maintenance [24].

of the fault conditions of the system [26], they expected the autonomously among events, and fixed before another happens [27].

3. New proposal in the failure mode analysis and reliability

3.1. New system reliability analysis using failure modes

First, malfunction of the circuit breakers can produce a power line failure [28]. The failure study is done for investigate the origin of the failure, to obtain more information about the devices, component level and explain the root cause in the analysis [29]. The Table 1 indicates the cause failure patters, then, several tests are selected to evaluate the reliability of the switchgear. Nevertheless

Table 1
Failure patters.

Item	Cause
1	Low level of gas pressure
2	Electric system alarm
3	Mechanical components damaged
4	Low pressure equipment
5	Low remaining life
6	Electrical components damaged
7	Oil leaking
8	Insulation problems
9	Packing
10	Cable damaged
11	Resistance contacts chamber
12	Oil leaking hydraulic actuator
13	Compressor damaged
14	Deterioration (corrosion)
15	Resistance box
16	Dielectric oil
17	Motor blocked
18	Porcelain broken
19	Bad purity SF6
20	Relay failure

"the test items may not be so efficient or direct to stimulate the exact failure" [3]. Modification of the "sorts of stress or the strength level are needed according to the relativity of the test results", if it is compared with the field failure engineering analysis [30].

The competing failures model have the followings characteristics:

- The failure modes has a simultaneously behavior. All the FMEA have influence of each other.
- For the FMEA, the failure time could be determined; for the analysis of the degradation associated to the failure mode. Furthermore, "the performance characteristic degrades over the life span" [31], due to this performance, the failure happens "when performance crosses its threshold for the first time" [31].
- The life span of the assets is considered to be "the time to failure of series systems" [32].

- If it considers some examples, "the Weibull distribution is used to describe the statistical properties" [37] of the failure engineering analysis, then Tx ~ Weibull (ηx,δx), ηx and δx mean the measure and the form limits for the xth failure mode. ηx is often a log linear function of a stress [33]. And for the xth failure mode, the accelerations factors ax is equal to ηox/ ηax, where ηox and ηax are the scale of limits at use and enhanced stress respectively and δx is endless and self-governing of stress, according to Authors Luo W et al. (2015) [18].

$$F(t) = 1 - \exp\left[-\left(\left(\frac{t - To}{\eta}\right)^{\beta}\right)\right] \tag{1}$$

where: β, η and To are constant values. > 0.

- If an equipment has a FM, the test is finished.
- The ageing processes for the degradation FM and the failure engineering analysis, "for the other failure modes" of the unit should not be indicated [34].

In the Table 2, we describe functional failures and Failure modes for a circuit breaker, it has been prepared from Table 1.

The new proposal, this model is developed in Figs. 2–4.

With the purpose of "allow a system-related problem-approach, it should become mandatory to include participants" [15] and relevant data base.

Gathering information for calculations, it is for each family asset (Circuit breaker / switchgear) formed and list of the maintenance report ads with information (date, start time and end fault), it is relevant to estimate Reliability, Maintainability and Reliability Percent [31], [32] With the Eq. (1), the reliability function is in the Eq. (2).

Table 2
Failure patters and modes.

Item	Functional failures	Failure modes
1	It doesn't allow flow rated voltage and current to be closed	High voltage connector false contact for corrosion
2	It does not operate the main contacts, under normal condition.	Polarity lost bad contact between terminals. Humidity
3	It doesn't operate the main contacts, under normal open order	Opening coil failure by faulty manufacture
4	The movable contact is not fixed insulator	Low SF6 pressure
5	Not isolate the lower end of the extinguishing system and electrically grounded.	Low pressure SF6 gas leak failure by slow packing
6	It doesn't allow the filling and extraction SF6 as required	Pollution
7	It does not allow pressure relief to pressure switch failure	Pollution
8	No DC and AC for open or to closet the circuit breaker	Breaking spring.
9	It doesn't operate the closed scheme	Low Pressure for a defective valve
10	It doesn't operate for close and open position	Selector position failure.
11	It doesn't have a nominal pressure	Wear of components
12	Does not trigger the alarm micro switch low air pressure control system	By recalibration in the spring vibratory drive
13	It does not guarantee a closing operation for each closing by anti-pumping system	Anti-pumping relay defect, pollution
14	It does not protect people against surges touch	Grounding deterioration connector to ground moisture.
15	It does not protect the coils opening and closing against over voltages	Failure of the voltage limiters
16	It doesn't send to the system protection and control signals breaker failure	Circuit terminal blocks gas moisture monitoring
17	Does not protect the motor against overcurrent	Breaker failure by internal Sulfur by moisture ingress fault contact resistance heating.
18	The dampens don't open and to close maneuvers	For loss of hydro line
19	It does not allow venting	By deteriorated valve component
20	It does not allow manual emergency opening operation switch	Defect corrosion lockup the switch
21	It does not have the oil level within the range hydraulic system	Oil leaking gaskets Fault
22	It doesn't hold pipes and hydraulic system accessories	By corrosion supports / brackets / bolts and moisture contamination
23	It doesn't contain the tightness of SF6	By breakdown of pack ageing for wear

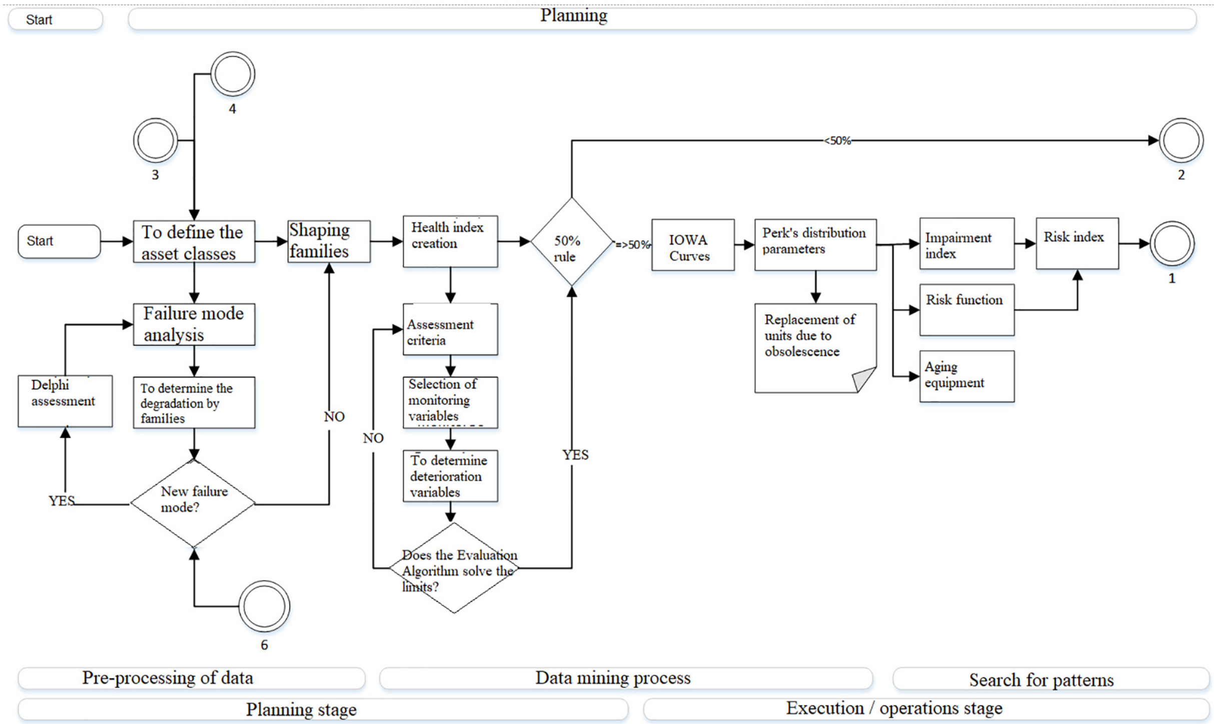

Fig. 2. Framework – A for system reliability analysis.

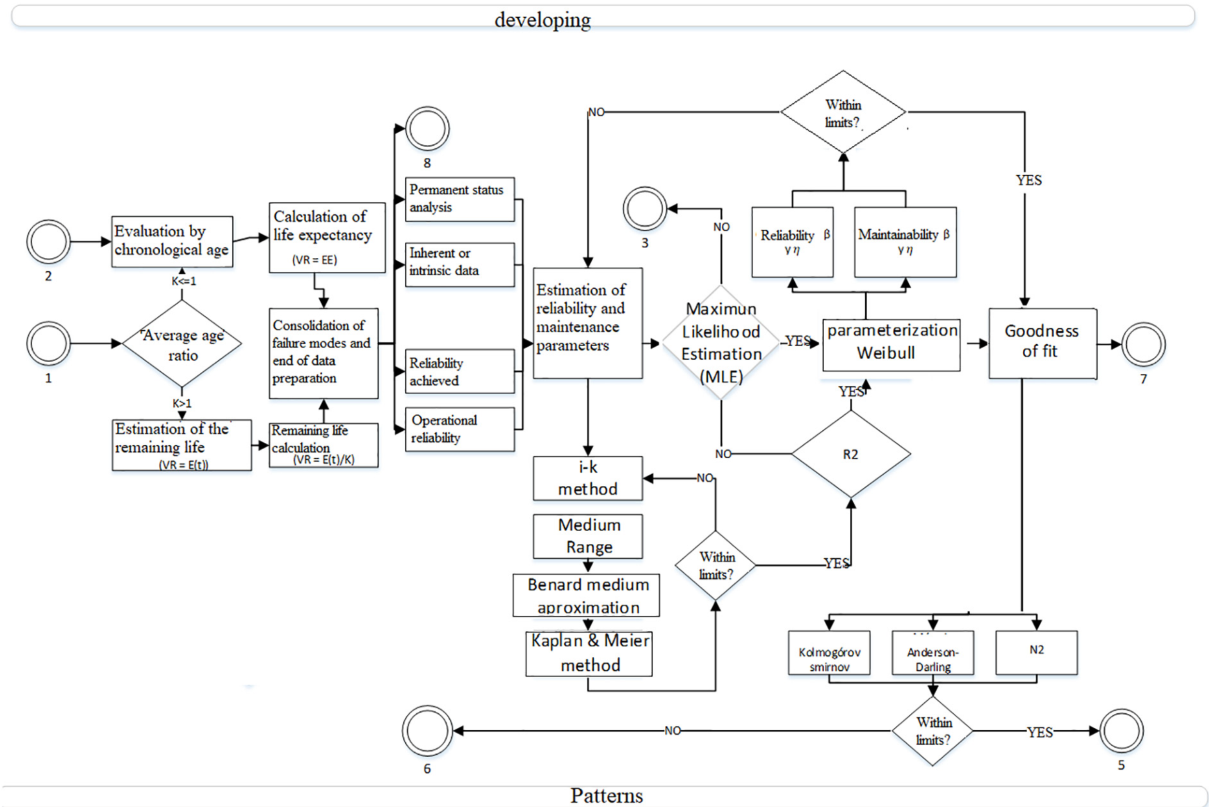

Fig. 3. Framework – B for system reliability analysis.

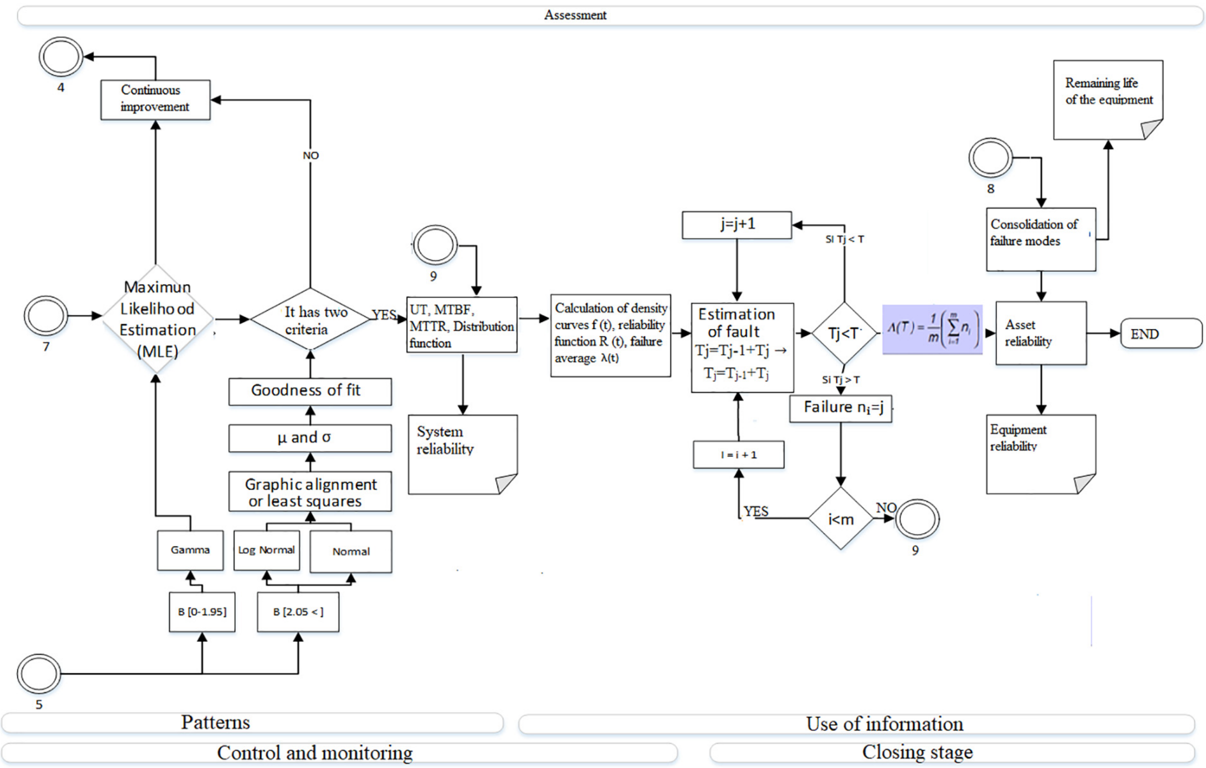

Fig. 4. Framework – C for system reliability analysis.

$$R(t) = \exp\left[-\left(\left(\frac{t - To}{\eta}\right)^{\beta}\right)\right] \tag{2}$$

where:

β: Geometric form parameter.
: Scale parameter.
To: Location parameter, with To > 0.

The probability density has calculated:

$$f(t) = \frac{dF(t)}{dt} = \frac{dR(t)}{dt} \tag{3}$$

It should consider:

$$\eta = \theta - To \tag{4}$$

The followings Eqs. (3) and (4) permit to obtain:

$$f(t) = \left(\frac{\beta}{\eta}\right) * \left(\left(\frac{t - To}{\eta}\right)^{\beta - 1}\right) * \exp\left[-\left(\frac{t - To}{\eta}\right)^{\beta}\right] \tag{5}$$

It is quite interesting to include interdisciplinary knowledge into such an equipment for the engineering analysis.
The second part from: Parameter estimation of unreliability and maintainability to Failure density curves:

- Probability graph.
- Parameter estimation.

This model needs a method: The Weibull distribution.
It has the advantage to simulate the behavior of probability failure function F (t) and maintainability M (t).

$$MTBMc = \eta^{*}Gamma\left(1 + \frac{1}{1+\beta}\right) \tag{6}$$

$$MTTR = \eta^{*}Gamma\left(1 + \frac{1}{1+\beta}\right) \tag{7}$$

MTBM: Mean time between Maintenance, corrective
MTTR: Mean time to Repair

Finally, the reliability percentage indicator is the followings:

$$Po = MTTR + MTBMc \tag{8}$$

Po: Reliability percentage indicator.

The real concerns are involved to the premature generation of failures. About the reparation task, it is usually derivated to the charge of the system and subsystem. In some cases, in opinion of the provider, it is covered by guarantee agreements in the contract.

Therefore, many researches and papers are associated to early life failures, in this case, a span life criteria is not well considered in the currently standards and methods, because there are many failures for montages, bad connections, materials for a specific task, it has a contribution as lesson learned for each participant in the maintenance. This means that the focus in root cause analysis should be directed into following directions:

- If there are any change in the early lifetime phase through each part of the system, stages, compared to future standard life.
- If a "failure rate level or does the failure rate decrease" [15] as if the repair never happens.
- "The failure rate within the regular life phase should be too high" [15], it might pact with a strength problem, it is to say, that the deteriorating equipment is perhaps worked out of conditions, due to the guarantee characteristics.

Instead of arguing the advantages and disadvantages of the 2 approaches (for example: Classical and Bayesian method), in this paper, we propose the results from different models can complement each other. Following discussions in section III, we now propose a general data – driven frameworks, using both classical and Bayesian degradation approaches to support the optimization.

- Step 1: Data Collection and Degradation data. These include the observed values of a physical process.
- Step 2: Data Preparation: Select degradation path. To determinate the path, select from among several candidates for the studied system/units instance, linear degradation, exponential degradation, power degradation, logarithmic degradation.

In the Fig. 5, the functionality profile is composed by time to failure (TTF) as a logic condition 1, it means an asset works as a normal condition, until it has a failure, in this point, the down time of the asset has a condition for a time in hours, later, it is repaired and the TTF happens again.

Where in the Fig. 5:

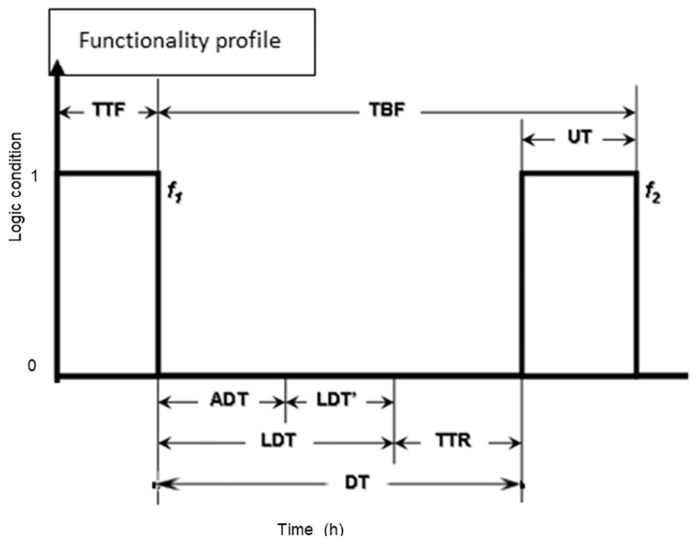

Fig. 5. Functionality profile.

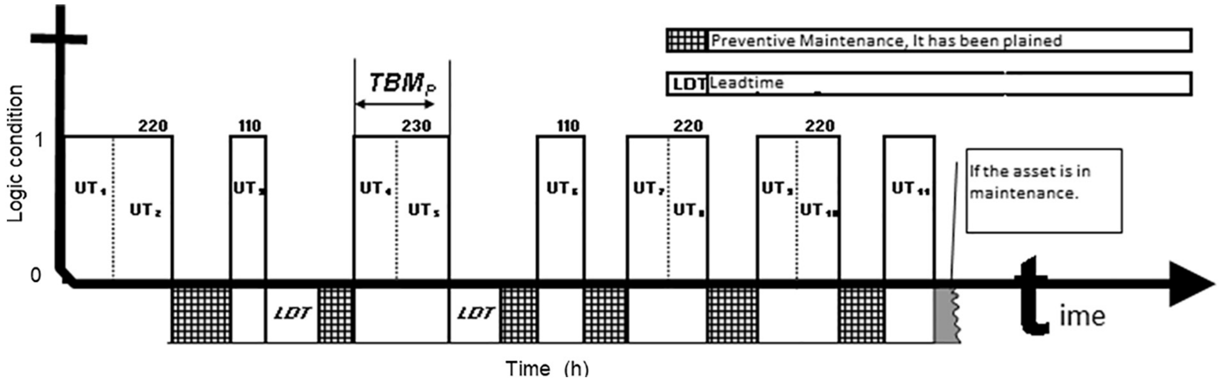

Fig. 6. Functionality for preventive profile events.

TTF = Time to failure.
TTR = Time to repair.

$$\sum TTR/m \tag{9}$$

MTTR = Mean Time to repair.
TBF = Time Between Failures.

$$\sum TBF/m \tag{10}$$

MTBF = Mean Time Between.
UT = Up Time.
DT = Down Time.
m = Failure number.

In the Fig. 6 the behavior of a system in operation and planned interventions or preventive maintenance has been observed in this step.

Besides, in the Fig. 7, the functionality for corrective maintenance profiles events are described for repairs and time.

- Step 3: Parameter estimation of unreliability and maintainability.
  "Predict and get lifetime data. This step uses the results" [2].

In the following paragraph, the formula of the Deterioration Index is as follows in Eq. (11).

$$HI = 100 - HI = \left(1 - \frac{\sum_{m=1}^{x} \propto_m (CPS_m{}^{*}WCP_m)}{\sum_{m=1}^{x} \propto_m (WCP_m)}\right) * \left(\frac{4}{3}\right) * 100\% \tag{11}$$

where:

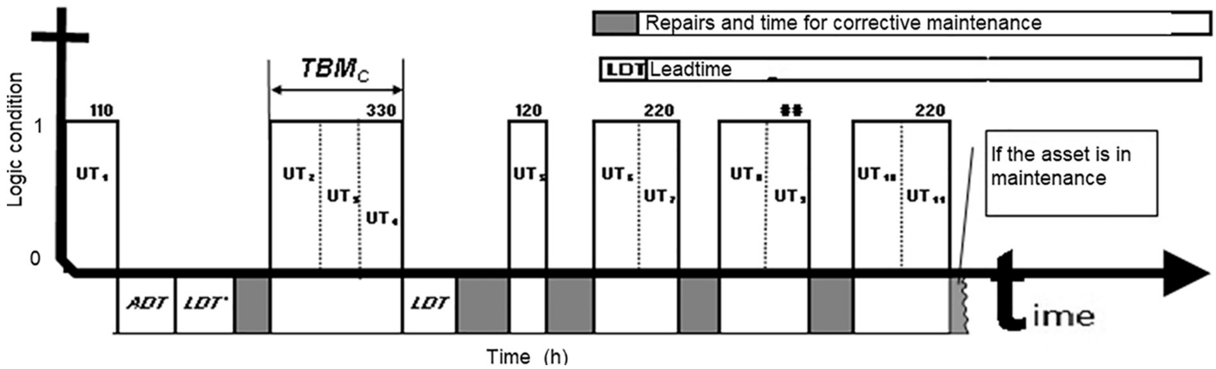

Fig. 7. Functionality for Corrective Maintenance profile events.

HI = Hazard index.
CPS_m = Rating parameter state of degradation.
WCP_m = Parameter weighting degradation.
α_m = Coefficient data availability. For the degradation parameter m (if the data is available, if the data is not available).

For determining the rating of the equipment condition shown in Eq. (12):

$$CPS_m = \left(\frac{\sum_{n=1}^{x} \beta_n (CPF_n{}^* WCPF_n)}{\sum_{n=1}^{x} \beta_n (WCPF_n)} \right) \tag{12}$$

where:

m = Number of parameters defined for the equipment impairment. “m”.
n = Amount of monitoring variables defined for each parameter of deterioration. “n”.
CPF_n = Rating state variable monitoring.
$WCPF_n$ = Variable Weight monitoring.
$\beta_n \rightarrow$ Coefficient data availability for monitoring variables.

For this parameter: An equipment has good condition if the Health index is zero. On the contrary, it is completely degraded if the health index is 100.

Data collection is very important in this step, however, when it is not a good quality data or partial data, it is possible to obtain a valid statistic health index if it is equal to 70% of the maximum possible score of statement of assets for a complete data set, according to Naderian J. et al. (2010), in this methodology a set of data greater than or equal to 50% (minimum rule) is allowed since there are several variables monitoring that are being implemented, this rule is summarized in Eq. (13).

$$50\%\_Rule = \left(\frac{\sum_{m=1}^{x} \propto_m (WCPF_m)}{\sum_{m=1}^{x} (WCPF_n)} \right) \tag{13}$$

where:

α_m = Coefficient data availability. For the degradation parameter, m (if the data is available, if the data is not available is equal 1).
$WCPF_m$ = Last measure of the weight monitoring.
$WCPF_n$ = Variable Weight monitoring.

- Step 4: Weibull Parameterization.

“Modelling, these steps consider reliability models using classical and Bayesian approaches” [2], it should considers the non-parametric and parametric approach, independently. The input data should be indicated in the last step [38].

- Step 5: Meets 2 test. Compare results.

It checks whether the result “from different approaches are consistent” [2].

- Step 6: Estimation of fault.

The inferences are important in this step, if it obtained satisfactory outcomes. It can achieve “reliability inference to determine system reliability, find the failure distribution” [2].

3.2. Framework development

A system reliability function has been implemented, starting with the description of the probability of failure, degradation and health index according to the Eqs. (14) to (21).

$$F(t,\theta) = \Pr\langle T < t \rangle = \int_0^t f(x,\theta)dx \tag{14}$$

$$f(t) = \frac{dF(t)}{dt} \tag{15}$$

$$r(t) = \frac{f(t)}{1 - F(t)} = \frac{f(t)}{S(t)} \tag{16}$$

$$R(t) = \int_0^t r(x)dx \tag{17}$$

$$F(t) = 1 - e^{-(t/\beta)^{\alpha}} \tag{18}$$

$$f(t) = \frac{\alpha t^{\alpha-1}}{\beta^{\alpha}} e^{-(t/\beta)^{\alpha}} \tag{19}$$

$$r(t) = \frac{\alpha t^{\alpha-1}}{\beta^{\alpha}} \tag{20}$$

$$R(t) = \left(\frac{t}{\beta}\right)^{\alpha} \tag{21}$$

These fuzzy sets can be integrated, based on main components, which describe the dominant modes of failure, determining the deterioration and remaining life index in Eqs. (22) to (29)

$$A = \sum_{i=1}^{n} (\mu_{\mathrm{A}}\ (\mathrm{xi}))/\mathrm{xi} \tag{22}$$

$$A = \int \frac{\mu_A(xi)}{xi} \tag{23}$$

$$\mu\mathrm{f(x)} = \begin{cases} 1 & ,\lambda, \\ \left[1 + \left(\frac{A-x}{a}\right)^{-1}\right. & ,\beta. \end{cases} \tag{24}$$

$$x_{j.raw}{}' = \frac{1}{m}\sum_{i=1}^{m} x_{y,raw};\ \sigma_{y,raw} = \sqrt{\frac{1}{m-1}\sum_{i=1}^{m} x_{y,raw} - x_{j,raw}{}'}, \tag{25}$$

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \cdots & \cdots & \cdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \tag{26}$$

$$\mathrm{Y = XA} \tag{27}$$

$$\begin{bmatrix} y_{11} & \cdots & y_{1n} \\ \cdots & \cdots & \cdots \\ y_{m1} & \cdots & y_{mn} \end{bmatrix} = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \cdots & \cdots & \cdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \cdots & \cdots & \cdots \\ a_{m1} & \cdots & a_{mn} \end{bmatrix} \tag{28}$$

$$y_{out} = \frac{\sum_{n=1}^{x} yi^{*}u(yi)}{\sum_{n=1}^{x} u(yi)} \tag{29}$$

Whose result applying the centroid allows to build the index in Eq. (30) and rating Eq. (31).

$$ID = 100 - HI = \left(1 - \frac{\sum_{m=1\alpha_m}^{x} (CPSm \bullet WCPm)}{\sum_{m=1\alpha_m}^{x} (4 \bullet WCPm)}\right) * (4/3) * 100\% \tag{30}$$

$$CPS = \frac{\sum_{n=1\beta_n}^{x} (CPFn \bullet WCPFn)}{\sum_{n=1\beta_n}^{x} (WCPFn)} \tag{31}$$

Whose factors allow verification by applying the minimum rule in Eq. (32).

$$Rm = \frac{\sum_{m=1} \propto_m {}^{*}\omega CP_m}{\sum_{m=1} \omega CP_m} \tag{32}$$

These results should verify the Eq. (32), and it can determinate the Eq. (33).

$$S(t) = \left(\frac{1 + e^{\beta * t_i + \mu}}{1 + e^{\mu}}\right)^{-\frac{e^{(\mu-\alpha)}}{\beta}} \tag{33}$$

The survivor curves are developed in the Eqs. (34) to (39).

$$H(t) = \frac{e^{(\beta^* t + \alpha)}}{1 + e^{(\beta^* t + \mu)}} \tag{34}$$

$$H(x) = A^* e^{(B^* x)} + C \tag{35}$$

$$A = \frac{\left[H\left(1/_2\right) - H(0)\right]^2}{H(1) - 2\bullet H\left(1/_2\right) + H(0)} \tag{36}$$

$$B = 2^* LN\left(\frac{\left(H\left(1/_2\right) + A - H(0)\right)}{A}\right) \tag{37}$$

$$C = H(0) - A \tag{38}$$

$$EE(t) = \frac{LN\left(\frac{H(x)}{e^{\mu *} H(x) - e^{\alpha}}\right)^*}{\beta} VU/100 \tag{39}$$

With it allowed to integrate the life expectancy in Eq. (40).

$$E(t) = \frac{\int_{t_i}^{t_{\max}} S(t)dt}{S(t_i)} = \frac{\int_{t_i}^{t_{\max}} \left(\frac{1 + e^{\beta * t + \mu}}{1 + e^{\mu}}\right)^{-\frac{e^{(\mu-\alpha)}}{\beta}} dt}{\left(\frac{1 + e^{\beta * t_i + \mu}}{1 + e^{\mu}}\right)^{-\frac{e^{(\mu-\alpha)}}{\beta}}} \tag{40}$$

Finally, the equations on successive faults are developed to find the reliability in the Eqs. (41) to (46)

$$F(t) = 1 - e^{\left[\left(\left(\frac{q}{\alpha}\right) \sum_{j=1}^{i=1} tj^{\beta}\right) - \left(\frac{ti + q \sum_{j=1}^{i=1} tj}{\alpha}\right)\right]} \tag{41}$$

$$P_f = \frac{n}{N} = \overset{Limite}{\rightarrow}_{N \to \infty} \left(\frac{n}{N}\right) \tag{42}$$

$$R(t) = P[t < T] \tag{43}$$

$$M(t) = P[T_t] \tag{44}$$

$$F(t) = 1 - R(ti) = \frac{j}{N + 1} \tag{45}$$

$$P = \sum_{j=1}^{N} \binom{N}{j} Z^j (1 - Z)^{N-j} \tag{46}$$

Applying the estimators in the Eqs. (44) to (46).

$$K - M = 1 - \prod_{j=1}^{N} \frac{N - j}{N - j + 1} \tag{47}$$

Futhermore, with the Eq. (47) is posible to build the reliability index.

$$MTBMc = \eta \bullet Gamma \bullet \left(1 + \frac{1}{1 + \beta}\right) \tag{48}$$

$$MTTR = \eta \bullet Gamma \bullet \left(1 + \frac{1}{1 + \beta}\right) \tag{49}$$

$$\text{MTBMc} = \eta \bullet \text{gamma} \bullet (1 + 1/(1 + \beta)) \tag{50}$$

$$\mathbf{P_O} = \frac{MTBMc}{MTBMc + MTTR} \tag{51}$$

$$\hat{F}_T(t) = 1 - [1 - \hat{F}_1(t)] * [1 - \hat{F}_2(t)] \quad (52)$$

In the Eq. (52) is possible to developed the basis of the average failure time estimate in the Eq. (53).

$$\hat{MTTF} = \int_0^{\infty} [1 - \hat{F}_T(t)]dt \quad (53)$$

With the Weibull distribution, it is developed using the following parameters:

- Using the parameters "β": If "β" < 1, it is called failure due to infant mortality, or decreasing failure rate; On the other hand, when it takes values close to one, the phase with the name of useful life (constant and random failure rate) is described; finally if "β" > 1; finally, the value and characteristics are described by Eq. (54).

$$F(t;s) = 1 - e^{-\left(\frac{t}{\beta(s)}\right)^{\alpha}} \quad (54)$$

With this novel framework in the Figs. 2–4 and described in the Eqs. (14) to (54), it is possible to do a diagnose, degradation, ageing and assessment of the quality of the maintenance applied to power systems.

It allows improving performance through greater reliability (equipment availability), through indicators predictive (degradation index and remaining life) of the equipment, which allows improving competitiveness, applicable to the current environment that guarantees growth with global indicators, proactively and with full knowledge of the state at the species (system) and individual level.

4. Case study

In this section, firstly, the efficiency and applicability of the system reliability analysis using failure modes for PM has been done for 34 circuit breakers and 3201 electrical test for the analysis. The results will be compared.

4.1. Step 1 data collection

In the Fig. 8, we indicate the equipment quantities; it is 34 hydraulic switchgears.

The collection data is since 2007 in the Fig. 9.

In the Fig. 10, the availability of the equipment is representing 1 to 8 times:

4.2. Step 2 data preparation

For the step 2, the data preparation determinates the track, it selected between quite a lot of applicants for the studied system or equipment. About the Table 3, the Index for the Preventive maintenance is the followings:

In the Table 4, it prepares a Mean Time Between Maintenance (MTBM) for PM.

About the Table 5, it obtains the Mean Time to Repair (MTTR).

Finally, the Table 6 describes the index for Mean Time Between Maintenance, for corrective actions.

4.3. Step 3 parameter estimation

For the step 3, the parameter estimation of unreliability and maintainability are described in the Table 7.

Step 3:

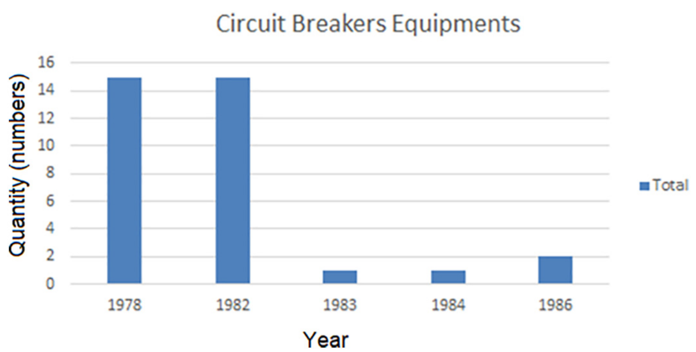

Fig. 8. Year of commissioning for study case analysis.

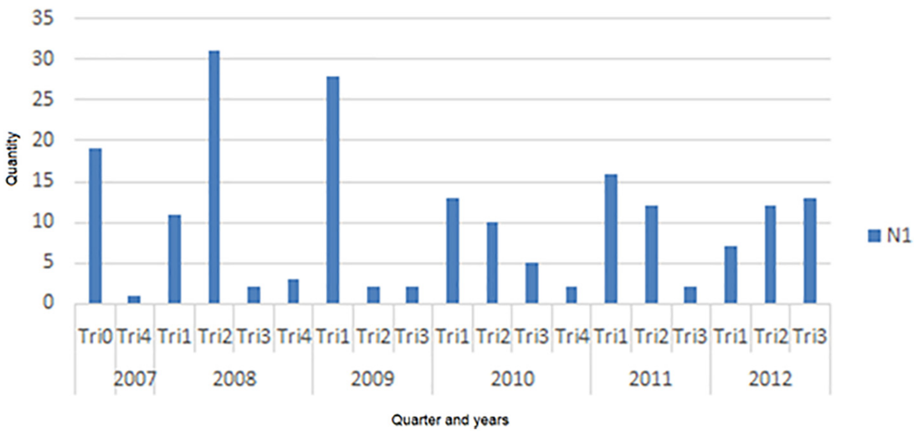

Fig. 9. Fault history.

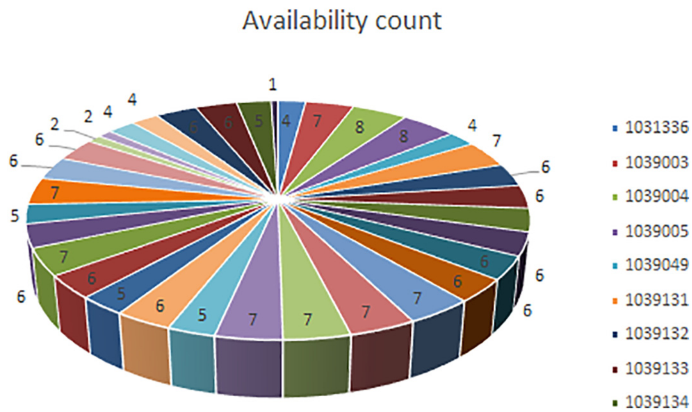

Fig. 10. Availability account.

Table 3
Index for preventive maintenance.

Index Mp (hours) Without adjustment	Index Mp (days) Without adjustment	Index Mp (hours) With adjustment	Index Mp (days) With adjustment
57.785	2.408	13.337	0.556
Standard deviation Hours 329.3826	Standard deviation Days 13.7243	Standard deviation Hours 13.8714	Standard deviation Days 0.5780

Table 4
Index for MTBMp.

Index MTBMp (hours)	Index MTBMp (days)	Index MTBMp (months)	Index MTBMp (years)
8920.433	371.685	12.389	1.032
Standard deviation Hours 3978.7109	Standard deviation Day 165.7796	Standard deviation Month 5.5260	Standard deviation Year 0.4605

The parameter estimation of unreliability and maintainability.

It considered 34 circuit breakers, 3201 electrical test for the analysis, for calculating remaining life, as shown in the system. At Table 2, it demonstrates the electrical test and measuring points for estimating the remaining life assessment in hydraulic equipment shown in the Table 8.

Table 5
Index for MTTR.

Index MTTR (hours)	Index MTTR (days)	Index MTTR (months)	Index MTTR (years)
556.89	23.20	0.77	0.06
Standard deviation Hours 1428.80	Standard deviation Day 59.53	Standard deviation Month 1.98	Standard deviation Year 0.17

Table 6
Index for MTBMc.

Index MTBMc(hours)	Index MTBMc (days)	Index MTBMc (months)	Index MTBMc (years)
5565.000	231.875	7.729	0.644
Standard deviation Hours 8769.0218	Standard deviation Day 365.3759	Standard deviation Month 12.1792	Standard deviation Year 1.0149

Table 7
Reliability index.

Index MTTR (Hours)	Index MTBMc (Hours)
556.889	5565.000
Reliability percent Po	90.90%

With the corresponding information for deterioration rates, the hydraulic circuit breakers are set in the Table 9.

4.4. Step 4 modelling

The Step 4 use the modelling, these steps consider reliability model using classical and Bayesian approach, according to Fig. 11.

In the Fig. 11, a remaining useful lifetime estimation and deterioration of hydraulic circuit breakers, they have been described in this research. This prognosis probabilistic approach associated for the circuit breakers component, Bayesian Method, to obtain reliable values for the result of the electrical and mechanical test, models it.

A interpretation of maintenance policy is indicated in the Fig. 12, a new remaining life is provided.

This model is appropriate for an ageing singularity, with phenomenon does indirectly observable. A sifting of degradation model projected to use electrical and mechanical test, based on prognosis and probabilistic properties.

4.5. Step 4 comparative results

For the Step 5, Compare results, it checks the result from different approaches:

The physical asset remaining life allows to prepare for contingency plan, with a mathematical certainty. At the Fig. 13, we describe the theoretical life consider in CIGRE Working Goup 37–27 (2000), if it considers the new reliability assessment, in the Fig. 14.

However, if it is applying the criterion of remaining life, you will get a better representation of the equipment reality:

Step 6: The reliability inference to determine system reliability fin the failure distribution, in the Fig. 14 and Table 10.

Finally, the failure distribution indicated in the Figs. 15 and 16, they are associated to the Table 11 for the equipment.

Finally, the failure distribution indicated in the Fig. 15, associated to the Table 11 for the equipment.

With the Fig. 16 has the followings index details:

The TTR has the followings Weibull parameters:

- $\eta = 1045$
- $\beta = 0.4137$
- MTTR = 0.77

The TBMci has the followings Weibull parameters:

Table 8
Corrective and preventive maintenance.

CAUSE	CORRECTIVE	PREVENTIVE	TOTAL
Gas pressure SF6	117	185	302
Electric system	55	62	117
Mechanical components	30	81	111
Pressure equipment	11	73	84
Remaining life	2	54	56
Electrical component	18	24	42
Oil leaking	13	23	36
Test	7	29	36
Insulation problems	1	31	32
Packing	4	24	28
Cable	3	24	27
Resistance contacts chamber		27	27
Oil leaking hydraulic actuator	1	26	27
Compresor	17	9	26
Other (Especial items)	4	19	23
Thermography	1	22	23
Deterioration	11	11	22
Breaker control box		20	20
Resistance box	1	18	19
Maintenance problems		17	17
Dielectric oil	3	12	15
Motor	6	9	15
Porcelane	2	5	7
Relay	3	3	6
Purity SF6		5	5
Grounding	2	2	4
Humidity SF6		4	4
Pressure equipment		2	2
Syncronized relay		2	2
Civil works		2	2

Table 9
Remaining life for circuit breaker family.

Deterioration index	0.211
Hazard	0.0036
effective age (years)	12.595
Operational age (years)	31.00
Factor	0.374
Useful life (years)	42
remaining life (years)	20.85

- η = 7350
- β = 0.9016
- MTTR = 7.72

5. Discussion

In the Fig. 17, as a discussion, after of all the analysis, the physical parameter applied in circuit breakers condition capacities, with the main circuit characterizes the High voltage and medium voltage wires and circuit breaker terminals in addition "to the bushings in the case of a dead-tank design" [30].

Besides, in the Fig. 18, the grey points represent the failure risk probability distribution and the blue and red lines are the 90th and 10th percentile respectively. It has an important discussion as following:

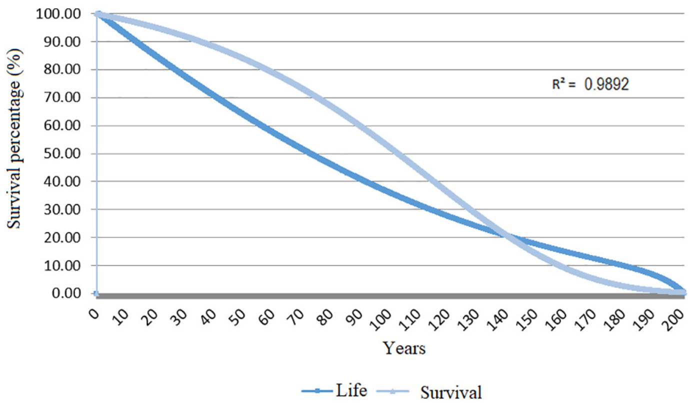

Fig. 11. IOWA curve family hydraulic circuit breaker.

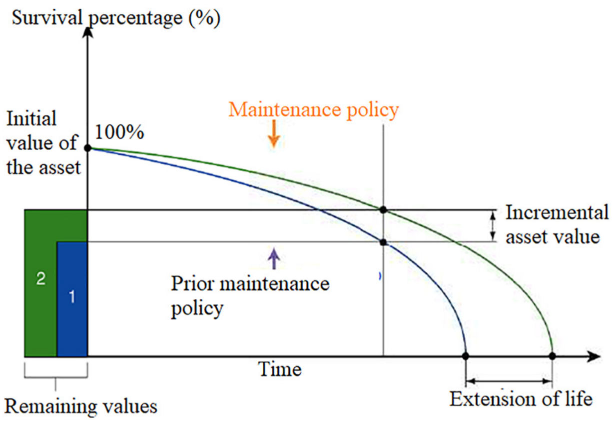

Fig. 12. Interpretation of survival curves for maintenance policy.

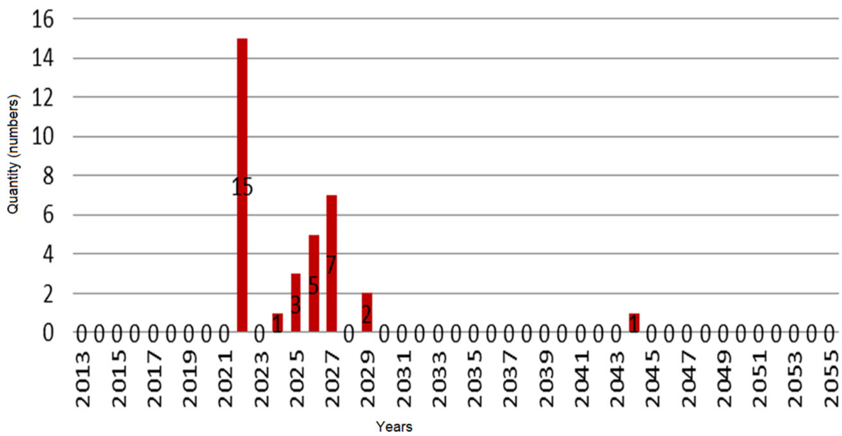

Fig. 13. Number of equipment to renew as theoretical life.

- If it considers the major failure frequency, a line interpolating a probability of failure could be assumed. The "failure engineering analysis and statistics applied, it should be taken from collected data" [35] on the specific asset. Just with this model proposed might offer guidance as a reference. The higher asset information available is and the more precise the assumed risk probability curve will be.
- The asset manager should define an acceptable failure risk probability (red dashed line).
- If "the failure risk probability is reached, refurbishment or renewal is needed" [36]. For example, it is assumed a probability of 2 major failures per 100 switchgear per year (red dashed line).
- Without any monitoring, an upper line of the available statistic should be used in order to cover the majority of the possible cases

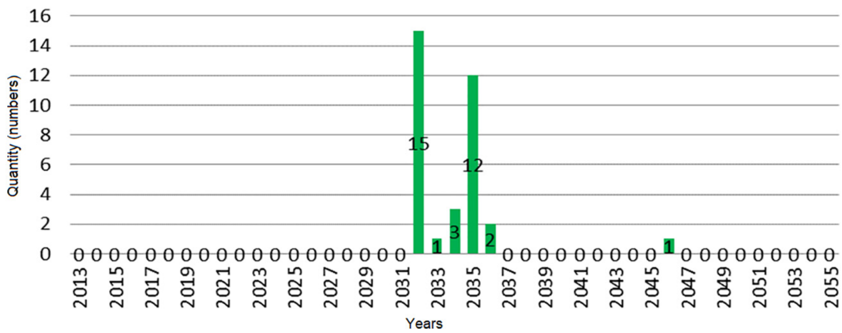

Fig. 14. Number of equipment to renew as Bayesian method.

Table 10
Key performance indicator for reliability.

MTTR		MTBMc		Mp		MTBMp	
Index							
Time (months)	0.77	Time (months)	7.72	Time (days)	0.55	Time (years)	1.03
Standard deviation	1.98	Standard deviation	12.17	Standard deviation	0.57	Standard deviation	0.46
CV	256.57%	CV	157.57%	CV	104.01%	CV	44.60%
Reliability Percent							
Po		90.90%					

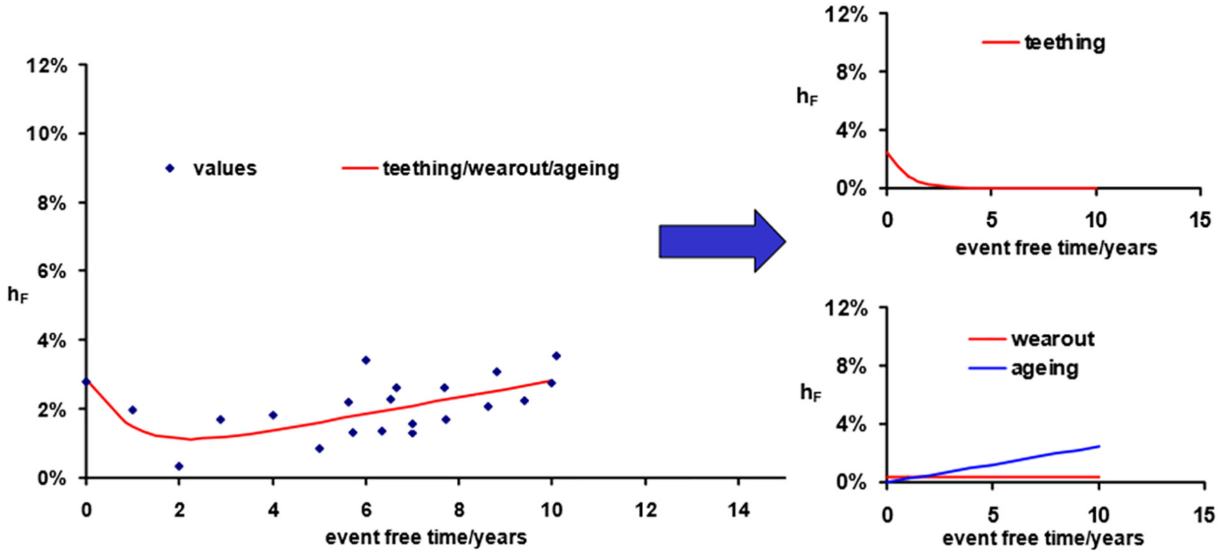

Fig. 15. Failure distribution.

(for example 90th percentile) [38].

- In economic scope, at the current year (i) the saving is proportional to the reduced failure Risk probability multiplied by the cost in the case of failure. To determine the total economic benefit along the whole asset life of (n) years, the benefit of every year (i) has to be taken into account with Eqs. (3) to (5) once the update rate (r) has been defined. This updated rate considers that the value of money today will be not the same in the future.

About the test, the static contact resistance measurement is performed while the Circuit Breaker is offline. "The contacts are closed and the test leads are applied to the primary path on both sides". For safety "reason it is recommended to ground at least one side".

Typical measured anomalies are:

- Increased resistance; typical value between 10 and 100 micro Ohm

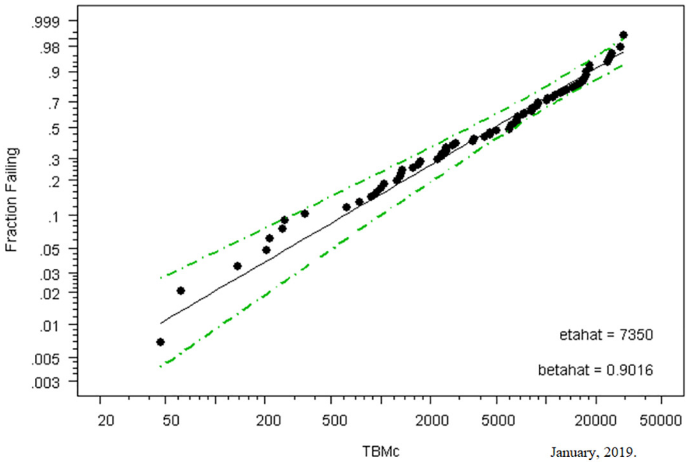

Fig. 16. Weibull probability plot – MTBMc data.

Table 11
Results for the equipment.

Number equipment	34	
Corrective reports	40	
	MTTR	MTBMc
Number data	40	35
Valid data	36	19
Percent valid data	90.00%	54.29%
Preventive report	191	
	Mp	MTBMp
Number data	191	177
Valid data	178	141
Percent valid data	93.19%	79.66%

- Fluctuating resistance
- High variations between similar contact systems (i.e. between phases)

The contact degradation process is a self-accelerated process which slowly develops over years until it finally speeds up dramatically before it causes a failure. Because of this behavior, it is sufficient to perform this test during regular maintenance work and commissioning.

There the applied DC current is separated from the voltage drop measurement. This separation results in a higher "accuracy because the contact resistance of the current leads can be neglected". Recommended injection current levels are at least 50 [17] or 100 A up to the rated current of the equipment. Occasionally there might be contact grease or decomposition products present at the contact surfaces and thus causes a lower resistance value at higher currents.

On the other hand, The Dynamic Contact Resistance Measurement (DCRM) is usually applied at medium and high voltage on SF6 circuit-breakers, which are characterized by two sets of parallel contacts, namely the arcing and the main contacts. During the opening operation, main contacts separate first and the current is commutated to the high-resistance arcing contacts, which separate a few milliseconds later. Thus, measuring the contact resistance during the opening operation reveals the condition of the arcing contact whereas measuring the contact resistance while the CB is closed shows the condition of the main contacts, as the Fig. 19.

The measurements are usually done during an opening operation and the test leads are applied to the primary path on both sides. Anomalies, which can be detected in a dynamic contact resistance measurement by changes in the resistance characteristic as following:

- Arcing contact wear.
- Abnormal current path current, as in the Fig. 19.
- Misalignment and wrong assembly in the interrupter, in the Fig. 20.

These changes can be detected by comparing with previous measurements, i.e. during commissioning, or by comparing between the three phases.

It results may become complex and some diagnostic misinterpretations are thus possible. In fact, the arcing contacts resistance should be strongly influenced by many factors, such as:

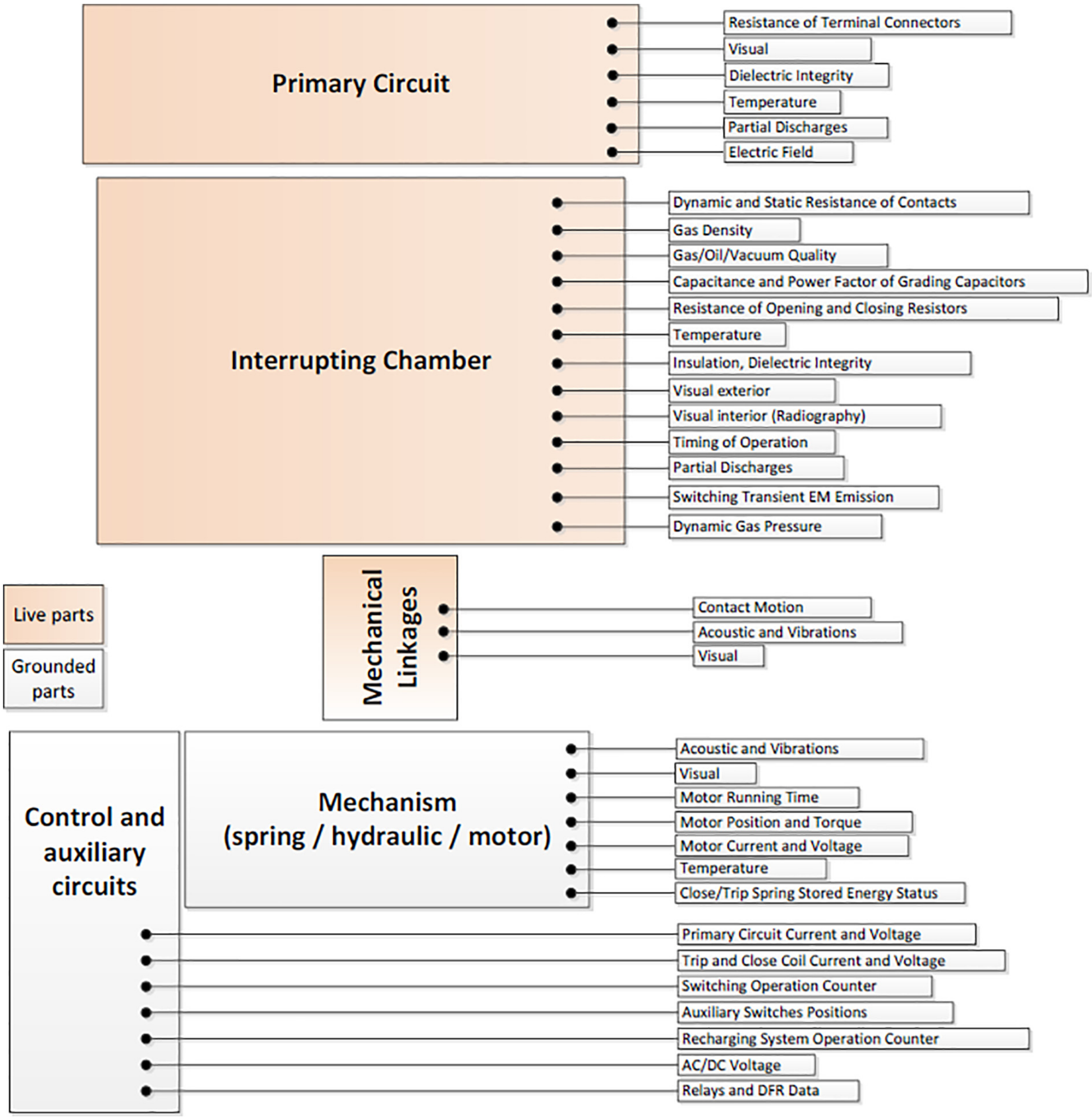

Fig. 17. Measured physical parameters in switchgear condition evaluation.

- The injected DC current intensity
- Fast changing force at the contact fingers causes a fast changing resistance value; in particular during the closing operation
- The possible presence of metallic fluorides deposited on the contacts
- The possible poor connections between current cables and the CB terminals

About the mechanical components problems in the Fig. 21, the fatal attempt to charge calculates the occurrence of unexpected recharges of the spring. Due to the recharge mechanics, there might be a sudden slip-through which triggers a recharge operation. This failed attempt to charge can be detected in the following way: in normal operation the motor is started at a closing of the breaker and a sensor detects when the spring is completely charged. Therefore, an approach to track a slip-through is to check whether the sensor signals that the spring has been charged without any closing operation.

In the Fig. 22, with this new framework, a new maintenance policy could be made, in this case, if it happens, a new performance is achieved, it is calculated in the Table 12.

According to this research, it is necessary to analyze the failures in the power systems, by equipment, by family and configuration

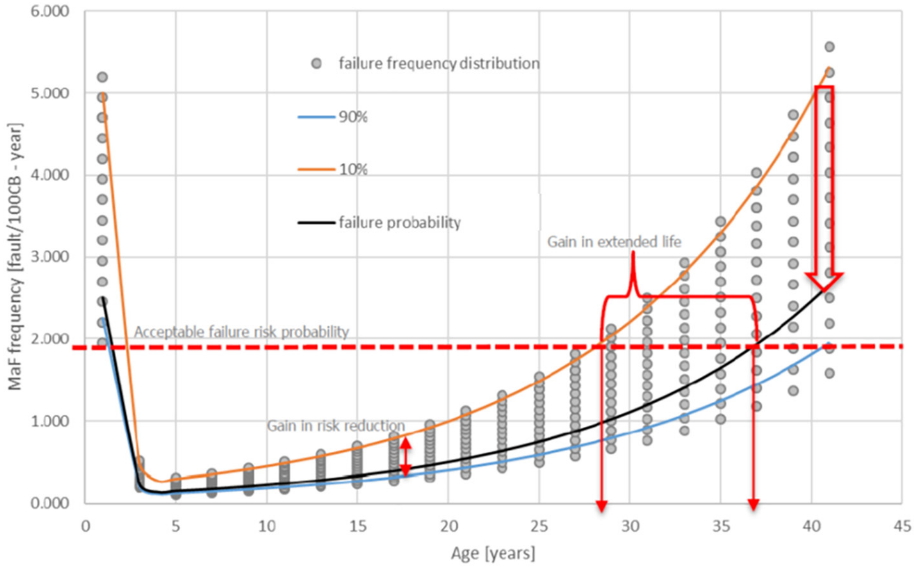

Fig. 18. Frequency major failure risk probability.

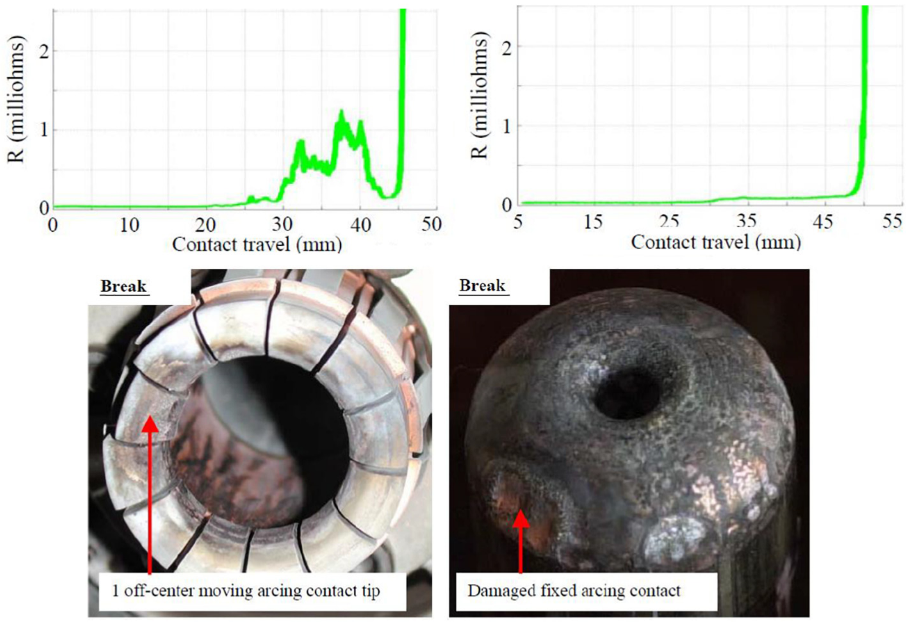

Fig. 19. Example of contact degradation with Dynamic Contact Resistance Measurement.

in the system, in order to establish an improvement in decision-making. The creation of models in both assets [43] and components [44] has been an important task for the improvement of policies, manufacturers and continuous improvement process.

Finally, the information is described in the Fig. 23 for Perk's parameters distribution, besides, the Fig. 24, the effective age is analyzed with the deterioration index.

According to the Figs. 23–25, the characteristics are the following:

- The average life is 97% of the useful life: 31 years, Table 13.
- The maximum life expectancy is 64 years.
- The probability of life of 40 years is recommended. In which an overhaul or repowering of the system should be performed to control the failure modes of the system.

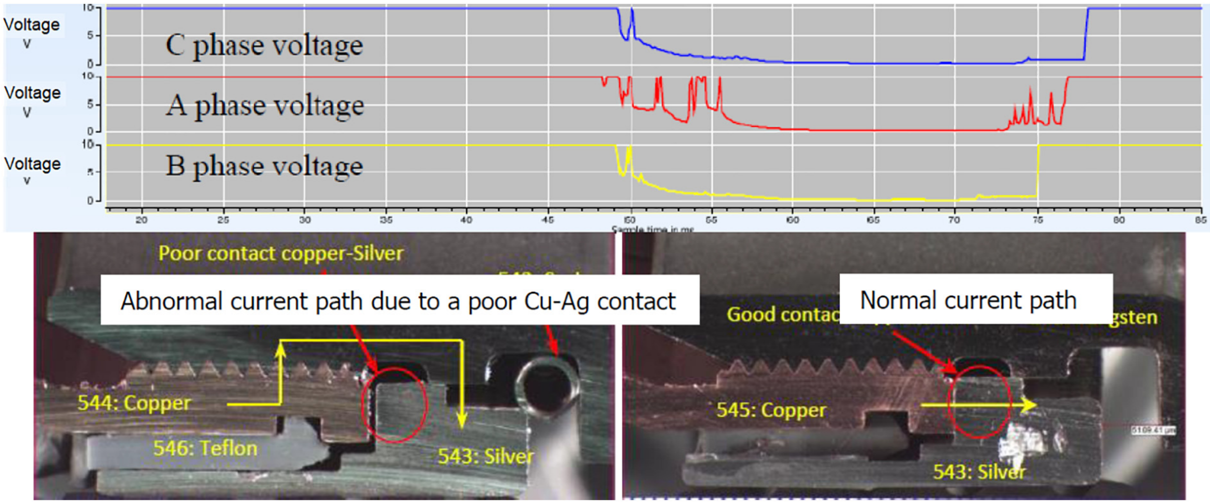

Fig. 20. Abnormal current path current.

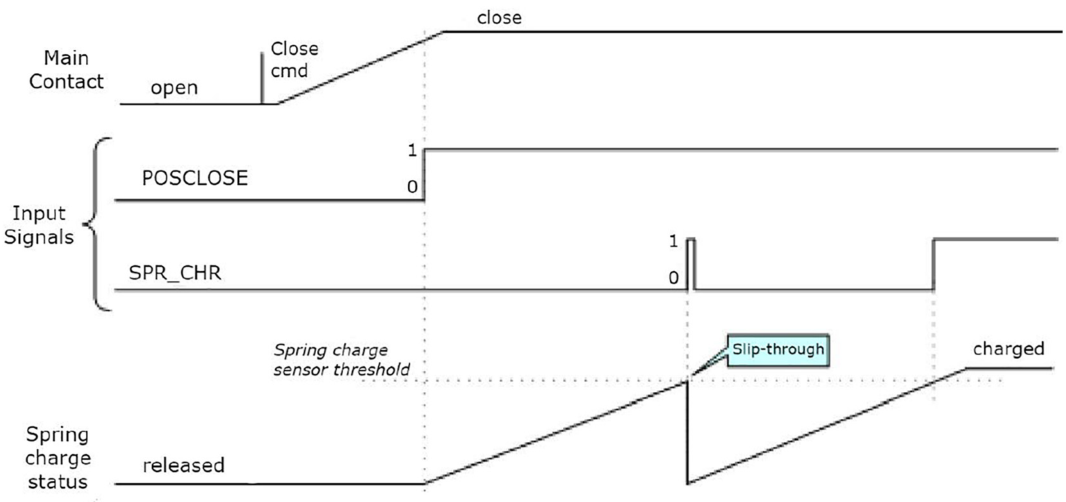

Fig. 21. The Fatal attempt to charge.

6. Conclusions

By using the discussed evaluation method, it is possible to recommend maintenance intervals for conditions based maintenance. This method was applied to calculate the intervals for circuit breakers with hydraulic drives, the new method is a completed for improvement of the IEC standards [17].

This research suggests a reliability model based on information available in the maintenance system – driven framework using both classical and Bayesian methodologies. It illustrates the ageing process and the necessary data for the creation of the model. This model can be demonstrated and analyzed, with an important factor; it is the flexibility to build the reliability expected during the maintenance strategy making and the knowledge of the equipment. The case study considers both an Exponential and an ageing (degradation) path for thirty-four circuit breakers. Using a classical approach, it uses both accelerated life test and design of experiments technology to determine how each critical factor.

The gamma weaknesses support with discovering the unobserved covariates and, thus, they improve the model's precision. it can define the circuit breaker reliability features, together with the starting point hazard rate or Health index and reliability R(t).

The closer knowledge the user has about the condition indicators to be assessed and their typical failure modes, the easier the selection of the non-intrusive method and its evaluation. Several failure modes are presented for a live tank high voltage circuit breaker. Three main cost elements have been identified: investment in the non-intrusive method, maintenance costs with and without the non-intrusive method and failure/outage costs with and without the non-intrusive method. The cost calculation contains several values that should be set by the user, as some costs are difficult to estimate or to quantify, as the cost for outage.

Generally, the failure modes as presented in the international standards as IEEE [39] and CIGRE [40] cover most of the failure

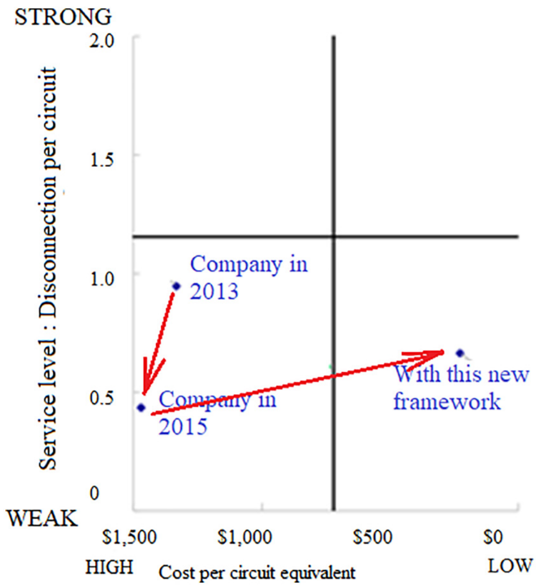

Fig. 22. Improvement in the reliability of the circuit breaker.

Table 12
Calculation for service level and cost per circuit equivalent.

Item	Year	Service level	Cost (USD/km)
1	2013	0.95	1490
2	2015	0.45	1310
3	With a new framework	0.70	250

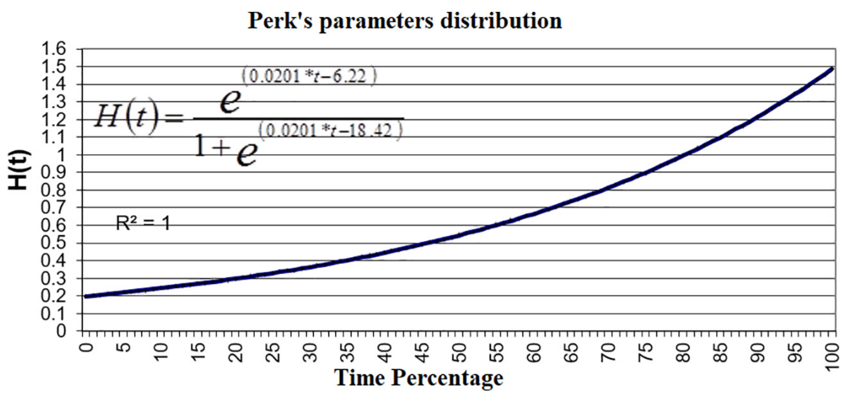

Fig. 23. Circuit breaker Perk's distribution.

characteristics typical of transmission and distribution switchgear. In the particular case, a specific failure characteristic is not available or unknown, a frequency of failure that increases exponentially with age provides good guidance. This is based on the Gompertz-Makeham law of mortality. Different asset groups experience different failure rates and, therefore, different probabilities of failure so the shapes of the failure and probability curves are different [41,42]. Without overgeneralizing, typical failure mechanisms of transmission and distribution switchgear can be attributed to any condition indicator of an asset in the grid. This research has a complete contribution for failure engineering analysis for circuit breakers using theoretical data and site acceptance test as a complement of the international standards IEC, IEEE and CIGRE.

Finally, the proposal has a data – driven framework in this research; it can be developed to circuits breakers for electrical and mechanical problems.

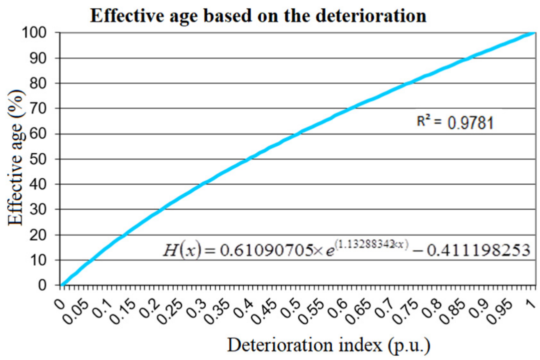

Fig. 24. Effective age and deterioration index.

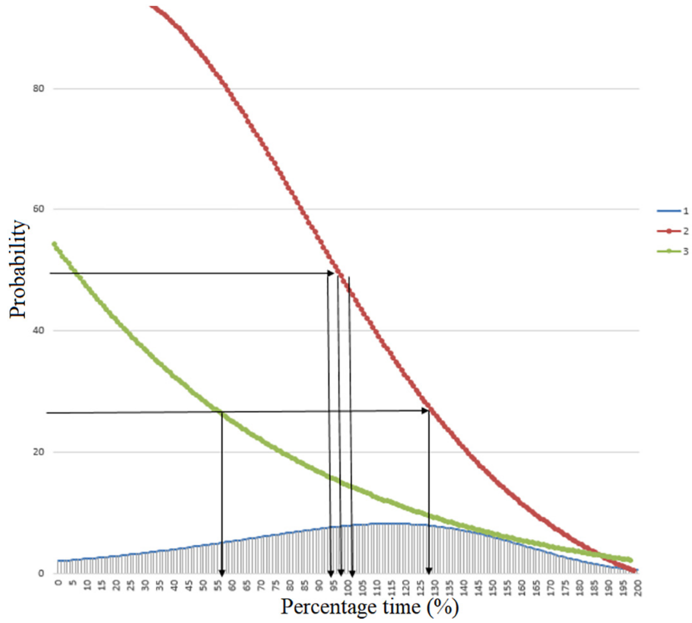

Fig. 25. Survivor curve for circuit breaker.

Table 13
Average life.

Asset	Useful life for Perú	Useful life model	Curve
Switchgear / circuit breaker	31	[28–31–40]	R1

Acknowledgment

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