Reliability analysis of power equipment in a combined-cycle power plant

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Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Resumo

De acordo com a Agenda para Desenvolvimento Sustentável para 2030 definida pela ONU, [1], um dos objetivos é assegurar energia acessível, fiável, sustentável e moderna para todos. Esta tese visa em contribuir para a melhoria da fiabilidade de energia, de forma a cumprir com as expectativas traçadas pela ONU. Focando nos equipamentos de potência de uma central elétrica de ciclo combinado de 28MW 61,5kV, três tipos de estudos de avaliação de fiabilidade e disponibilidade foram realizados: substituição, influência e adição de componentes. De forma a servir como termo de comparação, a fiabilidade e disponibilidade originais da central elétrica foram calculadas e usadas como um caso padrão de referência (CP). Adicionalmente, um estudo de manutenção preventiva foi efetuado para quatro frequências distintas. A metodologia aplicada nos estudos referidos foi uma combinação de três métodos: “Reliability Block Diagram”, “Markov Chains” e “Monte Carlo Simulation”.

Relativamente a resultados, do estudo de substituição de componentes, onde se realizou uma simulação focada na troca de disjuntores clássicos por eletrónicos, resultou uma melhoria da média total de fiabilidade de 22%, em relação ao CP. A respeito do estudo de influência de componentes, os transformadores redundantes foram analisados para os seguintes casos: remoção dos transformadores redundantes e uso dos mesmos transformadores em “standby”. O primeiro caso levou a uma diminuição da média total de fiabilidade de 35%, enquanto que a segunda situação melhorou o referido valor 7%, ambos relativamente ao CP. O estudo de adição de componentes, que se baseou em adicionar um SVC ao esquema original da central elétrica, teve um desempenho 4% inferior ao CP em termos de média total de fiabilidade. Sobre o estudo de manutenção preventiva, a média total de fiabilidade foi melhorada em 54%, 50%, 40% e 28%, para as frequências anual, bienal, quinquenal e decenal, respetivamente.

Palavras-chave: estudo de fiabilidade, estudo de disponibilidade, central elétrica de ciclo combinado, equipamento de potência, Reliability Block Diagram, Monte Carlo Simulation

Abstract

In accordance with the 2030 Agenda for Sustainable Development defined by ONU, [1], one of the goals is to ensure access to affordable, reliable, sustainable and modern energy for all. This thesis aims to contribute in improving the reliability of energy, in order to comply with the expectations set by ONU. Focusing on the power equipment of a 28MW 61.5kV combined-cycle power plant, three types of reliability and availability assessment studies were performed: component substitution, influence and addition. To serve as a term of comparison, the original reliability and availability of the power plant was computed and used as reference standard case (SC). Additionally, a preventive maintenance study is performed for four distinct frequencies. The methodology applied in these studies was a combination of three methods: Reliability Block Diagram, Markov Chains and Monte Carlo Simulation.

Regarding results, in the component substitution study, a simulation focusing on the replacement of classic circuit breakers by electronic ones, results in an 22% improvement of the SC's total mean reliability. Concerning the component influence study, the redundant transformers were analyzed, considering the following cases: removal of the redundant transformers and usage of the redundant transformers in standby. The first, lead to a decrease of total mean reliability of 35%, while the latter outperformed the value of total mean reliability by 7%, both comparing with the SC. The component addition study, where a SVC was added to the original power plant scheme, is outperformed by the SC in total mean reliability by 4%. Regarding the preventive maintenance study, the total mean reliability is improved by 54%, 50%, 40% e 28%, for the annual, biennial, 5-in-5 years and 10-in-10 years frequencies, respectively.

Keywords: reliability assessment, availability assessment, combined-cycle power plant, power equipment, Reliability Block Diagram, Monte Carlo Simulation

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Nomenclature

BN Bayesian Networks.

CB Circuit Breaker.

ETA Event Tree Analysis.

FTA Fault Tree Analysis.

IEC International Electrotechnical Commission.

IEEE Institute of Electrical and Electronics Engineers.

MCS Monte Carlo Simulation.

MT Mission Time.

MTTF Mean Time To Failure.

PRM Probabilistic Relational Models.

RBD Reliability Block Diagram.

SAS Substation Automation System.

SVC Static Var Compensator.

Chapter 1

Introduction

1.1 Motivation

In accordance with the 2030 Agenda for Sustainable Development, [1], which consists in the world's resolution to 2030, defined by the General Assembly of the ONU, one of the 17 sustainable development goals is to "ensure access to affordable, **reliable**, sustainable and modern energy for all". This thesis aims to contribute in improving the reliability of energy, in order to comply with the expectations and resolutions set by the United Nations to help the development of the society in general. Unquestionably, nowadays' society is heavily reliant on electric energy, meaning that the systems related to it – power systems – are vital and of the utmost importance. With the increase of the world's population and commercial and industrial activities, it is expected a continuous growth on the power system and electricity demand. The power system is composed by the generation, transmission and distribution systems, which in turn are constituted by numerous subsystems, comprised of a high number of components. A failure in one of these components can compromise the whole system, which can result in high economic losses. This is why it is of the outermost importance to have a reliable power system, as it benefits both sides: the users, which expect a continuous source of electricity, and the enterprises responsible by the power systems, as they do not have to intervene as much in them to comply with their obligations as service providers. Thus, it is only natural that studies regarding reliability – quantification of how reliable a system is – have been accomplished and receiving more and more attention, as the level of the power system's response is constantly being defied by the expansions in the power system and the consequent increment in power usage. Reliability is also used to evaluate maintenance studies, which have been performed in order to improve system reliability, while taking in consideration financial constraints, as the complexity, increased size of the power system, as well as the general aging of equipment justifies these studies. The objective of these kind of studies is typically to evaluate the trade-off between the increase of reliability and the monetary cost of that improvement.

1.2 Objectives

In this thesis, the generation system will be the focal point, as the study is based on the reliability evaluation of a combined-cycle power plant, with a focus on the power equipment. A series of studies are performed in order to determine the reliability and, additionally, the availability, of the power plant. These studies are divided in three distinct types, and were accomplished with the intention of evaluating how the reliability of the original power plant – the standard case – responds to certain modifications. The referred three types of study are further enumerated:

1. Component substitution, more specifically an upgrade of the classical mechanical circuit breakers to modern electronic circuit breakers;

2. Component influence, where it is studied the influence of the central power equipment – the transformer.

3. Component addition, in which it is simulated the introduction of a modern power equipment – a Static Var Compensator (SVC).

As a term of comparison, the standard case, which is the situation where there are no alterations to the power plant, is firstly computed, and then used for the referred purpose. Conclusions and discussion of whether or not the different scenarios were advantageous in comparison with the standard case and between themselves are drawn. A preventive maintenance study is also performed, in order to determine the influence it has on the reliability and availability of the power plant.

The methodology applied in these studies was a combination of three different but associative methods – Reliability Block Diagram, employed to calculate the reliability itself, while helping to graphically visualize the relations between components; Markov Chains, whose concepts of component states and transition rates were applied; and Monte Carlo Simulation, which was used not only to simulate the system several times, but also to withdraw the probabilistic events of the power plant.

1.3 Dissertation Structure

This thesis is structured as follows: Chapter 2 includes a state-of-art analysis of the published literature relevant to the thesis theme and it is organized by methods; in Chapter 3 it is introduced the methodology used in the thesis, and the basic concepts associated with the reliability and availability are clarified; Chapter 4 features the results of the work, where an explanation of the whole development process is undertaken, ranging from the initial considerations of the case study to the details of the Matlab processes and how they were approached and worked around. Also, graphical outcomes of the referred Matlab processes are presented, analysed and discussed; Chapter 5 comprises of the conclusions taken along the thesis.

Chapter 2

State-of-the-art

Throughout the recent years, a large amount of reliability assessment studies has been conducted in energy distribution, transmission and generation systems, which include installations like substations and power plants. In these studies, many methodologies have been used to quantify reliability (as well as availability) and to model the referred installations. In [2] the authors suggest a classification for the reliability methodologies, dividing them into two main approaches: analytical-based approach and simulation-based approach. Between the analytical-based methods are:

- Fault Tree Analysis - FTA
- Reliability Block Diagram - RBD
- Event Tree Analysis - ETA
- Reliability Indexes
- Probabilistic Relational Models - PRM
- Markov Chain/Processes

The simulation-based method is:

- Monte Carlo Simulation

Note that these two types of approach can be combined – the analytical method calculates the reliability itself, while the Monte Carlo Simulation randomly generates the occurrence of failures in components. Simulating this a series of times, it is possible to obtain a mean value of reliability/availability. Further, these two types of approach are briefly explained, and then its correspondent advantages and disadvantages enumerated.

2.1 Analytical-based Methods

2.1.1 Fault Tree Analysis - FTA

Starting with the Fault Tree Analysis, often abbreviated to FTA which is used to analytically quantify not only reliability ([3] and [4]), but also availability of systems ([5]).

The authors of [3] state that "the FTA method is an applicable tool for reliability and safety assessment of complex and critical engineering systems." The authors of the same paper applied FTA to analyze the critical components of a standardized substation system used for smart grids in distribution and substation automation, which can be useful for "several purposes such as efficiency and reliability improvement". Authors of the paper [4], agree on that premise as they also apply the FTA to calculate the probability of failure of a substation monitoring system based on branch phasor measurement units. In the paper [5], the reliability evaluation of a substation automation system is evaluated using availability. The availability of the referred system is computed using the fault tree analysis.

The FTA methodology is based on the definition of "undesired states" of the system (or component) in which it is applied. This "undesired state" is named "top event", and corresponds to a state in which the system ceases its operation, i.e, as [3] mentions, "the undesired state (...) is usually a state that is critical from the reliability point of view". So, a "tree" is graphically constructed, consisting in the parallel and series combinations of failures that can lead to the "top event". The combination of failures is made using logical gates. The quantification of the probability of failure of the top event is made through boolean equations based on the logical structure of the tree. The equation to the top event is obtained by the sum of the products of basic events, also called cut sets([3]). A minimal cut set is a combination of events/component failures that cause the failure of the system. As a matter of fact, some authors consider the "minimal cut set" as an disassociated method from the fault tree analysis. The applications, are, however, similar to the FTA ones: in [6] it is utilized the minimal cut set to assess the reliability of a substation equipped with fault current-limiting devices; while the paper [7] identifies the minimal cut set as being a method used to assess the network reliability, and uses it to quantify a condition-based failure rate, which, when considered in distribution systems, along with substation's reliability, minimizes the total cost of active power losses. The minimal cut set can also be associated with other analytical and graphic-based methods. In [8], where the minimal path set, which is the inverse of the minimal cut set in the way that it is the combination of events/component that cause the system to work, is used with the Reliability Block Diagram to optimize and determine the reliability of offshore wind farms. In [9], it is also used a algorithm based on the minimal path set, which is implemented to reduce the order of the execution time, saving computational effort in reliability assessment of power distribution systems.

2.1.2 Event Tree Analysis - ETA

The Event Tree Analysis (ETA) is a analytic method somewhat similar to the FTA, even though with some differences. One of the differences, as [10] identifies, is that the Event Tree is constructed with deductive logic (forward logic) in contrast with the Fault Tree that is built inductively (backward logic).

So, this means that instead of building from an undesired event, the Event Tree is built from a initiating event. According to [10], all possible sequences of following events are laid out and the outcome of each considered sequence is determined. However, the methodologies are not equivalent, neither the Event Tree is an inverted Fault Tree. Fault tree computes the probability/reliability of the top event as a function of the basic events, while the Event Tree computes the probability/reliability of all the possible outcomes starting from the initiation event. Also, citing from [10] ”a fault tree displays relationships among events (...) event trees, by contrast, display relationships among juxtaposed events on the basis of conditional probability”.

In terms of similarities, as it was said, they are both graphical analytical based methodologies. They also share the use of Boolean logic, being common the binary definitions of ”Successful” and ”Failure” to classify the outcomes of the event trees.

Regarding examples of the methodology application, the authors of [11] apply the Event Tree to evaluate the impact of automated substations, distribution systems and the interaction between them. They do so by computing the probability associated to various possible classes of switching action, in order to describe automatic switching action from a functional point of view. Some of the authors of [11], wrote a similar paper, [12], but more focused on the automated industrial substations. The methodology used is similar to the one of [11]. The paper [13] is also related to the substation automation system (SAS), and like [11], it uses Event Tree Analysis to calculate the reliability effect of functional integration of a specific group of SAS components.

2.1.3 Reliability Block Diagram - RBD

RBD, short for Reliability Block Diagram, is, similarly to the FTA and ETA, a graphical analytical approach. This methodology is going to be more profoundly studied and examined in the chapter 3, however a brief resume is further provided. In the paper [12], a short definition of the RBD method is given: ”The RBD shows the logical connections of components needed to fulfill a specified system function where the components that are used together to perform a function are put in series, and the redundant components are put in parallel.”. This essentially resumes the RBD: it is an analytical method used in reliability assessment that graphically disposes a system/component by the means of a block diagram. Depending on the relations between blocks – series or parallel – formulas are used to reduce the RBD to a unique block representative of the whole system. As was already mentioned, RBD can be combined with other approaches. This is the case in the paper [12], where RBD was used to model a SAS, while an ETA was used to represent the functional model of the referred system. By applying the RBD they reduced the SAS ”original” RBDs, but calculated the availability by the minimal path sets method. A distribution system case study is performed, reliability indexes (explained next) assessed and comparisons between industrial distribution substations are executed. The same authors utilize an equal methodology in [11], applied in automated substations in general, instead of focusing in the industrial ones. Paper [8], also employs the RBD methodology, to model an offshore wind farm, whose reliability is evaluated by reliability indexes. A case study is then consummated, where different architectures of the offshore wind farms are compared by their reliability index results, and considering economic advantages/disadvantages.

2.1.4 Reliability Indexes

Another method that analytically assesses the reliability are the reliability indexes. Note that this methodology is different from the previously studied, since it is purely analytic, whereas the RBD, ETA and FTA are not only analytical but also graphical and can be used to model a power installation (substation, power plant, etc.).

According to [14], different types of reliability indices can be calculated for the analysis of reliability to all electrical power facilities, and used to compare the reliability of different electric utility companies. The authors of this paper use the reliability indexes to evaluate a real electrical distribution network in Debre Berhan, Ethiopia, in order to adequately intervene in the network, so that improvements in its reliability can be performed. Also, having this evaluation, it can serve as a standard case, and be used to future comparisons.

The authors of the paper [15], conducted a study in Gejayan, Indonesia, with the same mindset of the performed in [14]. They computed the reliability of their countries distribution system using reliability indexes, in order to identify and solve problems in it. Also, they comparatively evaluate the results with the ones from foreign countries, so they have a notion on how much they have to improve. Similarly to those two, the paper [16] also evaluates and suggests intervention in the distribution system of Nigeria, using the same methodology.

The authors of paper [17] propose that reliability evaluation of substations should be done in the planning phase, in contrast with the previously mentioned studies that are calculating the reliability indexes in already existing distribution systems. So, they calculate the indexes for different network configurations of distribution systems, as they identify that the main adversity of computing reliability indexes in planning studies is the constant variation in the network configuration.

The most common computed reliability indexes, found in the multiple referenced papers ([16],[14],[17],[15]) are the following:

- System Average Interruption Frequency Index (SAIFI)
- System Average Interruption Duration Index (SAIDI)
- Customer Average Interruption Duration Index (CAIDI)
- Average Service Availability Index (ASAI)
- Customer Average Interruption Index (CAIFI)
- Average Service Unavailability Index (ASUI)
- Excepted Energy Not Supplied Index (EENS)
- Average Energy Not Supplied Index (AENS)

Note that all the referred papers study the distribution system in particular, so it is natural that the indexes are adapted to the distribution system reality.

2.1.5 Probabilistic Relational Models - PRM

Probabilistic Relational Models, often abbreviated to PRM, is a methodology based in BN, short for Bayesian Networks. Bayesian Networks is another method that merges a graphical model and analytic computation, just like the RBD, FTA and ETA. This model is acyclic and typically composed by nodes that represent variables (components) and arcs that illustrate the dependencies between variables, which are quantified using conditional probabilities ([18]). The term ”parent” is often used to characterize the component from which other components are dependent of. The probability in BNs is evaluated using forward logic (like ETA), meaning that the probability of the parent node is used to calculate the subsequent nodes, taking in consideration their logical relation.

PRM, according to [19], extends Bayesian networks with the concept of objects, their properties, and relations between them. So, basically, PRM is a more complete BN, that sets a template for a probability distribution and applies it in an architecture model, where the probabilistic dependencies between attributes of the architecture's objects are described. This probability distribution, associated with the attributes of the objects, can then be used to quantify ”unknown attributes”, in this case the reliability, which the authors of [19] do, by applying the PRM methodology in a SAS based on the standard IEC 61850.

2.1.6 Markov Chains

Markov Chains is a reliability assessment method that differentiates from the others for being a state-space approach, which means that state variables that can change overtime will be involved, as well as differential equations. The State-space is the set of all possible states of a system/component. A way to represent it is by applying the Markov Chain methodology, which represents all the states in a diagram connected between them by variables called transition rates (CITACAOALVAREZ). Typically a component is considered to have two states: operating state and failure state, and the transitional rates between these two states are represented by the component's failure and repair rates. The reliability is computed using the transition matrix, which is a matrix that contains the transition rates between states. Note that since this method is one of the used in the thesis' developed work, and so additional details of this methodology is given in the chapter 3.

Regarding applications of this method in the literature, a series of works that either use Markov Chains, methods based on the referred or combinations of other methods with the Markov Chain can be evoked.

The authors of [20] argument that the ”increasing size, aging equipment and complexity of power systems, coupled with present day financial constraints” oblige the use of probabilistic methods and reliability assessment in order to maintain the quality of service provided to the consumers of electricity. They utilize a Markov process to model the aging power equipment with minor/major maintenance and inspection, taking in consideration deterioration states. Also, with a Markov derived process – Markov Decision Process – they are able to introduce monetary constraints, and consequently, optimum maintenance policy. They apply the methodology to a substation where reliability and economic cost analysis is conducted, and conclude that, with the developed method they can study the impact of the equipment maintenance on the reliability and other indices like availability.

Another application of Markov is given in the paper [21], whose authors state that in other reliability studies, there is the assumption that the failure rate of the components is constant, in order to simplify reliability assessment. However, they believe that in real systems this does not happen, i.e, the value of failure rate is time-varying and stochastic with the changes of the operating conditions like the weather conditions and the aging and deterioration of components. So, they decide to formulate a reliability model where these operation conditions are taken in consideration, and apply the Markov to model the failure rate with distinct weather expression. Using a combination of other techniques, as the Minimal Cut Set, they conclude that the extra operating conditions they considered significantly affect the magnitude of the substation reliability estimation.

In the same tone of considering operating conditions, in this particular case the aging of circuit breakers, the authors of the paper [22] also developed a Markov model to include the circuit breakers' ageing failure. The intend was to evaluate the impact that is caused in considering the wear-out of the circuit breakers, since the traditional methods only take in consideration the natural age of the CBs and not actually the "wearing status" of the circuit breakers. Applying the methodology in a case study of a Chinese substation, the conclusion was that in end of life, considering the "wearing status" of the CBs influenced greatly the reliability value of the substation where they were inserted.

Another method to take in consideration these operating conditions, defined by the authors of the paper [23] as "uncertain parameters", is the Markov with Fuzzy mathematics. Fuzzy mathematics was developed in order to model uncertainties, and has recently started to be applied into power systems and reliability assessment, since those areas deal with uncertain events. As the previous examples, a methodology based on Markov that includes aging equipment models is proposed. Optimum maintenance rates can also be obtained using the developed method. The state-space Markov model includes deterioration, failure and maintenance states, while inspection states could also be added. The methodology was tested in a case study, and authors conclude that the algorithm provides a general approach for solving Markov models with uncertain transition rates/probabilities and that the existing Markov models are compatible with their method. They also state that uncertainty regarding reliability indices can be quantified in their approach, in contrast with the traditional Markov studies.

However, as was already briefly mentioned, the Markov can be used in combination with other methods, including with non-analytical methods, like the Monte Carlo Simulation. The authors of the paper [24], use the Markov Chain to create the state space for a Static Var Compensator operation. They state that the representation using the Markov Chain is "convenient for the reliability evaluation using SMCS (Sequencial Monte Carlo Simulation)". The later is going to be described in the Simulation-based Methods, and is further detailed in the methodology chapter 3.

2.2 Simulation-based Method - Monte Carlo Simulation

The only method that is going to be covered as a Simulation-based approach is the Monte Carlo Simulation, since it is one that is more times referenced in the literature. According to the paper [2], there are two types of Monte Carlo Simulation: State Sampling and Sequential Sampling. In the State Sampling, the states of the studied system are randomly sampled, whereas in the Sequential Sampling the operating states are attributed chronologically. In both types, the sampling obeys a probability distribution function (or more than one). Sequential Sampling is particularly useful to multi-component systems, as they are defined by multi-states. Typically, the Monte Carlo Simulation that uses the Sequential Sampling is abbreviated to Sequential Monte Carlo Simulation – SMCS. So, Monte Carlo Simulation, in general, is useful to simulate large systems with a lot of components/states. In reliability assessment, it is applied by simulating the studied system multiple times (with the referred randomness), in order to obtain the mean value of reliability of all the simulations, which represents the most probable value of reliability for that system, by the probabilistic law of large numbers. A more in dept explanation on the Monte Carlo Simulation is provided in the chapter 3.

Concerning literature application of the method, [2] utilizes Sequential Monte Carlo Simulation together with parallel computing, in order to maximize the processors usage, while minimizing the communication among different processors, which has the purpose to save time and simulate faster. Also, a economic evaluation is considered, associated with the equipment states and calculated at the same time as the reliability. They test the methodology in a case study and compare it with the results of an analytical Markov process, concluding that with the help of parallel computing, their MCS is faster while still accurate and detailed when compared with the traditional MCS. As was previously mentioned, the authors of [25] developed a methodoly based on the Markov Chain and Sequential Monte Carlo Simulation, as well as an Accelerated Quantum Particle Swarm Optimization (AQPSO), a computation technique to get an optimal solution employing the concept of velocity. This optimal solution is discovered by minimizing a reliability index – Expect Energy Not Supplied (EENS). They test the developed conjunction of methods in the IEEE 24 bus reliability test system, in order to evaluate the impact of a SVC in the system's reliability. Before this, the same authors published another paper, [24], using only the Markov Chain and the MCS, where initial modelling and reliability quantification of the SVC as a whole, as well as of the components that constitute it, was executed and then used as basis to the referred paper.

2.3 Advantages and disadvantages of different approaches

Between the analytical methodologies, even though they are differentiated, they all share some advantages and disadvantages. According to [2], the analytical approaches include high accuracy and relatively fast computation time; the disadvantages are the limited number of states to be considered, and the inability to provide more reliability information.

About the Monte Carlo Simulation approach, they state that "is suitable for large-scale systems and is capable of providing more comprehensive results than analytical methods.". Regarding its disadvantages, the high computation burden is mentioned. Authors of [19] add that "Graphical models provide an effective tool for understanding and analyzing systems and their architecture. They are also useful for the understanding of dependencies between components, for example when analyzing and identifying the impact of a single component's failure on the rest of the system.". Remember that the graphical models covered in this State of Art are the FTA, ETA, RBD, Markov chains and the Bayesian Networks that compose the PRM. The authors of [19] also refer some pros and cons of state-based analysis, i.e, methods that employ component/system states: "state-based methods enumerate all possible system failure states and are not limited to stochastically independent failure of components. This expressiveness comes at a price: models for state-based analysis using Markov chains grow exponentially with the number of system components". So basically, the state-based methods are complete approaches in a way that specify every state of a system, however they have the setback that comes as a consequence of being "complete" – memory and " state explosion".

A series of uncertainty and assumptions was noted in some papers, for example value assumptions. Even thought some assumptions might be needed, like the two-state assumption or the constant failure rate assumption, value assumptions in general, for instance a component's repair rate, will be avoided in this work. This value assumptions can be justified by the lack of actual data, vital to reliability studies, like the failure rate and the repair rate. To counter that, in this work, a series of databanks were consulted in order to compute reliability with the most possible real data, listed further: [26], [27], [28], [29], [30], [31], [32], [32], [33]. Also, other paper authors used inaccessible software or performed their studies in systems that are hard to replicate due to their cost and high-end technology. The results of this thesis were computed in MATLAB, and were performed using a single computer/processor. Reliability studies of complete power plants are not very common in the literature, as most of them focus on a specific system, so a "combined-cycle + substation" power plant was chosen to be the focal point of this study.

In conclusion, having reviewed the literature on reliability studies, a method or combination of methods cannot be individualized as being the best, as there is no unanimous methodology. Given that, and considering the available resources and limitations, like the lack of computational power and of available data, a combination of three methods was chosen as the methodology for this thesis: RBD, Markov Chains and Monte Carlo Simulation. These methodologies are further detailed in the next chapter 3.

Chapter 3

Methodology

In this chapter, the suggested methodology and basic reliability and availability concepts are explained, as well as their application in the reliability/availability assessment. All the information presented in this chapter was supported by the following works: [34] and [35]. This methodology is based fundamentally in the implementation of the following three procedures:

1. Reliability Block Diagram (RBD)

2. Markov Chains

3. Monte Carlo Simulation

However, it is important to first clarify some basic concepts of reliability and availability before advancing to the methodology itself.

3.1 Reliability & Availability Concepts

3.1.1 Reliability

Reliability is defined as the probability that a system, or component, will perform a specific function as intended, for a certain period of time and under particular conditions, i.e, without failures. So, it is a way to represent component's quality over time.

Defining $\tau > 0$ as being the time to failure for a component, i.e, the total time duration of operating period of an item, from the instant it is first put in an operational state until failure or, from the instant of restoration (by maintenance) until its next failure, the component's reliability function for a given time *t*, *R(t)*, can be defined as :

$$R(t) = P(\tau > t), \text{ for no failures in [0,t].} \tag{3.1}$$

Being *P* the nomenclature for probability.

Introducing *F(t)* as the probability distribution function of failure time :

$$F(t) = P(\tau \leq t), \text{ for no failures in [0,t].} \tag{3.2}$$

From (3.1) and (3.2), it is possible to deduce, from probability basics:

$$F(t) = 1 - R(t). \tag{3.3}$$

The probability density function for failure time, *f(t)*, to a given time interval, Δt, is determined as:

$$f(t)\Delta t = P(t < \tau \leq t + \Delta t) \text{ , with} f(t) = \frac{\partial F(t)}{\partial t}. \tag{3.4}$$

From (3.3) and (3.4), it can be deducted that :

$$f(t) = \frac{\partial F(t)}{\partial t} = -\frac{\partial R(t)}{\partial t}. \tag{3.5}$$

Considering the following limit conditions, expressed from (3.6) to (3.9), it is possible to draw the probability distribution function and the reliability over time, *F(t)* and *R(t)* respectively, present in figure 3.1. The probability density function, f(t), is also represented in the referred figure. Consider that *t* is a given time limit.

$$F(0) = 0; \tag{3.6}$$

$$F(\infty) = 1; \tag{3.7}$$

$$R(0) = 1; \tag{3.8}$$

$$R(\infty) = 0. \tag{3.9}$$

Another important concept, associated to the reliability, that needs to be elucidated is the failure rate. Failure rate is the probability, per unit time, that the system, or component, will fail at some time $\tau < t + \Delta t$ given that it has not yet failed at time $\tau > t$. Typically, failure rate is represented by $\lambda(t)$ and is mathematically defined as :

$$\lambda(t)\Delta t = P(\tau < t + \Delta t | \tau > t). \tag{3.10}$$

The conditional probability formula in (3.11) can be applied to (3.10), resulting in (3.12):

$$P(A|B) = \frac{P(B) \cap P(A)}{P(B)} \tag{3.11}$$

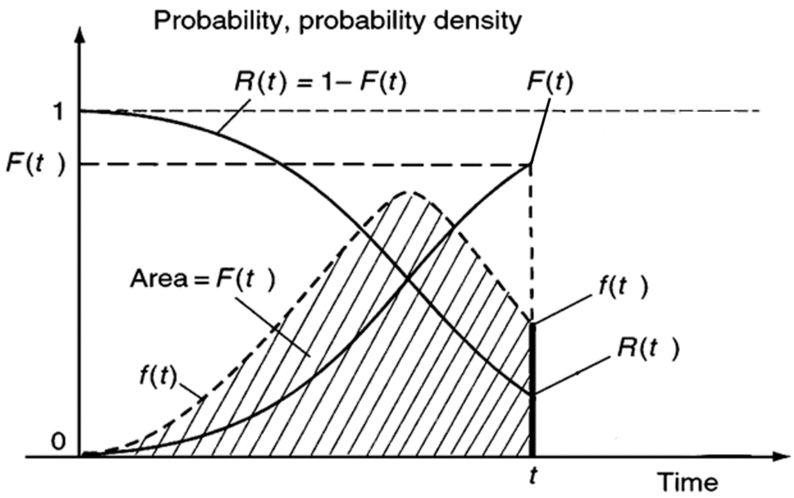

Figure 3.1: Distribution function and reliability over time.

$$P(\tau < t + \Delta t | \tau > t) = \frac{P(\tau > t) \cap P(\tau < t + \Delta t)}{P(\tau > t)} = \frac{P(t < \tau < t + \Delta t)}{P(\tau > t)}. \quad (3.12)$$

Linking (3.4) and (3.1) to (3.12), consummates the failure rate expression :

$$\lambda(t)\Delta t = \frac{f(t)\Delta t}{R(t)} \Leftrightarrow \lambda(t) = \frac{f(t)}{R(t)}. \quad (3.13)$$

Being the failure rate described by (3.13), applying it to (3.5) outcomes:

$$\lambda(t) = -\frac{1}{R(t)} \frac{\partial R(t)}{\partial t}. \quad (3.14)$$

The solution of *R(t)*, considering the expression in (3.14), is given by (3.15):

$$R(t) = \exp\left[-\int_0^t \lambda(t)dt\right]. \quad (3.15)$$

Applying the relation between *R(t)* and *F(t)* , expressed in (3.3), is obtained the expression of F(t) in terms of $\lambda(t)$:

$$F(t) = 1 - \exp\left[-\int_0^t \lambda(t)dt\right]. \quad (3.16)$$

Also *f(t)* in terms of $\lambda(t)$ can be deducted by substituting (3.15) in (3.13):

$$f(t) = \lambda(t) \exp\left[-\int_0^t \lambda(t)dt\right]. \quad (3.17)$$

Another important concept of reliability is the mean time to failure (MTTF), which corresponds to the expected value of τ:

$$MTTF = E[\tau] = \int_{-\infty}^{+\infty} tf(t)dt. \quad (3.18)$$

Applying the equation (3.5) in the (3.18), and given that $\tau > 0$ it is obtained:

$$E[\tau] = -\int_0^{+\infty} t\frac{\partial R(t)}{\partial t}dt. \quad (3.19)$$

Solving (3.20):

$$E[\tau] = [-tR(t)]_0^{+\infty} + \int_0^{+\infty} R(t)dt, \quad (3.20)$$

results that:

$$MTTF = \int_0^{+\infty} R(t)dt \quad (3.21)$$

In this thesis, it was considered that the probabilistic transitional rates, where the failure rate is included, were constant in time, i.e:

$$\lambda(t) = \lambda. \quad (3.22)$$

The failure rate over time, $\lambda(t)$, is typically characterized by the graphic represented in the figure 3.2, commonly named ”bathtub curve”.

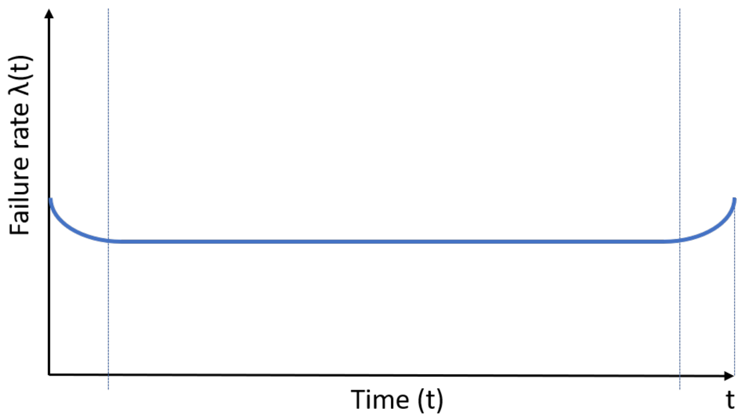

Figure 3.2: Bathtub curve representing failure rate along the time.

Analysing the figure 3.2, it can be visualized that for the majority of the time, the failure rate is constant. Moreover, this kind of bathtub curve is particular of electric and electronic components, which are the ones mainly employed in the studied power plant. All this support and justify the decision of considering the failure rate as constant over time.

So, the expression (3.15) can be actualized with the application of the equation (3.22), resulting in:

$$R(t) = \exp\left[-\int_0^t \lambda dt\right] \Leftrightarrow R(t) = e^{-\lambda t}. \tag{3.23}$$

Note that the reliability, considering the failure rate as constant, is represented by a exponential equation, as expressed in (3.23). This is going to be relevant for the Monte Carlo Simulation, upon the choice of a probability distribution, in the section 3.4, as the reliability formula fits the exponential distribution.

Substituting the result of the later expression (3.23) in the (3.21) it is finally obtained the MTTF for a constant failure rate:

$$MTTF = \int_0^{+\infty} e^{-\lambda t} dt = \frac{1}{\lambda}. \tag{3.24}$$

3.1.2 Availability

To further understand the concept of availability it is important to define first the one of maintainability. Maintainability is the probability of a failed system or component to return to the operational state in a particular period of time. Given the time *T*, which is a variable that represents the repair time of a component/system, the probability distribution function of maintainability can be described, analogously to the reliability counterpart probability distribution function, (3.2), as:

$$M(t) = P(T \leq t). \tag{3.25}$$

Likewise, the probability density function (for the repair time *T*) is represented as:

$$m(t) = \frac{\partial M(t)}{\partial t}. \tag{3.26}$$

Similarly to reliability, the maintainability also has an associated rate – repair rate. Repair rate, often represented by $\mu(t)$, is defined as the probability that a equipment is repaired at some time, *T*, which occurs between *t* and $t + \Delta t$, with the condition that it had not been repaired before *t*. Mathematically, the repair rate can be expressed as:

$$\mu(t)\Delta t = \frac{P[t \leq T \leq t + \Delta t]}{P[T > t]}. \tag{3.27}$$

The equation (3.26) can alternatively be expressed as:

$$m(t) = \frac{M(t + \Delta t) - M(t)}{\Delta t}, \tag{3.28}$$

which is equivalent to the numerator of the equation (3.27). Being the denominator the inverse of the expression (3.25), it can be concluded that (3.28) is equivalent to:

$$\mu(t) = \frac{m(t)}{1 - M(t)} \tag{3.29}$$

The repair rate, identically to the failure rate, is considered as being constant:

$$\mu(t) = \mu. \tag{3.30}$$

However, in contrast to the failure rate, there is no characteristic curve to the repair rate. So, the consideration of a constant repair rate was firstly due to simplicity, and in order to establish an analogous relation between failure and repair rate. Also, in the databases used for this work, all the repair rates are presented as constant, which supports this decision.

Analogously to the MTTF, the mean time to repair – MTTR – is defined by :

$$MTTR = \frac{1}{\mu}. \tag{3.31}$$

Having elucidated the concept of maintainability, it is now possible to introduce the availability one. The availability is like a merge between the reliability and maintainability, i.e, the availability results from the combination of a failure and a repair process. This is graphically showcased in the figure 3.3.

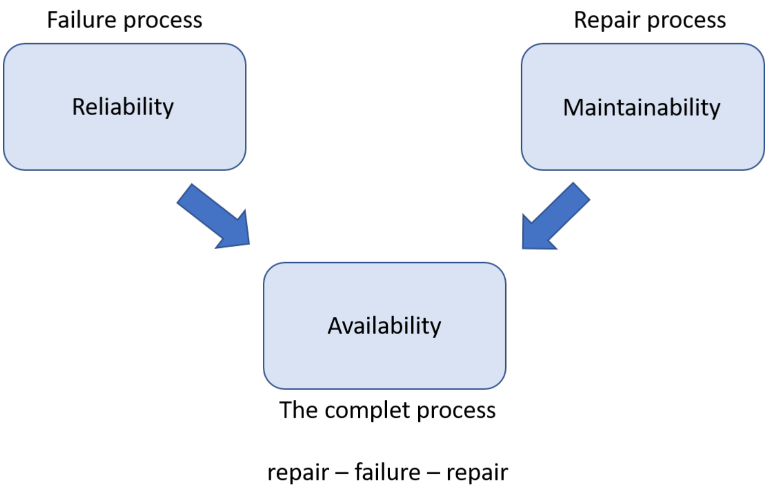

Figure 3.3: Availability concept.

So, the availability can be defined as the component or system's ability to be held in an operative state. Thus, the availability of a component (or system) in a given time instant *t* – $A(t)$ – is the probability of the referred component being in the operational state at time t, taking in consideration that it is on the operational state at zero time.

The variation of the availability between the times *t* and $t + \Delta t$, has a negative component related to the failure rate, since it makes the availability decay, and a positive component associated to the repair rate, once it increases the availability. The system only fails when it is available and the repair is exclusively performed when the it is unavailable, so they are respectively associated to the availability (A(t)) and unavailability (1- A(t)). Mathematically, this can be expressed as:

$$A(t+\Delta t) - A(t) = -\lambda \Delta t A(t) + \mu \Delta t (1 - A(t)), \tag{3.32}$$

which is equivalent to:

$$\frac{\partial}{\partial t} A(t) = -(\lambda + \mu) A(t) + \mu. \tag{3.33}$$

From (3.33), with some mathematical manipulation it is possible to obtain the final availability formula:

$$A(t) = \frac{\mu}{\lambda + \mu} + \frac{\lambda}{\lambda + \mu} \cdot e^{(-(\lambda+\mu)t)}. \tag{3.34}$$

Likewise to (3.23), the previous equation (3.34) has an exponential part, so it can be represented by the exponential distribution, even though not perfectly. This will be relevant for the Monte Carlo Simulation when the probability distribution needs to be choose.

Having introduced the required basic concepts of reliability and availability, it is now conceivable to advance to the explanation of the methodology itself, starting with the Markov Chains.

3.2 Markov Chain

Markov Chains emerged as a common solution to create complex reliability models that were too difficult to compute. Note that Markov Chains is a stochastic model that was adapted to reliability computation, not directly developed to this particular end, like for instance the RBD. Markov Chain is a representation of all the possible states of a component or a system, and its interconnections. Typically in reliability assessment, the Markov Chain is represented as a two-way diagram, like the single component one depicted in [24], showcased in the figure 3.4. Note that in this representation were considered two possible states – 1 which corresponds the state that the component is operational, typically named UP state, and 2 that, in contrast, represents the state in which the component failed, DOWN state – and two possible transitions – failure rate, λ, and repair rate, μ, commonly named as transition rates. These rates are probability driven. Also notice that a component might not be repairable, even thought, for the case to be studied all the components were considered as so.

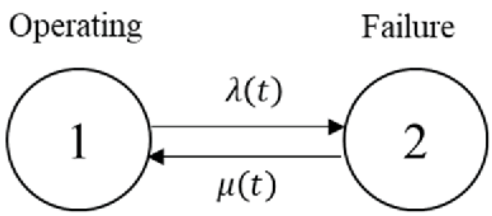

Figure 3.4: Single component two-way Markov Chain representation from [24].

Notice that the quantity of states of a Markov Chain increases exponentially, 2^n, being n the number of components that comprise the Markov Chain. To this particular single component example, figure 3.4, there is only one component, so there would be $2^1 = 2$ states. However, to bigger systems the Markov

Chain can become impractical and even infeasible. As it is within the scope of this work to study the power equipment of a power plant, which is a multi-component system, another approach to determine the reliability and availability of a system is necessary. So, it was decided to use the combination of the RBD and Monte Carlo methods to analytically calculate the reliability and availability of the to be studied system. Given this, the application of the Markov Chains in this thesis ended up being residual – it was not directly applied, as the RBD combined with the Monte Carlo Simulation provided the quantification of the reliability. However, its concepts of probabilistic transitional rates are intrinsically associated not only with the reliability and availability concepts, but also with the modelling, itself, of a state-space and the notion of states and state transitions, reasons why it deserves a mention in this work.

3.3 RBD

The RBD, short for reliability block diagram, is a quantitative method designed to determine the reliability of a system. However, it can also be used to assess availability, with some formula alterations. Generally, as its name suggests, it is represented graphically by an association of blocks, forming a diagram. These blocks typically portray individual components, but it can also illustrate groups or other subdivisions of the system.

So, the RBD method is intended to construct an integrated reliability model which represents the time to failure of the entire system, based on the individual failure probability function for each component. Again, it can be analogously adapted to an availability model.

To achieve this model, the operational interrelation between the components (or subsystems) must be considered, which does not always coincide with the physical connection between these elements. To this kind of interrelation, vital to the reliability and availability study is named onward "functional relation".

Note that the RBD performs a static analysis, which synergies well with the constant failure and repair rates considered for this work.

Regarding the equations used to quantify the reliability and availability, they depend on the functional relations between blocks of components and/or groups of components. Essentially, these relations can be either series or parallel, however there are complex cases where the functional relation can be expressed by a mix of series and parallel. An example of this "mixed" relation is later studied in the chapter 4. The formulas correspondent to both basic types of functional relation, series and parallel, are detailed in the following subsections.

3.3.1 Series Functional Relation

Firstly, it is showcased in the figure 3.5, an simple example of a system constituted by two components in series.

The equation that quantifies the reliability of the system with n components in series, R_s is:

$$R_s(t) = \prod_{i=1}^{n} R_i(t) \quad \text{; for } i = 1, 2, ..., n \tag{3.35}$$

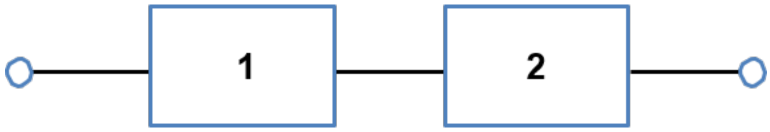

Figure 3.5: Example of a system with 2 series related components.

For the example present in the figure 3.5, applying the equation (3.35), the reliability of the system would be defined as:

$$R_s(t) = R_1(t) \cdot R_2(t) \tag{3.36}$$

The series relation can be summarized to a non-redundancy, meaning that whenever a component fails, i.e, when the reliability of a component becomes zero, the reliability of the series relation, as a whole, will also be null. So, essentially the series relation is like a dependency between components in terms of functional relation. If a component does not work without another, i.e, it is dependent or is directly influenced by it, they are series related.

Notice that the availability of a series functional relation is calculated by the analogous formula of the reliability (equation (3.35)):

$$A_s(t) = \prod_{i=1}^{n} A_i(t) \quad \text{; for } i = 1, 2, ..., n \tag{3.37}$$

Regarding the MTTF, for constant failure rates and exponential distribution, which is the case in this work, the equivalent system with n components failure rate, λ_s, is given by:

$$\lambda_s = \lambda_1 + \lambda_2 + ... + \lambda_n \tag{3.38}$$

The MTTF of the n-series component system, $MTTF_s$, using the expression (3.24) and applying the later (3.38) is defined by:

$$MTTF_s = \frac{1}{\lambda_s} = \frac{1}{\lambda_1 + \lambda_2 + ... + \lambda_n} \tag{3.39}$$

3.3.2 Parallel Functional Relation

The RBD parallel functional relations can be divided in two distinct types: the active parallel and the standby parallel.

Active parallel

Starting with the active parallel, similarly to what was done to the series functional relation, an example of 2 active parallel components is showcased in the figure 3.6.

The reliability of the active parallel system composed by n components,$R_p(t)$, is defined by the following equation:

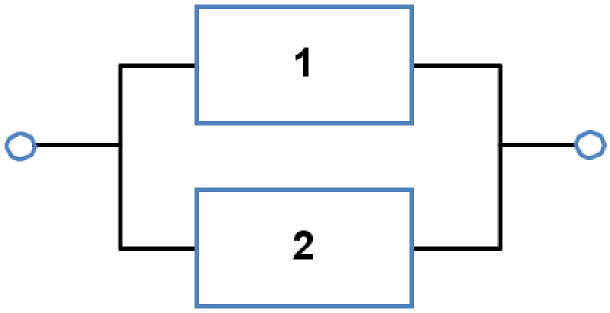

Figure 3.6: Example of a system with 2 active parallel related components.

$$R_p(t) = 1 - \prod_{i=1}^{n}(1 - R_i(t)) \quad \text{; for } i = 1, 2, ..., n \tag{3.40}$$

From the expression 3.40, the reliability of the example represented in the figure 3.6 would be calculated by:

$$R_p(t) = 1 - (1 - R_1(t))(1 - R_2(t)) = R_1(t) + R_2(t) - R_1(t)R_2(t) \tag{3.41}$$

In contrast with the series, the active parallel functional relation is defined as a redundancy, which means that even if one of the components fails – its reliability is 0 – the other component(s) are unaffected by that. So, the reliability of the parallel system as a whole only drops to 0, i.e, ceases its operation, if and only if all of the components fail at the same time. So the parallel components are characterized by the independence between them, the exact opposite of the series functional relation.

Regarding the availability of a parallel system constituted by n components, $A_p(t)$, it is calculated with the analogous equation of (3.40):

$$A_p(t) = 1 - \prod_{i=1}^{n}(1 - A_i(t)) \quad \text{; for } i = 1, 2, ..., n \tag{3.42}$$

Standby parallel

Concerning the standby parallel, likewise to the other cases, a two component system example is depicted in the figure 3.7

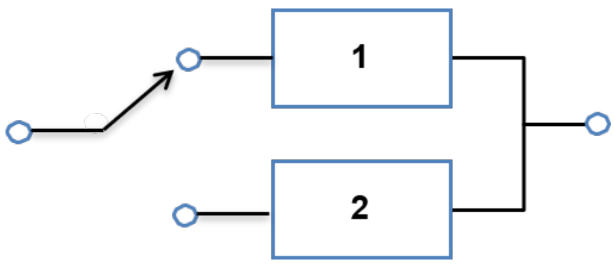

Figure 3.7: Example of a standby parallel system with 2 components.

When considering a standby parallel, also called standby redundancy, it is considered that a component can have 2 states - active state when it is operating and the standby state, which corresponds to when the component is ready to operate in case of a failure in the active component. This being said, the standby component has to be always operative, at least when the main component is not, in order to be truly in the standby state.

So, the reliability of a standby for any time t, $R_{sb}(t)$, is the probability that the standby component will not fail until a time greater than t, with the condition that it cannot fail until after the active component fails. In other words, it is the probability of the active component to not fail until a certain time t, or to fail after that certain time t with the condition that the standby component does not fail until t. Mathematically, a two component standby parallel can be expressed by the probability expression (3.43):

$$R_{sb}(t) = P[\tau_1 > t \cup (\tau_1 < t \cap \tau_2 > t)] \tag{3.43}$$

Being τ_1 and τ_2 the times that the active component and the standby component fail, respectively. From (3.43) it can be obtained (3.44):

$$R_{sb}(t) = R_1(t) + \int_0^t R_2(t-\tau_1) f_1(\tau_1) d\tau_1 \tag{3.44}$$

Being $R_1(t)$ the reliability of the active component to the time t, and, analogously, $R_2(t)$ the same for the standby component. Applying the (3.5) equation in the later (3.44), it results (3.45):

$$R_{sb}(t) = R_1(t) + \int_0^t R_2(t-\tau_1) \frac{dR_1(\tau_1)}{d\tau_1} d\tau_1 \tag{3.45}$$

The equation (3.45) is complex to apply, due to the fact that it has, not only a primitive, but also a derivative, both harsh to introduce in long and demanding simulations, like the ones that were carried in the section 4. Fortunately, equation (3.45) can be simplified if the active and standby components are identical, i.e, the active group has the exact same failure rate as the standby group: $\lambda_1 = \lambda_2 = \lambda$. Having the components exponential distribution, applying the equation (3.23) into (3.45) results (3.46):

$$R_{sb}(t) = \exp(-\lambda t) + \int_0^t \exp[-\lambda(t-\tau_1)] \frac{d[\exp(-\lambda\tau_1)]}{d\tau_1} d\tau_1 \tag{3.46}$$

With some mathematical manipulation, (3.46) can be reduced, resulting the final simplified equation to quantify the reliability of a parallel standby system:

$$R_{sb}(t) = (1 + \lambda t) \exp(-\lambda t) \tag{3.47}$$

Notice that in the case of the standby parallel there is no transposition of reliability into availability equations. Thus, the availability assessment in this particular component relation is not possible.

Having covered the RBD method, it is left to explain its actual application in this work. So, the RBD is going to be used in this work mainly to quantify the reliability and availability. Firstly, the block diagram has to be designed, taking in consideration the functional relations between all the components of the power plant to be studied. Accomplishing that, then the RBD formulas are used to compute the reliability and availability, in the first place of individual components, and then of groups of components, taking in consideration its relations previously defined, until it is calculated the total reliability of the system.

3.4 Monte Carlo Simulation

Monte Carlo simulation, often abbreviated as MC simulation, can be defined as a procedure that relies on repeated random sampling and statistical analysis to compute a result. The generated random numbers are independent and identically distributed. Alike the Markov Chain method, Monte Carlo simulations were not exclusively developed to reliability and availability studies, but were adapted to them. MC Simulation is particularly useful in complex systems, i.e, to systems with a high number of components and, for consequence, a high number of states, in contrast to the Markov Chains. According to the authors of the [24], it is also appropriate to "develop experiments that are not possible to do it directly due time involved", as it allows to simulation systems over time.

So, the MC Simulation operates by generating samples $(x_1, x_2, ...x_n)$ of a random variable *X* that obeys any probability distribution *F(X)* from a sample of the variable *Z*, which is equally distributed between 0 and 1 by the transformation $x_i = F^{-1}(z_i)$. Alternatively, if the referred inversion cannot be plainly executed, the opposite can be performed, i.e, it is generated the $(z_1, z_2, ...z_n)$ samples of the variable *Z*, and then the *X* values can be obtained by the expression $F(x_i) = z_i$. In reliability studies the variable *X* represents a certain time (to failure or to repair) and the *Z* variable the actual set of random generated numbers in the interval [0,1]. Since for this work it is intended to generate the time to failure and the time to repair, the referred alternative was the chosen way to apply the Monte Carlo. Note that all probability distributions can be generated from uniform random numbers in the interval [0,1].

Focusing on the exponential probability distribution ($F(x)$), which for the reasons already discussed in the subsection 3.1, particularly the assumption of a constant failure rate that leads to the reliability formula (3.23) and adding the fact that there is not much valuable information about other types of distribution in reliability studies, is the one that fits best the reliability and availability studies related to electric components. This probability distribution can be characterized by the following equation:

$$F(x_i) = 1 - e^{-\lambda \cdot x_i} <=> Z = 1 - e^{-\lambda \cdot X} \tag{3.48}$$

Being *Z* = $(z_1, z_2, ...z_i)$ = *F(x)* and *X* = $(x_1, x_2, ...x_i)$.

Applying the logarithm to both sides of the equation (3.48), results:

$$ln(1 - Z) = -\lambda \cdot X \tag{3.49}$$

Isolating X from the expression (3.49), and considering that $1 - Z$ and Z have the same distribution, outcomes the following equation:

$$X = -\frac{ln(Z)}{\lambda} \tag{3.50}$$

The later equation (3.50) is used to calculate the time to failure of a certain component, i.e, the time that the component takes to fail (the working time of a component), named t_{up}. Analysing the equation (3.50) and translating it to the real world, it makes sense, since the higher the failure rate - the likelihood to a component to fail - the lower the time until an occurrence of a failure, and vice-versa (the lower the failure rate the higher the time to fail). This is analogous to the repair rate, as X in the mathematical expression (3.50), instead of representing the time until failure, can represent the time until repair, t_{dwn} (the down time of a component):

$$X = -\frac{ln(Z)}{\mu} \tag{3.51}$$

So, in conclusion, from the expressions (3.50) and (3.51) results:

$$t_{up} = -\frac{ln(Z)}{\lambda} \tag{3.52}$$

$$t_{dwn} = -\frac{ln(Z)}{\mu} \tag{3.53}$$

So it can be said that t_{up} and t_{dwn} occur in a "semi-random" time. "Semi-random" because they are not entirely random – they directly depend not only on the probabilistic distribution, but also on the failure and repair rates of the components, even thought there is some randomness in their computation associated with the variable *Z*.

In order to compute the Monte Carlo Simulation in this work, it is necessary to determine time boundaries, i.e, limits to the simulation itself, due to RAM memory restrictions. These limits are onward named MC Simulation test values, and correspond to the number of stories and the mission time (MT). The number of stories is the number of times that the process– simulation– is going to repeat itself. This is a very important part of the MC Simulation. Remember that the stories are all different from each other, due to the randomness associated to the method, so, it is critical to compute a mean of a high number of stories, in order to obtain a result close to the real probabilistic solution. Regarding the mission time, it corresponds to how much in time the simulation will actually simulate (in each repeat). The referred mean of stories will be computed for each and every hour of the mission time, culminating in a total mean of the whole stories, and for consequence, of the whole simulation.

3.5 Markov Chain, RBD and Monte Carlo Simulation combination

The three utilized methods were explained individually, however the combination and interaction between each other was not clarified.

As was already referred, the RBD and Monte Carlo Simulation are the two methods responsible for the assessment of the reliability and availability. Using the RBD, it is possible to create a model that groups all the components to be studied, taking in consideration its functional relations. Depending on the functional relation between components/groups of components, the reliability and availability of the whole system is calculated by the proper formulas previously introduced in the section 3.3.

So, the RBD provides a static (in time) reliability assessment. Applying the state and state transition notions of the Markov Chains to the RBD functionally related components model, the static reliability assessment becomes a dynamic (in time) reliability assessment.

Employing the Monte Carlo Simulation to this dynamic reliability assessment, it is possible to simulate it throughout time. Firstly, it is ”semi-randomly” determined the component states throughout the previously set mission time. Once all the states are attributed to every component to every time in the mission time, it is possible to analytically calculate the whole system reliability, for every time in the mission time, using the RBD formulas. Repeating this process a pre-defined number of times (number of stories), it is possible to obtain a total mean reliability of the system for the simulated number of stories and mission time, fulfilling the purpose and objective of the method combination.

The method interaction and actual implementation in MATLAB script is later detailed in the section 4.2.

Chapter 4

Results

4.1 Case-Study

Firstly, in order to apply the methodology discussed in the chapter 3, there was the need to choose an appropriate case-study. It was chosen a real 61.5kV combined-cycle power plant, with a substation and two generating groups of 14MW each (28 MW in total). In the following figure, a representation of the referred power plant' simplified electrical scheme is displayed.

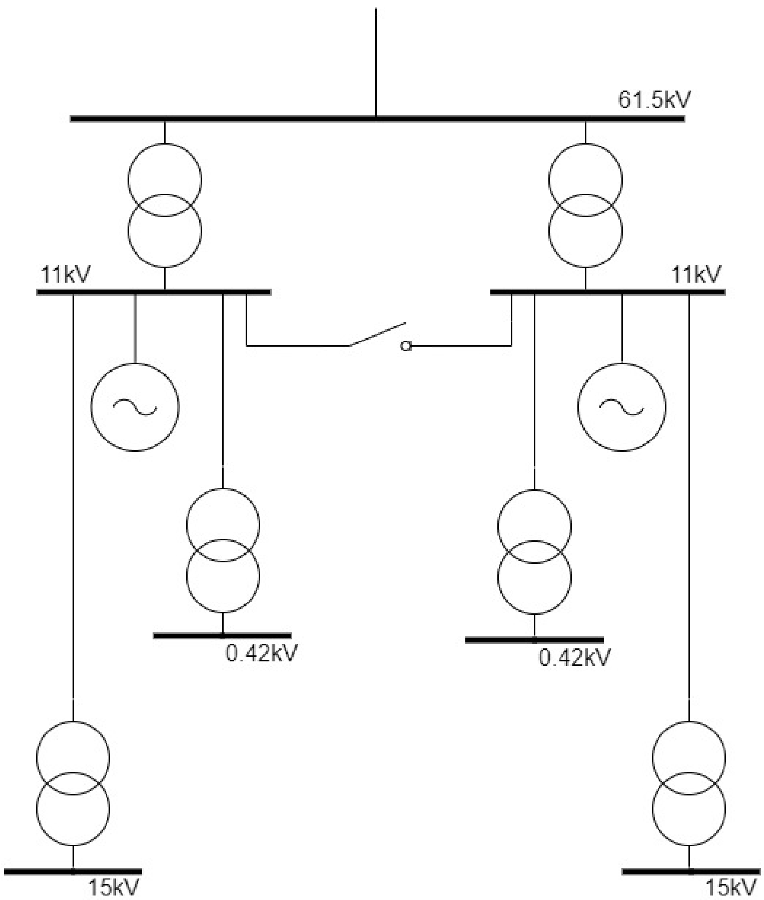

Figure 4.1: Power plant's electrical scheme

The chosen power plant architecture, i.e, its components and respective relations, would serve as a "basic frame" to this work. It is important that this "basic frame" is flexible in a way that it is simple to add, remove or replace components, in order to properly study the influences of certain components in the overall system. This will assure a complete and detailed reliability and availability study, since a plenitude of different scenarios will be examined.

Deconstructing the power plant into functional relations, two main groups stand out: the group of the substation itself and the generation group. In the figure 4.2, the "basic frame" is showcased and the referred two main groups identified.

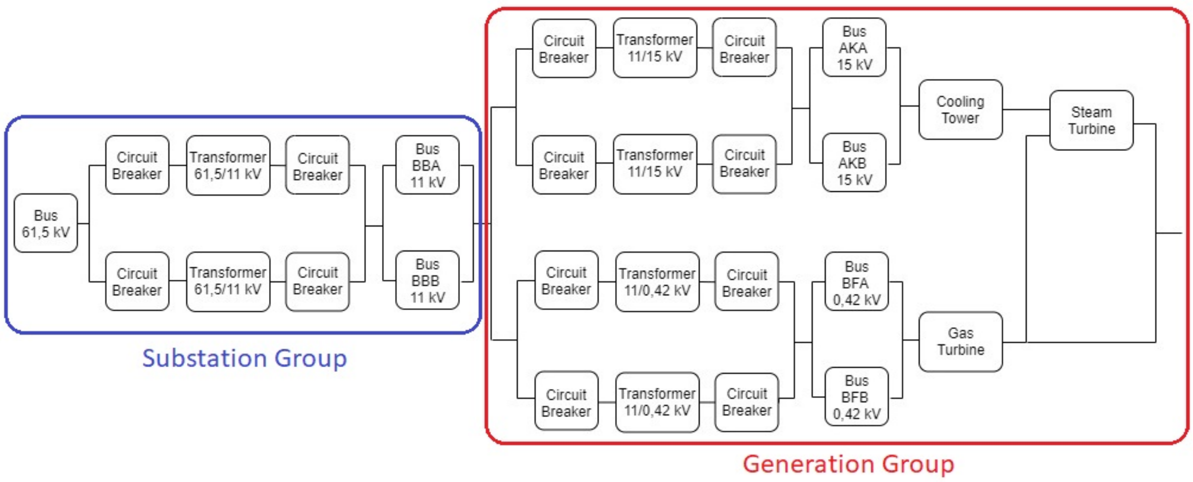

Figure 4.2: Power plant's "basic frame" and main component groups. In blue the Substation Group and in red the Generation Group.

Inside these main groups, there are other smaller groups that have a specific function within the group. These are called the subgroups, and are represented in the figure 4.3.

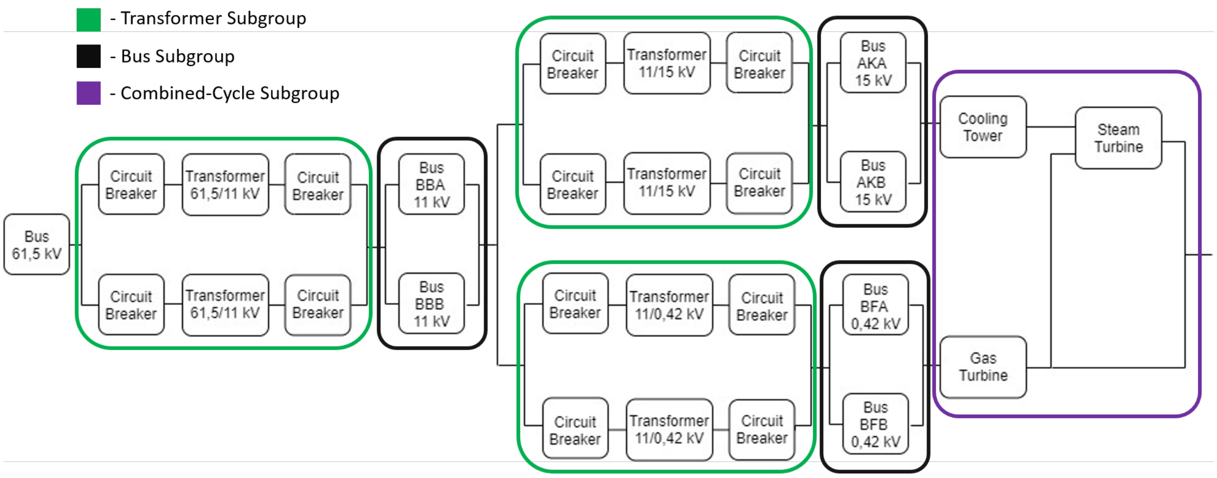

Figure 4.3: Subgroups of the power plant.

The function of the Substation Group is to receive the grid high voltage, 61.5 kV, transform it into a medium voltage, 11 kV, deliver it to the Generation Group, and later, once the power generation starts, transmit the generated power to the grid. This means that the substation is functionally bidirectional.

The Substation and Generation Groups are series related, since the Generation Group depends directly on the Substation Group. The transformation of high to medium voltage is accomplished by the two parallel Transformer Subgroup, represented in green at the figure 4.3.

These Transformer Subgroups, which can be found in both Substation and Generation groups, consist in a transformer and its respective two circuit breakers, doubled in parallel as was mentioned. This means that there are two identical transformers (and their respective circuit breakers) that ultimately act as redundant, i.e, if one of them fails, there is another still working and securing the operation of the Subgroup (and dependent groups/subgroups). These transformers operate separately and independently, which unveils that they have a functional parallel relation. Depending on the source of a malfunction, either outside of the transformer or in it, the circuit breakers can open to protect the transformer, or the rest of the power plant, respectively. The circuit breakers can carry out this protection since they have the capability to interrupt current flow. One of the circuit breakers is placed at the transformer's entrance, while the other is placed at its exit. From the figure 4.1, it can be visualised that the transformer and the associated circuit breakers are in series, by an electric point of view. This translates to their functional relation, since all the referred components are dependent of each other, meaning that they all are in series. It can also be concluded that this subgroup is essential to the operation not only of the substation, being its core, but also to the power plant in general. Regarding the Transformer Subgroup present in the Substation Group, its particular function is to transform the voltage needed by the medium voltage equipment, present in the Generation Group. Without the existence of this Transformer Subgroup, the referred equipment would not be able to function. This being stated, it is evidenced that this subgroup is in series with all other subgroups, since a fault at it affects the remaining of the power plant.

The other function of the Substation Group, as previously mentioned, is to deliver the step-downed voltage to the Generation Group. This kind of delivery can be executed by buses, in this case, two 11kV buses, named BBA and BBB, that form another subgroup - Bus Subgroup, represented in black in the figure 4.3 (also present in both groups). Again, there are two redundant parallel 11kV buses in order to assure that the transformed voltage is successfully transferred to the Generation Group, for the same reason there are two parallel transformers in the Transformer Subgroup. So, the Bus Subgroup, present in the Substation Group, is in series not only with the whole Generation Group, because if there is the total failure of the Bus Subgroup the fundamental medium voltage cannot be delivered, but also with the Transformer Subgroup (of the Substation Group), since the Bus Subgroup will not operate without the transformed voltage.

Note that in the Substation Group there is also a bus before the Transformer Subgroup, which conveys the 61,5 kV voltage to the later. If this bus fails in someway, the voltage is not delivered to the subgroup. So, the 61,5kV is in series with the Transformer Subgroup, and for instance with the Bus Subgroup and the Generation Group.

Regarding the Generation Group, as can be observed in the figure 4.2, it has some similarities with the Substation Group. For example, both subgroups of the Substation Group - the Transformer Subgroup and the Bus Subgroup - are also utilized in the Generation Group, even thought with different transformation values and to fulfill distinct functions.

The objective of the Generation Group is ultimately, as the name indicates, to generate electric power. This generation is conceived by the two turbines represented in the figure 4.2: the Steam and the Gas Turbine that together form the Combined-Cycle generation. These two turbines synergise very well, since the Steam Turbine can avail the high temperature of the gases used in the Gas Turbine's operation, making this type of generation cost efficient. Also, once the turbine gases, which contain energy, are being used by the steam turbine, the global energy conversion efficiency is increased. The following figure 4.4, taken from [36], illustrates the operation of a standard Combined-Cycle generation.

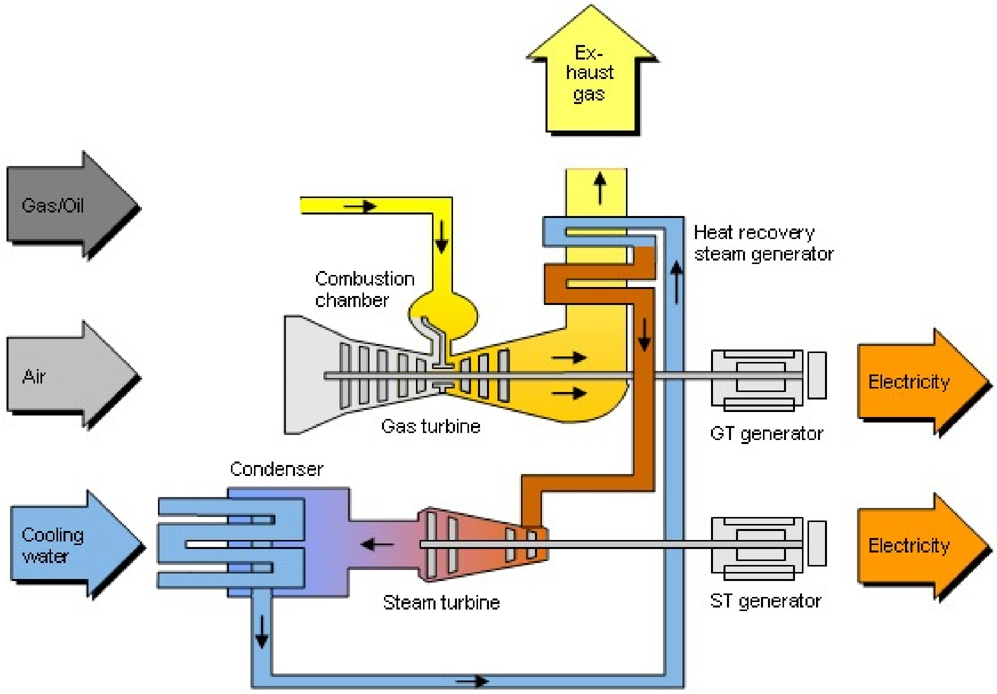

Figure 4.4: Operation of a typical combined-cycle generation.

Concerning the subgroups and its relations, there are not only, the already mentioned Transformer and Bus Subgroups, analog to the ones of the Substation Group, but also the Combined-Cycle Subgroup, represented in purple in figure 4.3, which includes the Cooling Tower as well as the Steam and Gas turbines.

As was mentioned, the Transformer and Bus Subgroups serve a somewhat different purpose to their counterparts of the Substation Group. Here they are present as a support to other components, i.e, to step-down or step-up voltage according to the needs of other equipment. So, ultimately, the Transformer and Bus subgroups have a more specific function in the Generation Group than in the Substation Group. There are two pairs of Transformer and Bus Subgroups in the Generation Group. For instance, the Cooling Tower equipment requires 15kV voltages, value which is higher than the 11kV delivered by the Substation Group. So a double parallel step-up transformer, and its correspondent circuit breakers, must be present, as well as the two parallel buses, AKA and AKB, to proceed the transport of the 11kV transformed voltage to the Cooling Tower. Analogously, the Gas Turbine and the auxiliary circuits, present in the buses BFA and BFB, demand a low 420V voltage (0,42kV), so the Transformer and

Bus Subgroups are also utilized, in order to step-down and deliver the voltage to the Gas Turbine, correspondingly. Remember that the Transformer and the Bus Subgroups are series related. Since the Cooling Tower and the Gas Turbine depend on the transformed voltages provided by their respective Transformer and Bus Subgroups, it can be concluded that each of these (the Cooling Tower and the Gas Turbine) are in series with the corresponding pair of subgroups (Transformer and Bus Subgroups).

Regarding the component relations of the Combined-Cycle Subgroup, they are more complex than the other component relations. Starting by the Cooling Tower, its function is to condensate the water (steam) used by the Steam Turbine, with the intent to reuse it in a cycle that allows the constant flow of water and the power generation. So, the Steam Turbine is dependent on the Cooling Tower, since it does not work without it, meaning that they are in series with each other. However, the Steam Turbine, operating in a combined-cycle configuration, also depends of the high temperature gases that are exhausted by the Gas Turbine, so that the liquid water (condensed in the cooling tower) is evaporated into steam, and then used to generate power. So, the steam turbine depends on two independent components, meaning that it is in series with two components at the same time - with the Cooling Tower and the Gas Turbine. This is represented with a double-entrance in a single component, as can be depicted in the figure 4.2. Although, note that the Gas Turbine is completely independent of the Steam Turbine, which would evidence a parallel relation between the two. This results in a unusual relation between turbines, which is series and parallel at the same time. By simplicity, this relation will be further mentioned as ”series-parallel”. Notice that if the Steam Turbine is at fault, the Gas Turbine can still continue its production normally, but if it happens to be the Gas Turbine in a failure state, the whole power generation ceases.

With all the groups and subgroups of components relations analysed and justified, it can now be discussed the computation of the power plant's original reliability and availability.

4.2 Basic-Frame – Standard Case

In first place, with the intention of making comparisons and studies on the power plant, it is important to evaluate the reliability and availability/unavailability of the ”basic-frame”, i.e, the standard power plant, without alterations – the standard case. So, in order to simulate the standard case, a MATLAB process, applying the Markov Chain, the RBD and Monte Carlo Simulation algorithms, was implemented. In the figure 4.5, a general representation of the main script functions is showcased, while in the figure 4.6, the formation of the Event, State and Temporal Reference Matrices is detailed. This detail was given, due to the fact that these matrices are the key points to the script's operation, as it will be further explained in the following subsection.

4.2.1 Reliability and Availability Evaluation Process

In order to start the simulations, some values associated to the used algorithms – Markov Chain and Monte Carlo Simulation – needed to be initialized.

The Monte Carlo Simulation test values correspond to the number of stories and the mission time (MT). The number of stories is the number of times that the process is going to repeat itself, whereas the mission time is how much in time it will simulate (in each repeat). Remember that these stories are all different from each other, since they are being simulated using the Monte Carlo algorithm (section 3.4). Regarding the mission time, it was set to be 350400 hours, which corresponds to the total number of hours in 40 years (40 x 8760h). This time was chosen in order to fit approximately the lifetime of a power plant. Concerning the number of stories, the higher the better, since the more repeats simulated, the more precision, and, consequently, the more quality and robustness of the Monte Carlo simulation. The number of stories was defined as being 10000, value that was maximized accordingly with the limitations of the available computer's RAM-memory. Notice that the study was conducted in hours with the intent to detail as much as possible the variations of the reliability and availability along the mission time.

The values associated with the Markov Chain algorithm are the failure and repair rates, often represented as λ and μ, respectively. These concepts have already been explained in section 3.2, but shortly, these rates allow the transitions between operational states. In this work there are only two states: UP state, when the component is fulfilling its function, and DOWN state when it is not. A research was conducted in order to determine the correspondent rates of each component present in the power plant. Although, in the standard case, all the components had a direct value associated, heed that in some cases there was no direct value of the rates, and those had to be estimated based on research data. A series of databases and research works were consulted in order to obtain the referred rates. The ones used were: [26], [27], [28], [29], [30], [31], [32], [32], [33].

With the initialization of the test values and the rates it was possible to advance to the creation of the Event, State and Temporal Reference matrices. As was previously mentioned, the creation of the matrices, in the proposed approach, is a fundamental point of the reliability and availability evaluation process. In the figure 4.6 it is depicted how these matrices are generated. In the stated figure it can be visualized that the conception of the matrices is split in two parts: the creation of the Event matrix and the creation of the State and Temporal Reference matrices.

The Event matrix, as the name suggests, is the matrix where the events that are randomly assigned throughout the mission time are registered. There are two types of event: the failures and the recoveries, which are attributed in the matrix as -1 and 1, respectively. As was explained in the section 3.4, these events occur in a "semi-random" time. Remember that it was determined an exponential distribution for all the components in this work.

The first assignment in the creation of the Event matrix is to determine the working time, t_{up}, of the component in study, through the expression (3.52). In other words, it is "randomly" simulated how long the component in question is going to be operational. Note that it is assumed that all the components start completely functional. Obtaining the t_{up}, in order to flow through the mission time, MT, it is necessary to update the "current" time, t_{cur}, which corresponds to the times the events occur. So, and assuming that t_{cur} starts in the beginning of the MT, it is incremented to the previous t_{cur} the "randomly" generated t_{up}. In this way, t_{cur} always corresponds to the exact time of occurrence of an event – failure or recovery. So, the event in question is registered for $t = t_{cur}$. After a failure, it is required to "randomly" simulate how long the repair will take, i.e, how long the component is going to be out of order, t_{dwn}, using the equation (3.53). Analogously, the t_{cur} is updated and the event is registered. This forms a cycle, with failures and recoveries in succession, which only breaks when the t_{cur} exceeds the mission time. When it does, there are no more events to mark in the matrix, meaning that its creation is concluded (for the "current" component).

With the Event matrix created, it is possible to start the creation of the remaining State and Temporal Reference matrices.

The State matrix has the function to save the states of every component throughout the duration of the mission time. As was previously mentioned, in this thesis there are two possible states: UP state, corresponding to 1 in the matrix, and DOWN state corresponding to 0. Considering the initial state as being 1, since it corresponds to the operational state and it was assumed that all components start operational in the beginning of the MT, the State Matrix is filled in a straightforward manner. A MATLAB *for* cycle runs the Event matrix to every time(event matrix column positions) from 0 to MT, in order to detect any events. If no events occur, it keeps the previous state and advances in time. Otherwise, if an event occurs, it evaluates the type of event, i.e, if it is a failure (-1) or a recovery (1). If it is a failure the new state is 0, if it is a recovery the new state is 1.

Regarding the Temporal Reference matrix, it was added to this work in order to adjust the timeline when a recovery happens. Recovery is when a component goes from out of order to operational, that is, from state 0 to state 1. The detail is that when a recovery occurs it should not go back to the pre-failure reliability, instead it should be fully recovered, as if it was being used for the first time. Notice that it was assumed a total recovery of the components. In reality, after a reparation, the intervened component should not regain its full functionality. It was considered like this due to the lack of information and studies on how recoveries actually influence the failure rate numerically. So, the reliability of the recovered component must be reset to the value it possessed at the beginning of the simulation, i.e, when the MT was equal to 0. Therefore, what the script does to fill the Temporal Reference matrix is to register the time when a component recovery occurs. This time was named "temporal reference", t_{ref}, and defines the name of the matrix. In the time just after the recovery, the t_{ref} is subtracted off the value of the former (remember that the event matrix is being studied from 0 to MT, hour by hour) and since t_{ref} has the value correspondent to the previous hour, the result of the difference is 1. To the hours after, the result is 2, 3, 4, and so on. In this way, the time is reset and it is like the component was starting its operation from the beginning. Note that this changes are only made to a specific component that received a recovery, to the other components the time runs as usual, hour by hour without alterations.

After completing the three matrices to all the components, it is possible to start the calculation of the reliability and availability of each component and of the substation in general.

The individual reliability and availability calculation is computed by applying the formulas (3.23) and (3.34), already explained in section 3.1, always taking in consideration the adjustments, associated with the Temporal Reference matrix, required by the repairs.

Having all the components individual reliability/availability and taking into consideration the functional relations between groups and subgroups of components, already detailed in the section 4.1, and by using the formulas correspondent to the RBD series and parallel relations, present in section 3.3, it is possible to compute the power plant's reliability/availability as a whole. Due to the fact that there is a total of 28 components, these calculations were computed subgroup by subgroup in order to maintain them clear and not susceptible to mistakes. Heed to the fact that each component has a state for every time, from 0 to MT. So, these calculations were done hourly (from 0 to MT) in order to consider the states of each component for each time. Also note that, because of the way the state matrix was computed, multiple failures or repairs can occur at the same time. The following group of equations (4.1) are an excerpt from the developed MATLAB process, which convey the calculation of the reliability of a Transformer Subgroup (see figure 4.3).

$$\begin{aligned} &transf\_subgp\_up = S2(t_i) \cdot comp\_relia(2) \cdot S3(t_i) \cdot comp\_relia(3) \cdot S4(t_i) \cdot comp\_relia(4) \\ &transf\_subgp\_dwn = S5(t_i) \cdot comp\_relia(5) \cdot S6(t_i) \cdot comp\_relia(6) \cdot S7(t_i) \cdot comp\_relia(7) \\ &transf\_subgp\_total = 1 - ((1 - transf\_subgp\_up)(1 - transf\_subgp\_dwn)) \end{aligned} \tag{4.1}$$

S_i, with $i = 1 : 7$, are the ith states for the "current" time, t_i. The "$comp\_relia$" is the individual reliability of a component. The "$transf\_subgp\_up$" represents the reliability of the 3 components in series represented on the top half of the subgroup, whereas the "$transf\_subgp\_dwn$" are the ones present in the bottom half. And finally, the "$transf\_subgp\_total$" is the final reliability of the subgroup, which is the parallel between the "$transf\_subgp\_up$" and "$transf\_subgp\_dwn$".

There is a reliability/availability computation that is somewhat different from the others – the computation of the Combined-Cycle Subgroup. As was already detailed in the section 4.1, the relation between the gas and steam turbines is an unusual series-parallel relation. The steam turbine depends on the gas turbine, even thought they function independently. For instance the gas turbine depends on the subgroups that precede it - a transformer and a bus subgroup. The total state of these two subgroups plus the state of the gas turbine is calculated. This state is then combined with the steam turbine state, resulting in a new state for the steam turbine. In conclusion, this new created state for the steam turbine takes into consideration the direct influence of the gas turbine, which for instance depends on other subgroups. The parallel part of the series-parallel relation is computed between the series of the cooling tower and the steam turbine (always taking in regard the gas turbine influence), and the gas turbine, considering the respective preceded transformer and bus subgroups.

This whole process of creating the matrices and compute the reliability/availability is repeated for every story. Once all the stories are simulated, it is calculated the mean of the reliability/availability values, to each hour of the mission time. This hourly mean is the final result of the power plant's reliability/availability, and its graphically outputted a x-y graphic, being x the hours in mission time and y the correspondent 10000 stories hourly mean of reliability/availability. Also, with the intent to make a more complete study and to evaluate the dispersion and consistency of the simulations, an hourly standard deviation was computed and included in the same graphic output of the reliability/availability over time. The values of this curve are in absolute value of reliability or availability, not in percentage.

These graphical outputs mark the end of the reliability and availability evaluation process. The results obtained to the standard case, of both reliability and availability, are detailed and analysed in the following subsection.

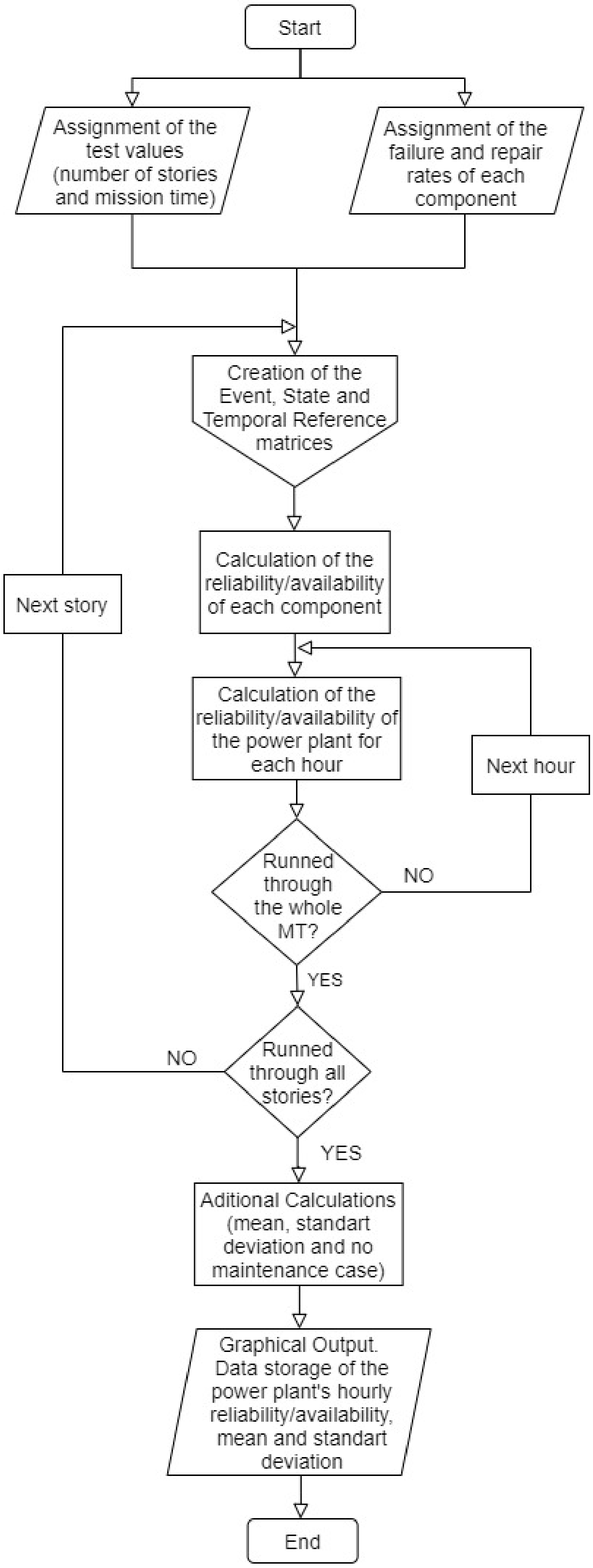

Figure 4.5: Flowchart with the main script functions.

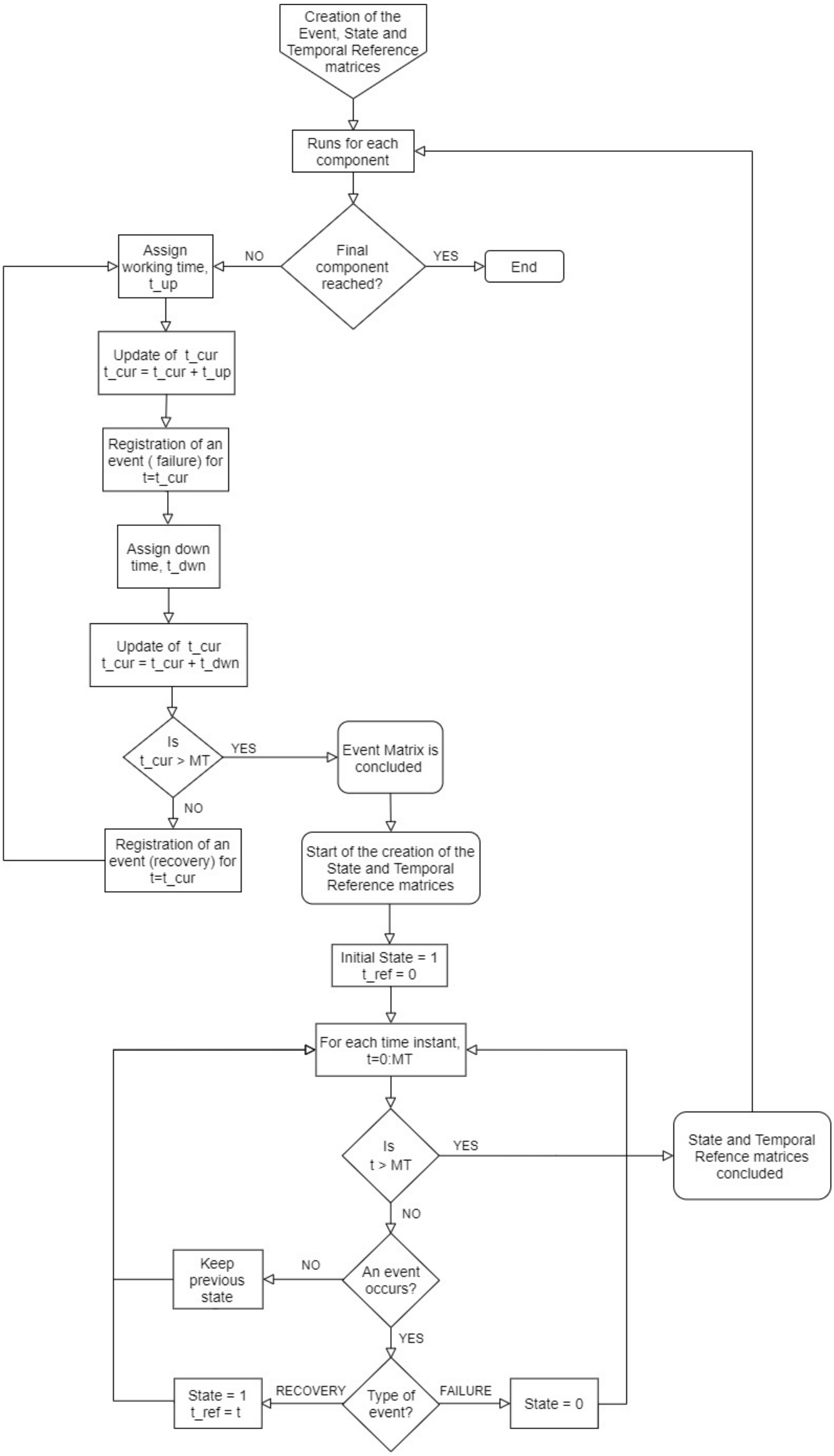

Figure 4.6: Flowchart detailing the creation of the Event, State and Temporal Reference matrices.

4.2.2 Standard Case Results

The standard case was simulated for 10000 stories, each one of them with a mission time of 350400 hours (40 years). It was obtained the graphics represented in figures 4.7 and 4.8 of reliability and unavailability over time, respectively. Additionally, the table 4.1 containing the total mean reliability and unavailability values is provided.

Remember that the standard case will be mainly used as a term of comparison with other cases, since this is the case where there are no alterations in the power plant.

In the reliability simulation, it was decided to add a curve of reliability without events, i.e, where the reliability of each component decays in time but no failure or repair events occur. This was implemented by fixing the state of every component to every hour of the MT as 1 (UP). The reason why it was added is to evaluate the influence of the failure/repair interaction on the reliability's curve behaviour. Its total mean value for the 40 years is present in the table 4.1.

Analysing the figure 4.7, it can be observed that the reliability starts off high, as it was expected, since the reliability formula for exponential distribution and a constant failure rate, (3.23), mathematically suggests just that. Furthermore, most of the components at the beginning of the mission time have high values of reliability, making the overall power plant's reliability also high. As it was also expected, the reliability decays over time, which makes sense: the older the components, and for instance groups of components, the less reliable they are. This is also confirmed by the reliability formula (3.23). In the first two decades it decays around 0.2 in each, reaching its mean value, present in the table 4.1, of 0.5484 by the end of the referred decades. In the last two, it decays around 0.1. Again, this is typical of a exponential, which is the distribution that is considered in this thesis to all components.

Comparing the hourly reliability with and without failures/maintenance events, some differences can be spotted. Firstly, the total mean value of reliability without events for the total mission time is roughly half of the case where events are considered, as is showcased in the table 4.1. This low value could be predicted by how much faster its correspondent reliability curve decays over time, actually reaching around 0 in the 40 year mark, when compared to the counterpart where failures/maintenance events occur. At first glance, it might seem odd that a case where failures do not take place has worst performance in terms of reliability than when fails do happen. But, as was already briefly mentioned, recoveries, i.e, repairs, of the components take place after they fail, so some maintenance, even though being forced, is applied, which ends up improving the reliability value of the components and of the power plant overall.

In terms of standard deviation, it starts low, for the first hours it is actually around 0, but rapidly increases to values around 0.08 of absolute reliability value. This initial low values were already previewed, since most of the component's reliability, and for instance overall power plant's reliability, is around 1 in the beginning of the simulations, revealing little to no dispersion. Heed to the fact that the standard deviation is calculated between the reliability for each and every hour of the simulation of each individual story, and the mean hourly reliability of overall system, including all the stories (hourly mean reliability), using the formula (4.2):

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \overline{x})^2}{N-1}} \tag{4.2}$$

Being x_i the hourly mean reliability for each individual story, $\overline{x}$ the power plant's hourly mean reliability, and N the number of stories.

The standard deviation from then on increases until it stabilizes at approximately 0.15 of absolute reliability value. This increase was foreseen, due to the "randomness" associated to the assignment of t_{up} and t_{dwn}, i.e, the failures and repairs can happen at different times in each story, increasing the data dispersion between the hourly results of each individual story and the hourly mean of them all.

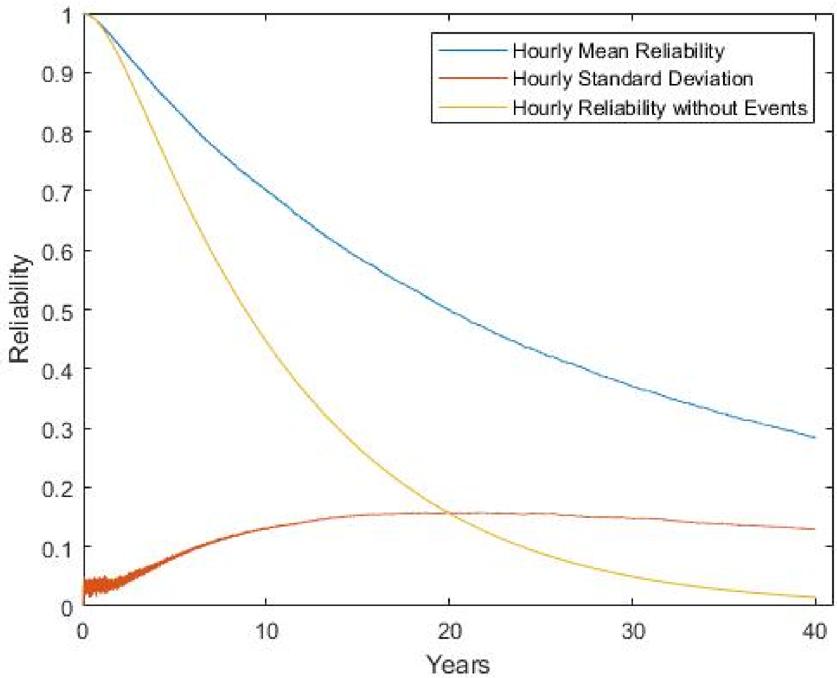

Figure 4.7: Reliability of the power plant for the standard case, over 40 years.

Regarding the availability, it was decided to express it as its opposite – unavailability – for the reason of being more practical in terms of data display. Unavailability is mathematically expressed by (4.3):

$$unavailability = 1 - availability \tag{4.3}$$

Observing the figure 4.8, it can be deducted that the hourly mean unavailability is mostly around its total mean value which is 0.00113, as can be beheld in the table 4.1. In practice this means that the power plant has a probability of 0.00113 of being unavailable, so it is, during the whole mission time, available at a 0.99887 probability. The reason why the unavailability is almost constant is justified by the fact that it is directly influenced by both the failure and repair rate of the components, in contrast with the reliability, which only is directly impacted by the failure rate. This dual direct influence, plus the great amount of stories simulated and the low frequency of event occurrence (fails and repairs), results in a balancing of the availability/unavailability value.

In terms of hourly standard deviation, it hovers around the 0.01 and 0.05 of absolute value, in a more or less constant matter, as was expected since the hourly mean unavailability has an identical behaviour. This standard deviation curve is a little noisy as can be perceived by the figure 4.8. In order to solve this, it was necessary more stories (repeats), which unfortunately is not possible due to the RAM memory limitations of the available computer. Another solution would be its average computation along each year, instead of hours, which would not make sense since all the other simulations are in hours. Also, the hourly detail would be lost. So, henceforth, the unavailability graphics will not be displayed in figures since they do not add too much but noisy curves and practically constant lines. Alternatively, the relevant values of the unavailability simulations will be displayed in tables, like the total mean unavailability is in the table 4.1.

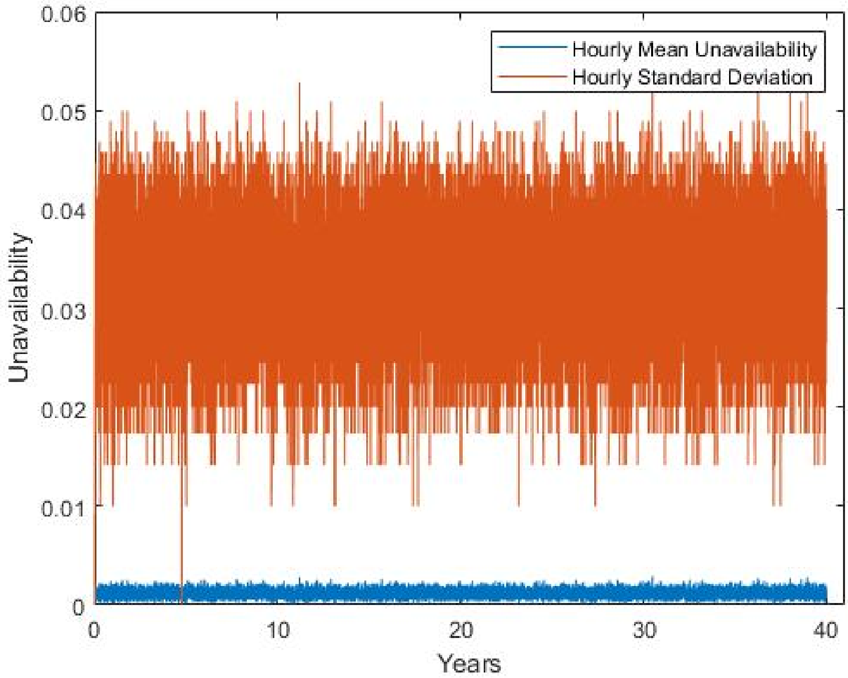

Figure 4.8: Unavailability of the power plant for the standard case, over 40 years.

Table 4.1: Total Mean Reliability and Unavailability values of the standard case.

	Total Mean Reliability	Total Mean Reliability without maintenance	Total Mean Unavailability
Standard Case	0.5484	0.2824	0.00113

Finishing the analysis of the reliability and unavailability results of the power plants' standard case, it is possible to advance to other cases and use this one as a term of comparison. These studied cases can be distributed in three distinct types of study:

1. Component substitution, more specifically an upgrade of the classical mechanical circuit breakers to modern electronic circuit breakers;

2. Component influence, where it is studied the influence of the central power equipment – the transformer.

3. Component addition, in which it is simulated the introduction of a modern power equipment – a Static Var Compensator (SVC).

These studies are detailed and analysed, respectively, in the further subsections.

4.3 Component Substitution: Substitution of Circuit Breakers

As was briefly mentioned, circuit breakers are used to protect other components, since they have the capability to interrupt current flow. In this particular power plant, circuit breakers are used to protect the transformers. The classical circuit breakers, operate mechanically, however, in recent years, a new type of circuit breaker has emerged: electronic circuit breaker, also called solid state circuit breaker or digital circuit breaker. As the nomenclatures suggests, these circuit breakers operate electrically. They still have the same purpose of the classic ones, but promise, according to the authors of [37], ”fast tripping speed and high reliability as well as sensitivity. An electronic circuit breaker can meet these demands of the modern industry.”. In order to evaluate if these electronic circuit breakers perform in a superior way in terms of reliability and availability/unavailability than the classical circuit breakers, used in the standard case, a study was conducted on them, and later the power plant's reliability and unavailability was simulated with them in the place of the classical circuit breakers.

Authors of the paper [37] suggest a block diagram of a ”smart ultra fast acting electronic circuit breaker”, represented in the figure 4.9.

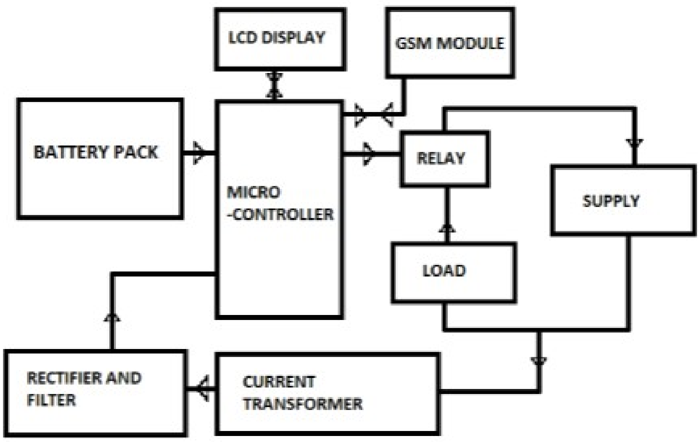

Figure 4.9: Block Diagram of the studied electronic circuit breaker, taken from [37].

Using the information further provided by [37] regarding the functions in the operation of the electronic circuit breaker of each component that compose their block diagram, represented in figure 4.9, it was possible to determine the functional relations between components and subsequently create a functional block diagram, present in the figure 4.10. Note that some of the components in figure 4.9 were not considered because they do not influence significantly the reliability of the overall electronic circuit breaker, meaning that they do not enter in the failure modes of the circuit breaker. These neglected components were the LCD Display, GSM module and the ”Load”, which in fact is not a component at all.

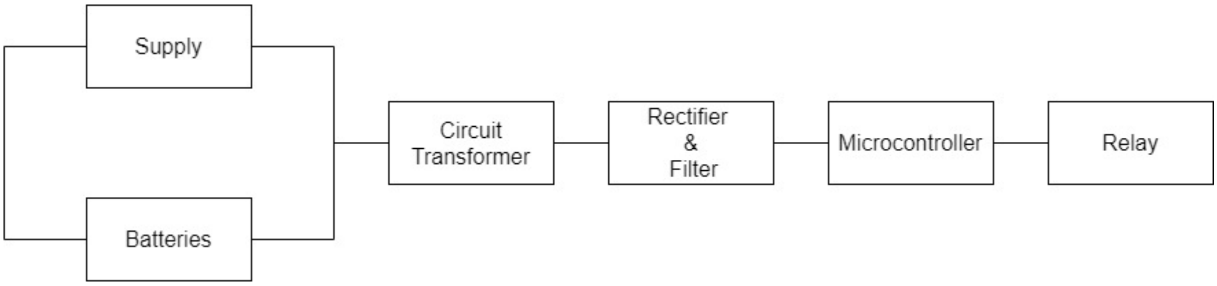

Figure 4.10: Functional Block Diagram of the studied electronic circuit breaker

Having the relations between components, showcased in figure 4.10, a research on the correspondent failure and repair rates was conducted, using data from [26] - [33]. After this, the aim was to define the failure and repair rates of the electronic circuit breaker as a whole, in order to substitute the rates of the classic circuit breakers and simulate the power plant already with the new-generation ones. Note that it is assumed that these circuit breaker design is applicable to a power plant's high demanding voltage and current, as it is suggested in the paper [37], and all the values of failure and repair rate of the components are in accordance with that.

To achieve this, it was necessary to individually study both the reliability and availability of the solid state circuit breaker alone, in order to determine its failure and repair rate, respectively. Starting by the reliability, it was calculated firstly to each component of the circuit break, and then to the circuit breaker as a whole, both to a generic time, t. To accomplish this, it was taken in consideration the functional relations expressed in the functional block diagram from the figure 4.10, the RBD series and parallel formulas from the section 3.3 and the researched failure rates of the components that compose the electronic circuit breaker. In order to obtain the failure rate, λ, it was used the formula (3.14), being $R(t)$ the calculated reliability for a generic t. The obtained failure rate, $\lambda(t)$, was simulated to a time span of 100 years, value large enough to precisely determine the mean failure rate of the electronic circuit breaker, which is going to be considered as the failure rate of the electronic circuit breaker. From this simulation, resulted that the mean failure rate of the solid state circuit breaker is approximately 0.001 failures/year, value that is around 10 times lower than the classic high current circuit breaker's 0.0096 failures/year. In order to validate the obtained mean failure rate value, it was simulated the reliability of the electronic circuit breaker without the mean value, which in practice is the result of the RBD formulas applied to the functional block diagram with t from 0 to 100, and with the mean value, to check if the difference between them was relevant. The results are present in the figure 4.11.

As can be observed in the figure 4.11, there is no significant difference between the reliability computed using the obtained mean failure rate value and without using it, meaning that the performed failure rate approximation is valid.

Regarding the determination of the repair rate for the electronic circuit breaker, a similar method, with some variations and adjustments, was utilized. The referred adjustments had to do with the fact that, while in the reliability computation there was only one variable, which was the time t, since the

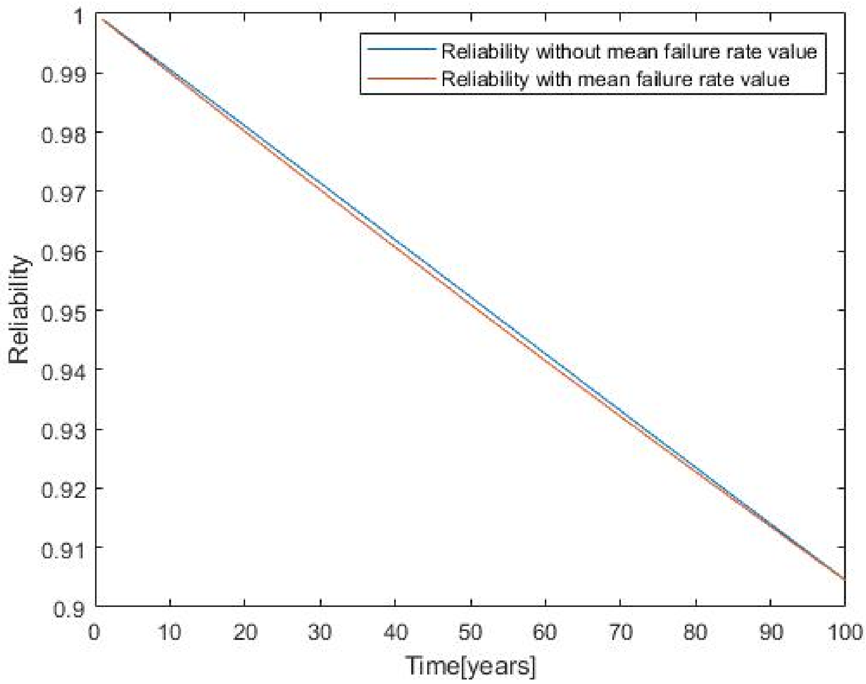

Figure 4.11: Reliability of the electronic circuit breaker with and without the obtained mean failure rate.

failure rate was calculable by the formula (3.14), in the availability case there are two variables - the time and the repair rate, once it does not have an associated formula. To solve this in a simple way, it was attributed values to time, in this case, from 0 to 100 years, in order to have a single variable.

So, to every time ranging from 0 to 100 years, the availability for each component present in the constitution of the electronic circuit breaker was computed. Afterwards, the availability of the whole circuit breaker was calculated, using the RBD formulas. Having the availability and considering the failure rate as the one calculated beforehand, 0.001 failures/year, it was possible to determine the repair rate of the overall electronic circuit breaker, to every year in a range of 100 years, by substituting all the referred values in the availability expression (3.34) and solving the subsequent equation in order to the repair rate. From this equation results the repair rate to every year from 0 to 100 years. So, it was calculated the mean of these values, consummating in the mean repair rate of the whole electronic circuit breaker. The result was an annual repair rate of 1431.3 years/failure, which corresponds to 0.1634 h/failure and a MTTR of approximately 6.12h/failure. The classic circuit breaker has a repair rate value of 0.125h/failure, which corresponds to 8h/failure of MTTR. So, this means that the electronic circuit breaker takes about 2 hours less to be repaired than the classic circuit breaker, which in percentage corresponds to 24 % less time. The comparison between the availability calculated with the computed mean repair rate and with the RBD formulas, both along 100 years, is represented graphically in the figure 4.12.

As can be concluded after observing the figure 4.12, there are no differences between the unavailability calculated without the mean repair rate, i.e, with the RBD formulas, and the one calculated with it, meaning that the obtained mean repair rate is valid.

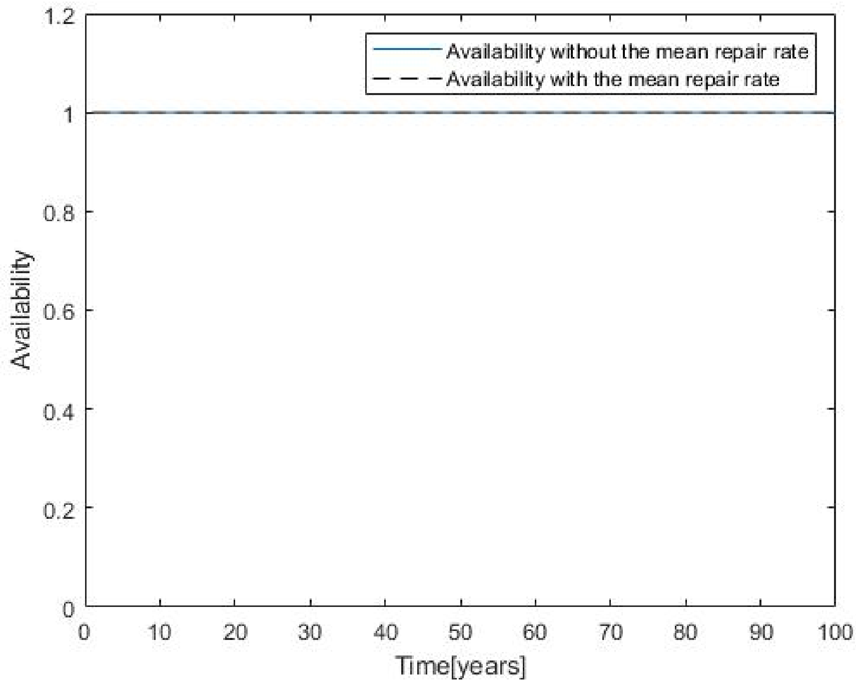

Figure 4.12: Availability of the electronic circuit breaker with and without the obtained mean repair rate.

In conclusion, the computed failure and repair rates of the electronic circuit breaker are better than the classical circuit breaker ones. Thus, it is predicted that the reliability and unavailability of the power plant is going to improve with the substitution between these electronic circuit breakers and the classical ones, used in the standard case.

So, the simulation of the power plant's reliability and unavailability with the electronic circuit breakers instead of the classical was conducted.

The reliability and unavailability results over time (40 years) are represented in the figure 4.13 and in the table 4.2, along with the standard case counterparts, in order to compare both cases.

Starting with the analysis of the figure 4.13, correspondent to the reliability of the power plant with the electronic circuit breaker over time, along with the results of the standard case, there are some points that immediately stand out when comparing both. Firstly, the hourly mean reliability increased, which can be visually confirmed in the figure 4.13, and by comparing the values of the total mean reliability of the power plant between the standard and this case, present in the table 4.2. In this simulation, the total mean reliability increased from 0.5484 to 0.6678, meaning an absolute value around 0.12 higher, which in percentage corresponds to 22 % higher. In practice, this means that for the same passed time, the power plant with the electronic circuit breakers has higher reliability than in the standard case, which is a positive outcome and makes an argument in the use of this type of circuit breakers.

Regarding the standard deviation, it has approximately the same behaviour of the standard case, even thought it stabilizes in a higher value of reliability. However, this difference is not significant enough to compromise the precision and low value variation and dispersion of the simulation as a whole.

In regard to the unavailability of the power plant with electronic circuit breakers, there are also some

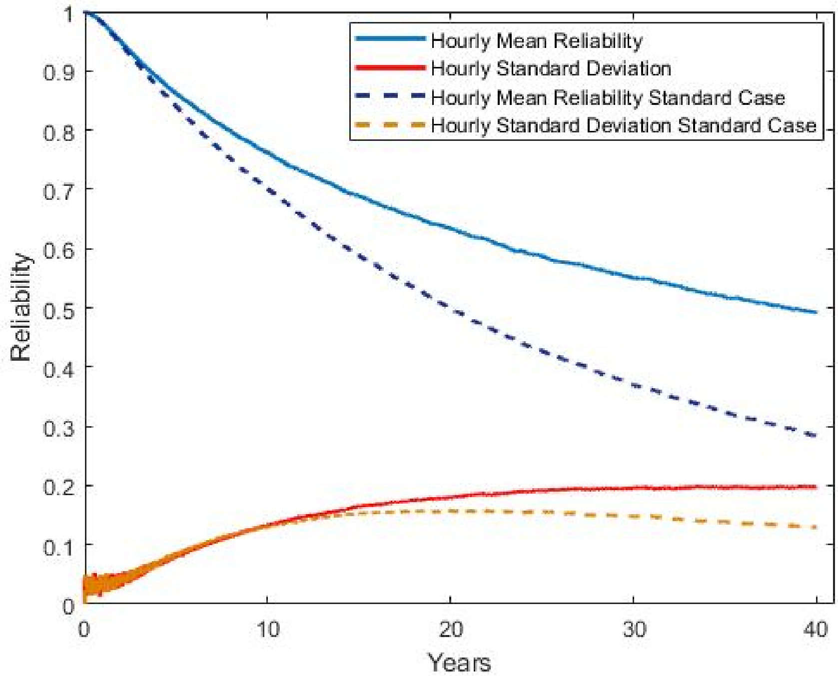

Figure 4.13: Reliability of the power plant with the electronic circuit breaker comparison with the standard case, over 40 years.

notes to share. Comparing the total mean unavailability values of both cases, present in the table 4.2, it can be concluded that the total mean value of the electronic circuit breaker case is approximately the same as the one registered for the standard case, as the discrepancy between the two is only approximately 0.3%. This low difference can be explained by the fact that the disparity between repair rates of the classic and electronic circuit breaker is only 2 hours, and also due the fact that both MTTR of the stated circuit breakers being fast, which end up having little impact on the unavailability.

Table 4.2: Total Mean Reliability and Unavailability values of the standard and Circuit Breaker Substitution cases.

	Total Mean Reliability	Total Mean Unavailability
Standard Case	0.5484	0.00113
CB substitution	0.6678	0.001127

In conclusion, the power plant with the electronic circuit breakers performed better in terms of, not only reliability, but also unavailability, when compared with the standard case that was simulated using the classical circuit breakers, even thought the reliability results are much more significant and visible. This was already predicted at the time of the computation of both failure and repair rate, and this results provide a basis for the implementation of electronic circuit breakers in substations and power plants, in detriment of the classical circuit breakers, since they do not have any apparent advantage over their electronic counterparts in terms of reliability and unavailability. However, it is suggested an economical study in order to evaluate the cost-benefit of the electronic circuit breakers, and whether or not its usage is worth cost wisely.

Finishing the study on the circuit breakers, it is also important to study the influence of the components they protect – the transformers – and how much impact they have in the overall power plant system reliability and unavailability.

4.4 Component Influence: Evaluation of Transformer influence

The transformers are fundamental to both the groups of the power plant - the substation and the generation groups. They are the main component in the Transformers Subgroup, as the group's name suggests, and their main function is to step-up or the step-down voltage, according to what is needed. This subgroup has two parallel transformers, with their respective circuit breakers, that act as redundant – if one fails there is the other one to substitute the faulted one. As a means to determine the influence of the parallel transformer in the reliability and unavailability of the power plant, two different studies were undertaken:

1. Simulation of the power plant without the parallel transformer – No Redundant Transformers Case
2. Simulation of the power plant with the parallel transformer in standby – Standby Case

In order to easily compare the two studies, between themselves and the standard case, it was decided to merge the reliability graphics of the three cases in a single one, represented in the figure 4.14. The same procedure was conducted regarding the unavailability, where the total mean unavailability values of the three cases are present in the table 4.3. The total mean reliability values can also be consulted in this table.

Starting with the comparison between the case were all the parallel transformers were not considered, and the standard case, it is possible to evaluate the actual influence of these transformers. So, in this case, instead of having a parallel in all the Transformer Subgroups, there is only a single transformer with the two respective circuit breakers.

Analysing the reliability simulations correspondent to the no redundant transformers and the standard cases, both present in the figure 4.14, a few differences can be observable. For instance, the hourly mean reliability of the no redundant transformers case is clearly lower than the standby case, which is also proven by the total mean power plant reliability values of the referred cases, located in the table 4.3: the standard case has a mean total reliability of 0.5484, whereas the case without the parallel transformer has 0.3559. This is a notable difference of around 0.2 of absolute reliability value, corresponding to 35 % of variation. Also, the hourly reliability decays much faster, since the slopes of the reliability curves are higher in the case without parallel transformers. For example, for the 10 year mark (87600 hours), the standard case is at 0.701 of reliability, while this case is at 0.4792, 32 % lower. This difference is even more accentuated for the 40 year mark, when it reaches 58 % variation, corresponding to the absolute reliability values of 0.1196 for the no redundant transformers case and 0.2838 for the standard one.

Concerning the standard deviation, the shape of the curve is similar to one obtained in the standard case, but peaks to a lower value: around the 0.11 of absolute value instead of the 0.16 registered in the

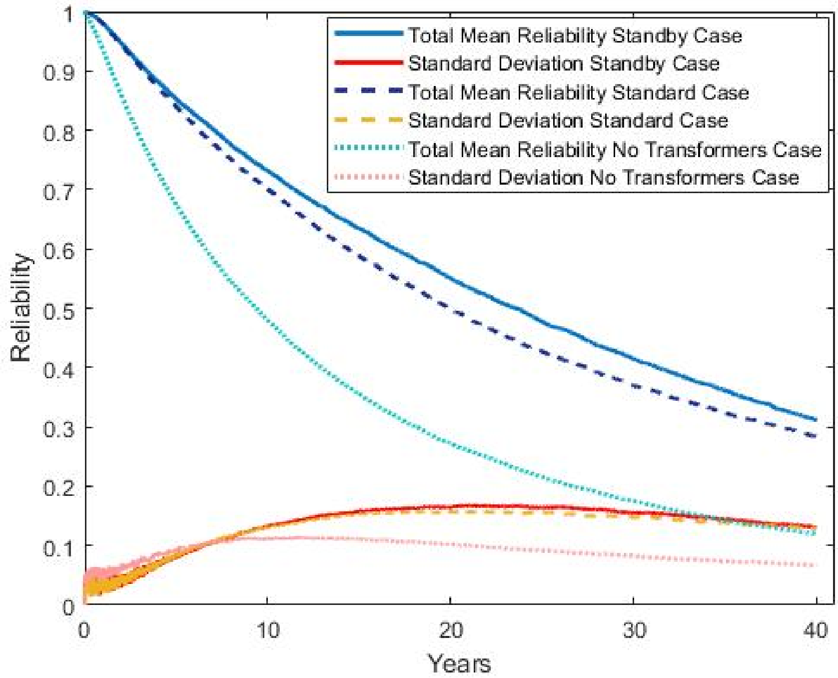

Figure 4.14: Reliability of the power plant for the no redundant transformers, standard and standby cases, over 40 years.

Table 4.3: Total Mean Reliability and Unavailability values of the standard and Transformer cases.

	Total Mean Reliability	Total Mean Unavailability
Standard Case	0.5484	0.00113
No Redundant Transformers	0.3559	0.005265
Standby Transformers	0.5845	-

standard case, 31 % lower. This is positive and reveals that the simulation is trustworthy and consistent for all the cases. Also, it indicates that the variation in the obtained values is not significant and the dispersion is low.

In regard to the unavailability results, the total mean unavailability value registered to the case without parallel transformers is 0.005265, whereas the standard case is 0.00113, a difference of around 0.004 of absolute unavailability value, which corresponds to a variation of 366 %. This difference is much more significant in percentage than the 35 % registered in the reliability simulation, due to the fact that, even thought for the majority of the time, the unavailability is very low in absolute value, when a failure occurs in a transformer, which has a long MTTR, the majority or the whole power plant shuts down, depending on which transformer the failure occurs. If it happens in a critical transformer as, for example, the one on the substation group, the power plant will be ceased for the entirety of the MTTR, which is around 1200 hours, corresponding to 50 days. During this time, the unavailability is total, i.e, equal to 1, which unbalances the typical low unavailability values and increases the total mean unavailability to the value present in the table 4.3. Note that this is one of the reasons that the reliability also drops, but the repair rate has no direct influence in the reliability, in contrast to the computation of availability/unavailability, and this is why the difference in percentage is larger in the unavailability than in the reliability, when comparing both to the simulation counterparts of the standard case, as the failure rate – the only rate that has direct impact in the reliability – is relatively low in the transformers while the MTTR is high.

Employing the equation (3.47), the application of the standby was performed. The reliability of the transformer subgroups, instead of being computed with the RBD parallel formula, were computed with the referred equation (3.47).

In terms of application method, some changes were needed. There was the necessity to know the state of both the active and standby series of the 2 circuit breakers and the transformer in order to define when the standby component is in fact in the standby state, so that the reliability can be computed by (3.47). So, if both the active and standby are UP, i.e, if the 2 series of the 2 circuit breakers with the transformer are all with the state 1 (UP), the reliability is calculated by (3.47). Otherwise, the reliability is calculated normally by the equation 3.23. Note that the reliability of the other subgroups that are not transformer subgroups is also calculated normally.

Heed to the fact that the unavailability study in this case is not possible, due to the fact that there is not an availability or unavailability version of any of the equations from (3.43) to (3.47). So, only the reliability standby study of the power plant was conducted, and its correspondent simulation is represented by the dashed lines in the figure 4.14.

Comparing the standby and the standard case reliability simulations, making use of the figure 4.14 and the table 4.3, it is possible to evidence some differences. For instance, the total mean reliability of the power plant of the standby case is 0.5845, whereas in the standard case was 0.5484, a variation of approximately 7 %. Even thought it is evinced that the variations between the standby and standard studies are relatively low, the standby case is still an improve. Concerning the standard deviation curves, as can be visualized in the figure 4.14, they are practically coincident.

Comparing the standby and the no redundant transformers reliability studies, dashed and point lines of the figure 4.14, respectively, the variations are more abrupt: the total mean reliability has a disparity of approximately 39 %. This is also noticed in the hourly mean reliability curves of both simulations. The percentage discrepancies demonstrate that the standby parallel transformer provides a better performance in terms of reliability than the absence of it, as was already expected since the standby case performed better than the standard one, while the no redundant transformers case performed worse than the standard.

In conclusion, the conducted reliability and unavailability simulations fulfilled its purpose to evaluate the impact of the redundant parallel transformers present in the Transformer Subgroups. In resume, these simulations revealed that the no transformers case had a worst performance than both the standard and the standby case. This proves that the parallel transformer is important, mainly in terms of unavailability, where the differences between the no transformer and the standard case were higher than the counterparts registered for reliability, since the absence of the parallel transformer influences greatly the unavailability as the variation percentages can confirm. Note that even though the case without transformers might be economically more appealing in terms of fixed cost than the standby and standard cases, since the parallel transformers do not have to be bought at all, the drop in reliability that arises from the absence of the parallel transformers might lead to a less beneficial scenario, economically wise. However, notice that having two transformers operating at the same time can turn out to be expensive, mainly due to the fact that, for a normal operation, a single transformer is enough to provide the required power connection. Also, the failures at transformers are not that frequent, as consequence of its low failure rate, which ends up restricting the fully operating parallel transformer to a backup function. Thus, it is recommended an economical study to address the advantages and disadvantages of the presence of the double parallel transformer in the Transformer Subgroups. Regarding the standby case, its reliability simulations performed slightly better than the standard case, and much better than the no transformer case. So, the standby case should also be an option to take into consideration, since it improves the reliability of the standard case. Nonetheless, it is advised to further evaluate the economical impact of the standby parallel transformer, in order to determine if its implementation is worth cost wise.

Until now, all the studies and simulations performed were with the intend to evaluate the components that already took part in the standard case. Finished the study on the influence of the parallel transformers in the power plant, it was decided to test the power plant with the implantation of a component that is not present in the standard case - the SVC, short for Static Var Compensator.

4.5 Component Addition: Static Var Compensator (SVC) addition

A SVC, Static Var Compensator, is a modern power equipment typically used in substations. Its main function is to control line voltages and power factor, i.e, regulate the voltage to compensate a change in reactive power, therefrom the name "Var Compensator", while "Static" comes from the fact that it does not have moving parts. It has a function similar to a capacitor bank, with the advantage that it is digital, meaning that the reactive power regulation can be always precision perfect, which is not possible in a capacitor bank.

In order to implement the SVC in the scheme of the basic-frame, there was the need to determine where it should be placed. Due to the fact that its function is to control lines, the chosen position must be by the 61.5kV bus, since it is the main bus and the one that is connected to the grid. It remains to determine the functional relation between the bus and the SVC. Its control function suggests that they should be in parallel. However, even though the bus can function independently of the SVC, the other way around does not check, i.e, the SVC is useless without the bus. A parallel relation between the two would not make sense also because in case of a failure in the bus, the whole power plant should cease its operation, and with a component in parallel that would not happen. So, their functional relation must be a series relation. Nonetheless, as was already stated, the bus is independent of the SVC, whose control is not vital for the bus operation. Being in series with the 61.5kV bus means that it will be in series with the remain of the power plant, but a SVC failure, in normal conditions, does not affect the rest of the power plant. The only way the SVC can in fact influence the power plant is if it catastrophically fails, i.e, if the failure in the SVC causes some kind of fire or explosion which obliges the shutdown of the whole power plant. In those cases, it can be considered that the SVC is in series with the 61.5kV bus and with the rest of the power plant.

Thus, a research was conducted with the aim to determine the failure and repair rates, in catastrophic cases, of the SVC. To achieve this, it was necessary to first determine the transitional rates in normal conditions. The authors of [24] make an extensive study on the SVC main components, as well as their correspondent failure and repair rates (in normal conditions). According to [24], a SVC is composed by three main systems – main circuit, auxiliary power supply and control and protection. The major components of the main circuit are the Thyristor Controlled Reactor (TCR), the Thyristor Switched Capacitor (TSC) and the harmonic filters (HF). The TCR is formed by a reactor air core and a thyristor valve. TSC has a similar composition, but, in addition, contains a capacitor bank. In a another paper of them, [25], a state space diagram is proposed for the SVC, present in figure 4.15, which was useful to determine the functional relations between systems. Note that A represents the main circuit, B the control and protection and C the auxiliary power supply.

Analysing the figure 4.15, it is noticeable that the SVC is only operating when both A and B are up. So, if either A or B are down, the SVC is not in operation. This reveals that the functional relation between systems A and B is a series relation. Also, system C does not interfere in the SVC operation, so it can be neglected.

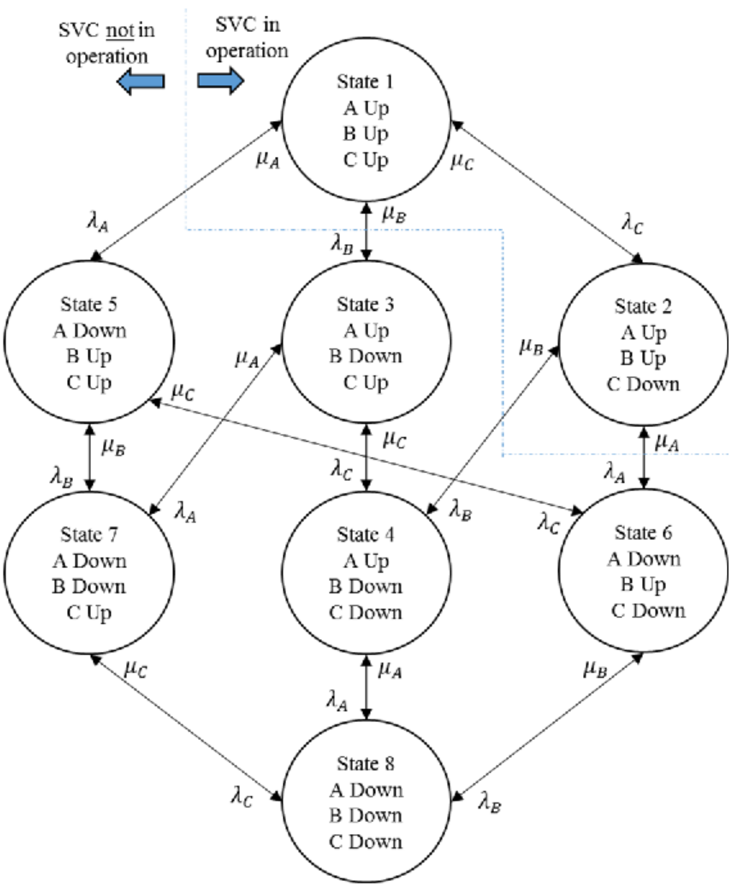

Figure 4.15: State-space diagram of a SVC from [25]. A, B and C represent the Main Circuit, Control and Protection and Auxiliary Power Supply systems, respectively.

The authors of [24] only consider the main circuit of the SVC in his computation of reliability, failure and repair rates. The results obtained by them are represented in the table 4.4, directly extracted from the referred paper.

Table 4.4: SVC results from [24] of the failure and repair rates, λ and μ respectively.

	λ [failure per year]	r [hours repair]	μ [repair year]
SVC	0.0906	1802	4.861

In order to complete the study carried in [24], it was decided to add the Control system to the simulation. The Auxiliary Power Supply was discarded as it is was considered not to be relevant to the reliability simulation, since it has, as its name indicates, an ”auxiliary” function and so, it should not be part of the SVC failure modes.

As was already stated, the control and the main circuit systems are in series, in terms of functional relation. The control system added was reduced to its main component – a microcontroller. So the total SVC is a microcontroller in series with the SVC from the authors of [24], named onward Alvarez-Alvarado & Jayaweera SVC, which corresponds to the main circuit, as is depicted in the figure 4.16.

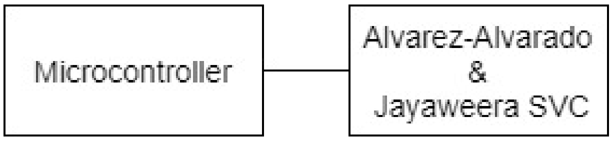

Figure 4.16: Block diagram of the total SVC.

There was the need to compute the failure rate and repair rate of the series of the microcontroller and the Alvarez-Alvarado & Jayaweera SVC. Once the failure rate between two series components is the sum of the failure rates of the referred, equation (3.38), having the two respective failure rates of the microcontroller and the Alvarez-Alvarado & Jayaweera SVC (table 4.4) it was computed the total failure rate of the SVC considering both control and main circuit systems, resulting 0.0907 failures per year. In relation to the repair rate, it was calculated in the same way as in the electronic circuit breaker: having the failure rate, fixing the time from 0 to 100 years and determining the availability of the SVC as a whole by initially computing the individual availability of both the microcontroller and the Alvarez-Alvarado & Jayaweera SVC, it is possible to isolate and calculate the repair rate using the formula (3.34) in order to the repair rate. From these, outcomes the repair rate for every year in a span of 100 years, whose mean is the final repair rate value. In this case, the obtained value was 4.8655 years/failure that corresponds to $5.5543 \cdot 10^{-4}$ hours/failure. With the intent to validate the repair rate value obtained, a unavailability simulation, graphically represented in the figure 4.17, was conducted in a time span of 100 years, using the referred mean value and was compared with the original unavailability assessment with RBD formulas where the repair rate of the series as a whole is not required.

As can be concluded after analysing the figure 4.17, the differences between the cases where the availability was computed using the RBD formulas (without the mean repair rate) and utilizing the obtained mean repair rate value, are minimal and the simulations practically coincide, which validates the mean value obtained for the series repair rate, as using the mean repair rate does not affect significantly the availability of the SVC.

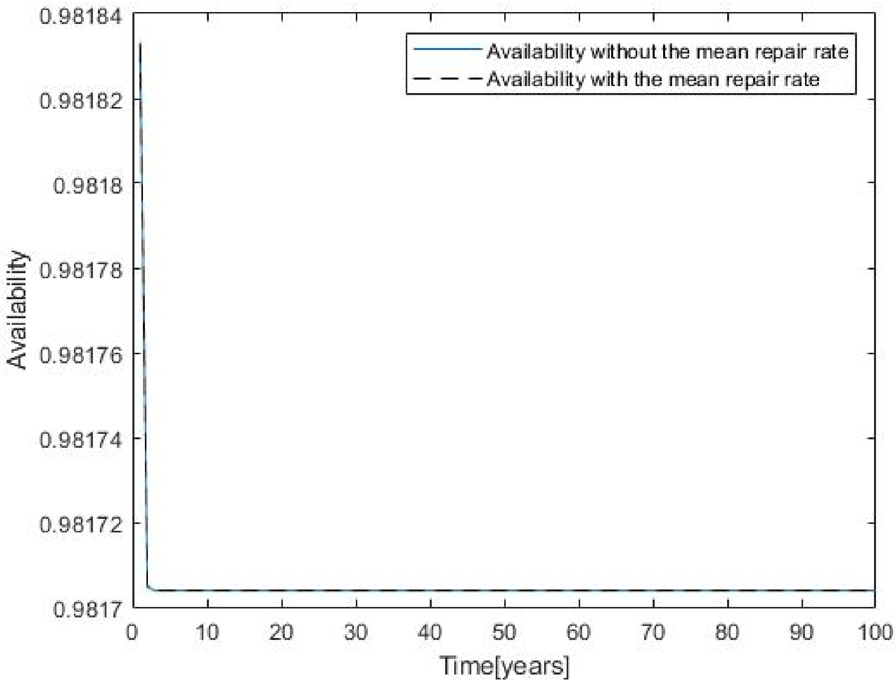

Figure 4.17: Availability of the SVC with and without the obtained mean repair rate.

Comparing the failure and repair rate values with the obtained in [24], present in the table 4.4, they are approximately the same, revealing that the control system does not affect that much the SVC. This is due the fact that the microcontroller, the only component considered to the control system, is very reliable, i.e, its failure rate and MTTR are relatively low.

Note that the values of the table 4.4 and the ones obtained from the series of the microcontroller and the Alvarez-Alvarado & Jayaweera SVC are with the SVC in normal conditions. As was explained previously, for this study the SVC is only being taken into account for catastrophic cases, like fires and explosions. So, the values of the table 4.4 and the ones obtained for the series between the Alvarez-Alvarado & Jayaweera SVC and the microcontroller cannot be used directly. Unfortunately, the data for this specific case was not found, since it is a rare occurrence. However, the authors of [38] did a survey on forced outages of SVCs used in 4 different structures – Pacific Gas and Electric (PG&E), TransGrid (TG), Powerlink (PL) and Hydro-Québec TranÉnergie (HQ). They also determined the origin of the forced outages and registered them by source, creating the forced outage distribution table, represented in the table 4.5.

Furthermore, they detail some incidents with SVCs corresponding to the percentages in the table 4.5, among which are fire and explosion reports that leaded to the shutdown of the structures where the SVCs were inserted. In the TransGrid it is reported an ”explosive failure with extensive fire damage”, however the data on the TransGrid is not very detailed as can be confirmed by the table 4.5, making it impossible to associate this particular failure to any percentage present in the table. Nonetheless, in the Powerlink, more specifically in the Nebo SVC, it is detailed catastrophic failures due to fires, one in the thyristor valve and other in the main circuit reactors. There are no more detailed incidents regarding these components,

Table 4.5: Table directly extracted from [38] representing the forced outages distribution.

Source of Forced Outages	PG&E	TG	PL	HQ
1. Main Circuit	-	15%	-	-
1a. Main Circuit Capacitor/fuse	0%	-	0%	3%
1b. Main Circuit Reactor	0%	-	1%	3%
1c. AC Filter	0%	-	16%	0%
1d. Thyristor Valves	5%	-	2%	9%
1e. Power Transformer	0%	-	1%	5%
1f. Disconnect Switches	5%	-	2%	4%
5. Valve Cooling	16%	18%	27%	30%
6. Station Service	26%	16%	8%	21%
7. Control and Protection	42%	24%	21%	25%
8. External	5%	20%	20%	-
9. Unknown	-	7%	2%	-

making it possible to associate a percentage in the table 4.5 to this particular incidents: 1% and 2% for the main circuit reactor and thyristor valve, respectively. It is also added that the repair was conducted by fully substituting the valve's equipment – the TCR (thyristor controlled reactor), which implies that the repair time in these catastrophic cases is approximately the same as in any other case as the substitution is practically as fast to any of them. In the Hydro-Quebec TranÉnergie it is also addressed occurrence of a fire in a TCR thyristor valve, however there are more reports associated to the thyristor valves in this structure, so an association to a specific value of the table 4.5 is not achievable. Nevertheless, a valuable information about the repair time is provided – the fire in the TCR valve was repaired within 3 months, which is approximately the repair time of the SVC suggested in [24], as the table 4.4 indicates, reinforcing the idea that in terms of repair, the SVC in catastrophic cases has approximately the same repair time as the SVC in normal conditions.

In conclusion, authors of [38] gave some important information that was fundamental to define the failure and repair rates of the SVC in catastrophic cases. The failure rate, expressed in the equation (4.4) as $\lambda_{catastrophic}$, was determined by the product between the percentage of occurrence of catastrophic incidents in the thyristor valves and main circuit reactor of the Powerlink's SVC Nebo (1% + 2%), $\%_{occurance}$, and the normal condition SVC failure rate, λ_{normal}.

$$\lambda_{catastrophic} = \%_{occurance} \times \lambda_{normal} \tag{4.4}$$

Like this, a more realistic value of failure rate is given to the SVC in catastrophic cases, since it is expected of a catastrophic case to have a probability much lower than in normal conditions. Heed to the fact that this is not a perfect way to compute the failure rate in catastrophic cases, however it was the possible procedure, due to the lack of information concerning this particular cases. Also, it is stated in [38] that some of these SVCs are in operation for more than 20 years, and refers that some SVCs were installed by the mid 1980's, so the mission time being simulated (40 years) is valid, as well as the percentages used to compute the failure rate of the SVC in catastrophic situations. Regarding the repair rate, as was already suggested and justified, it was considered to be the same as the repair rate in normal conditions.

It was then possible to simulate the reliability and unavailability of the whole power plant including the SVC in catastrophic cases, which are represented in the figure 4.18 and in the table 4.6, along with the standard case counterparts.

Some comparisons between the case featuring the SVC and the standard case can be made after analysing the figure 4.18 and the table 4.6. For instance, the total mean reliability of the power plant is at 0.5259, whereas in the standard case it is at 0.5484, a difference of 4 %. The reliability falls a bit with the introduction of the SVC, which is normal since it is in series with the whole power plant, even thought its failure rate has dropped due to the fact that it is being considered only the catastrophic cases. Also note that the SVC's MTTR is quite high, even higher than a transformer MTTR, which can negatively influence the down time of the SVC when a failure occurs and consequently the reliability of the power plant as a whole. Heed to the fact that the repair rate does not influence directly the reliability of each component, only the states of the referred, which has a repercussion on the power plant's reliability as a whole, since the states are used in the RBD formulas. So, the repair rate, and for consequence the MTTR, influence indirectly the reliability of the power plant.

Comparing the shapes of the hourly mean reliability with the ones registered in the standard case, they stay approximately the same, with the obvious differences in value – since the total mean reliability of the power plant is lower in the SVC case than in the standard case, it is natural that the curves of the hourly mean reliability drop in absolute value faster than the standard case one. Concerning the hourly standard deviation it hovers around the same absolute values as in the standard case, as has been a trend in the previous simulations, confirming the robustness and precision of them.

Regarding the unavailability simulation, some considerations need to be addressed as well. As was expected, since the reliability dropped, the unavailability increased (availability dropped) when comparing with the standard case. The power plant with the SVC in catastrophic cases registered, as can be consulted in the table 4.6, 0.002214 of total mean unavailability, which is approximately the double of the unavailability of the standard case, corresponding to 96 % higher. The discrepancy with the standard case, in percentage, is much higher than the one registered in the reliability simulation. This can be justified by the already stated fact that the MTTR of the SVC is very high, influencing not only the component state, in the form of the computed "semi-random" down time, but also the unavailability of the overall power plant, due to the direct influence that the repair rate, and for consequence the MTTR, has on the computation of unavailability.

Table 4.6: Total Mean Reliability and Unavailability values of the standard and SVC addition cases.

	Total Mean Reliability	Total Mean Unavailability
Standard Case	0.5484	0.00113
SVC addition	0.5259	0.002214

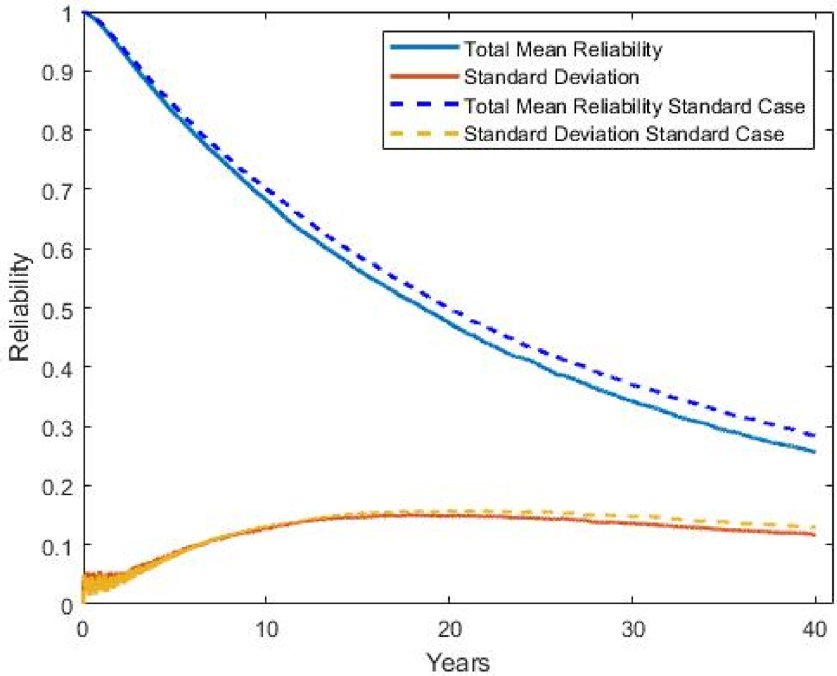

Figure 4.18: Reliability of the power plant with the SVC in catastrophic cases, over 40 years.

In conclusion, when considering the SVC's worst failure mode (catastrophic failure), its introduction in the substation has negative effects on both reliability and unavailability, as was expected since its positioning being in series with the whole power plant had to bring some negative consequences. It is of the upmost importance to undertake a trade-off study to determine if the implementation of the SVC is worth, i.e, if the compensation of reactive power is advantageous knowing that it will negatively influence the reliability and the availability/unavailability of the power plant. Note that the differences in reliability are not very significant, but the 96% rise of unavailability should be taken in consideration.

As was already stated in the subsection 4.2, the maintenance, even though forced, helped improving the reliability of the studied simulations. With this in mind, and finishing the reliability and unavailability studies to the different cases surrounding the standard case and its components, as well as the addition of new ones, it was decided to simulate the standard case once again, but taking into consideration different frequencies of scheduled maintenance, also called preventive maintenance – annual, biennial, every 5 and 10 years – with the intention to evaluate its effect on the overall reliability and unavailability of the power plant. This study is showcased in the following subsection.

4.6 Preventive Maintenance

Firstly, some considerations need to be clarified about the preventive maintenance study. As was already explained, it is intended to simulate a scheduled maintenance in the original power plant (standard case).

The implementation of the preventive maintenance is straightforward – a recovery/repair is fixed to a set of hours with a given frequency. Note that the forced maintenance can still occur, even though is not likely for shorter frequencies. Also, heed to the fact that the used repair rates in both forced and preventive maintenance is the same. It was decided to study two types of preventive maintenance – total and partial maintenance. In the total maintenance, all the components are repaired, in contrast with the partial maintenance, where it is only applied to the most important components, i.e, the transformers and the turbines, since they are the actives that can affect significantly the reliability and unavailability of the power plant and that are essential to its functioning. Remember that in this work, once repaired, the components are considered as good as new, so they regain their initial individual reliability and unavailability, just like it was before when they were repaired as consequence of the forced maintenance. Note that the total maintenance is an unrealistic and unpractical solution, as economically wise would be extremely expensive to substitute all the power plant's components, and should only be considered as a reference, and not as an actual solution.

The reliability and unavailability simulations are presented further, grouped in frequency – each figure will showcase the two types of maintenance, total and partial, as well as the standard case, to the same preventive maintenance set times.

4.6.1 Annual Maintenance

Analysing the figure 4.19 that portrays the reliability simulation of the two types of maintenance – total and partial – and the original standard case, it is visible some key characteristics that define this and the further maintenance studies. Both maintenance studies present a sawtooth-like curve. This was expected, since to all the computed stories, the reliability of all/some (depending on the type of maintenance) components is reset always to the defined frequency – in this case every year. Logically, as in the total maintenance simulation all the components' reliability is reset, the sawtooth curve stays straight along the whole mission time, i.e, the reliability is always reset to its correspondent initial value. In contrast, the partial maintenance simulation the sawtooth drops progressively in time, as not all the components' reliability is reset, so it is natural that the reliability still drops as the years advance, since the components that are not being covered in the preventive maintenance are ageing and decreasing its individual, and consequently, the whole power plant's reliability. However, both preventive maintenance simulations do not present as low reliability values as the cases where it is not taken in consideration, as can be verified in the figure 4.19 when comparing the sawtooth-curves with the standard case original one. Actually, as can be observable in the table 4.7, the total mean reliability of both total and partial preventive maintenance are drastically superior to the value registered to the standard case, 81% and 54 % higher, respectively.

Ideally, the total maintenance would be preferred over the partial counterpart, has it outperforms it with 27 % more of total mean reliability. However, the total maintenance, as was already mentioned, is an utopian solution, and should not be considered. Thus, an economical study should be taken in order to determine if the higher reliability provided by the partial maintenance is either worth or not, over the regular standard case.

The equivalent simulations performed for reliability were consummated for availability/unavailability,

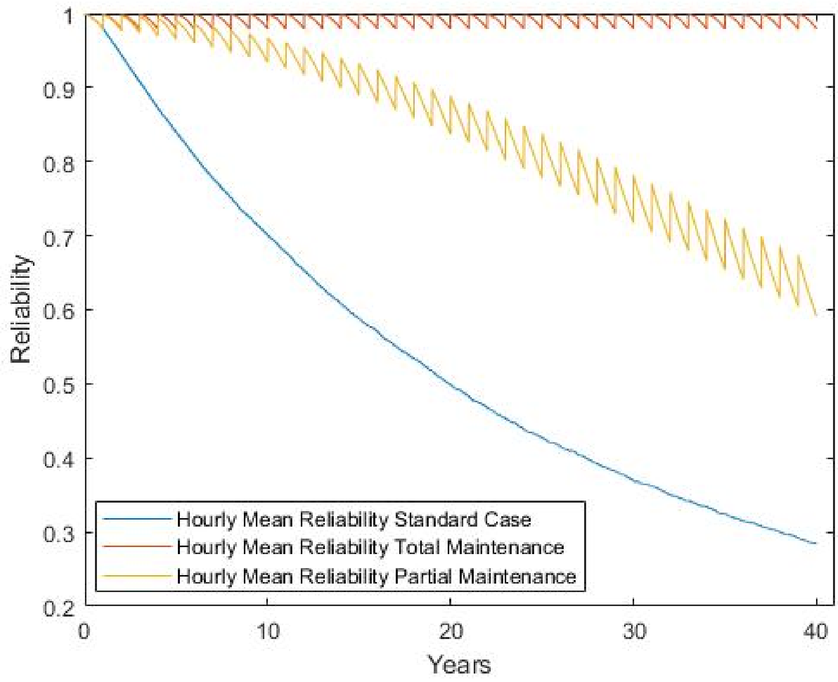

Figure 4.19: Reliability of the power plant comparison between annual total & partial maintenance and the standard case, over 40 years.

and the total mean unavailability values are presented in the table 4.7. These values correspondent to both total and partial maintenance, as can be observed in the referred table, reveal that there is not a great difference to the counterpart of the standard case, as only 0,3 and 1,3 percent points separate the partial and the total maintenance from the value of the standard case, respectively. Remember that these values are for an annual maintenance, which is expected to maximize the availability / minimize the unavailability, when compared with the other maintenance frequencies. This means that this result is the best possible in the studied maintenance frequencies, and since the difference with the standard case is minor, the availability study for the other frequencies is irrelevant, as none will top this value, which on its own is approximately the same as the one of the standard case. This outcome might seem odd, when considering that the availability takes in account the maintainability, and this is a preventive maintenance study. However, note that the associated rate of the maintainability – the repair rate – was not altered in this study of preventive maintenance. The availability also depends on the failure rate, which similarly to the repair rate, was not modified. So, it is only natural that the availability did not change significantly in comparison with the standard case.

Table 4.7: Total Mean Reliability and Unavailability results for both types of annual maintenance and for the original Standard Case.

	Total Mean Reliability	Total Mean Unavailability
Total Maintenance	0.9916	0.001115
Partial Maintenance	0.8446	0.001127
Standard Case	0.5484	0.001130

4.6.2 Biennial Maintenance

Doing the same simulation but to a biennial frequency, it results the following graphic showcased in the figure 4.20.

As can be observable, from the obtained simulation to a two-year frequency of preventive maintenance outcomes results somewhat similar to the previous one-year counterpart, but with some noteworthy differences. Notably, the "saws" in the sawtooth curves increase in magnitude and in width, for both types of maintenance (total and partial). This is due to the fact that the maintenance is more spaced out in time, so the reliability drops more in each non-maintenance period, when compared to the one-year maintenance. Consequently, the total mean reliability values of the biennial preventive maintenance are lower than the annual analogues, 2% and 3% for total and partial maintenance respectively, and 78% and 50% higher than the original standard case, as can be verified in the table 4.8. This was already expected – less maintenance leads to less reliability. The difference between annual and biennial maintenance is not that significant, but, again, an economical examination should be taken, in order to evaluate if the biennial maintenance is more advantageous than the annual correspondent.

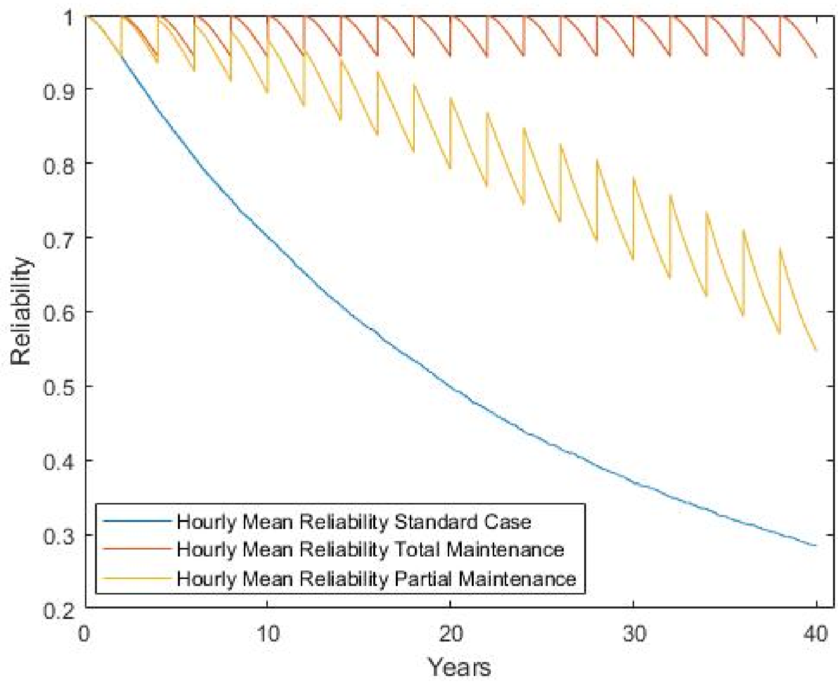

Figure 4.20: Reliability of the power plant comparison between biennial total & partial maintenance and the standard case, over 40 years.

Table 4.8: Total Mean Reliability results for both types of biennial maintenance and for the original Standard Case.

	Total Mean Reliability
Total Maintenance	0.9768
Partial Maintenance	0.8216
Standard Case	0.5484

4.6.3 5 in 5 years & 10 in 10 years Maintenance

The tendencies registered in the previous frequencies of preventive maintenance are yet again verified in the 5-in-5-years and in the 10-in-10-years maintenance, i.e, when there is a decrease of the maintenance frequency: increase in width and magnitude of the "saws" of the sawtooth curves, correspondent to both types of maintenance, total and partial; and the decrease of the total mean reliability. In the 5-in-5 year case, the total mean reliability is 69% and 40% higher than the one registered for the standard case, for total and partial maintenance respectively. For total maintenance, the total mean reliability is 5% and 7% lower than the biennial and annual maintenance, respectively, and for partial maintenance it is 7% and 9%. Regarding the 10-in-10 years maintenance, the percentage difference of total maintenance between the 10-in-10 year maintenance and the standard case, the 5-in-5 year, biennial and annual maintenance is 54%, 9%, 13% and 15%, respectively. Regarding the partial maintenance is 28%, 8%, 15% and 17%, correspondingly. The results correspondent to the 5-in-5 year maintenance are represented in the figure 4.21 and in the table 4.9, while the counterparts of the 10-in-10 year maintenance can be visualized in the figure 4.22 and in the table 4.10.

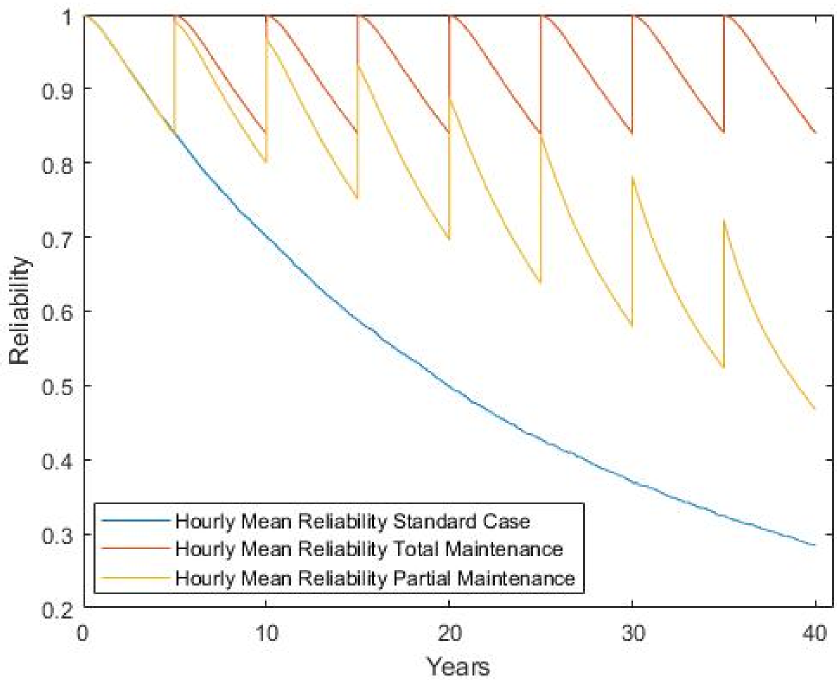

Figure 4.21: Reliability of the power plant comparison between 5-in-5-year total & partial maintenance and the standard case, over 40 years.

Table 4.9: Total Mean Reliability results for both types of 5-in-5-years maintenance and for the original Standard Case.

	Total Mean Reliability
Total Maintenance	0.9249
Partial Maintenance	0.7658
Standard Case	0.5484

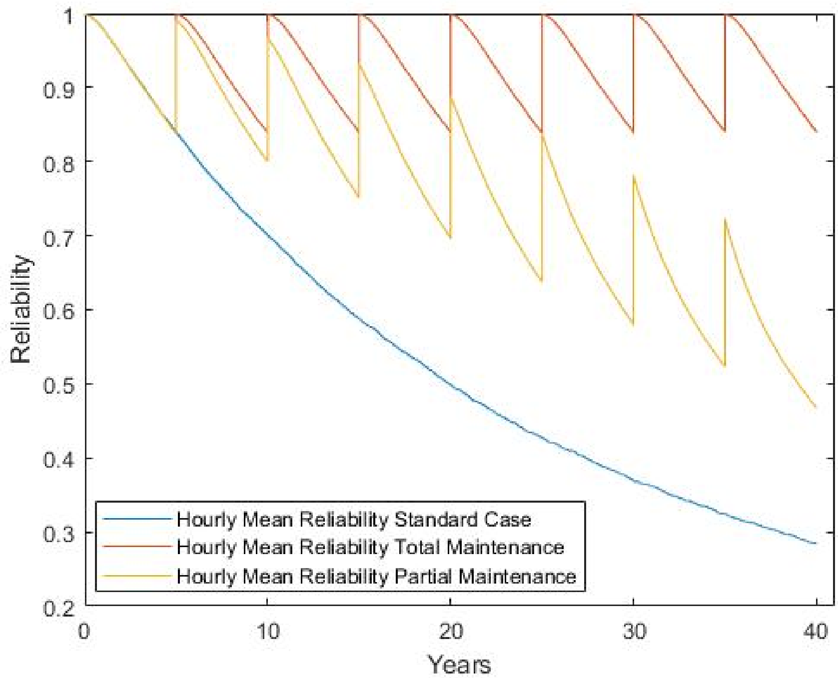

Figure 4.22: Reliability of the power plant comparison between 10-in-10-year total & partial maintenance and the standard case, over 40 years.

Table 4.10: Total Mean Reliability results for both types of 10-in-10-years maintenance and for the original Standard Case.

	Total Mean Reliability
Total Maintenance	0.8461
Partial Maintenance	0.7025
Standard Case	0.5484

Finally, having studied all the maintenance frequencies for the two types of maintenance, a table combining all these cases' total mean reliability and unavailability, as well as the standard case and circuit breaker substitution, which was the studied case not considering preventive maintenance that performed better is presented bellow in 4.11.

In the preventive maintenance studies, even though that the total and partial maintenance perform considerably better when comparing with either the standard case and the CB substitution case for all the studied frequencies, as has been said but in order to reinforce it is repeated now, an economical study is needed to properly evaluate the trade-off between reliability and cost. Firstly it is required to determine if the preventive maintenance is worth cost wise, and secondly which frequency and type of maintenance is more advantageous. Note that economical studies were not within the scope of this work.

Table 4.11: Combination of the Total Mean Reliability and Unavailability for all maintenance frequencies and types, the standard case and the Circuit Breaker substitution case

	Total Mean Reliability	Total Mean Unavailability
Standard Case	0.5484	0.001130
CB substitution	0.6678	0.001127
Anual Total Maintenance	0.9916	0.001115
Anual Partial Maintenance	0.8466	0.001127
Bienal Total Maintenance	0.9768	-
Bienal Partial Maintenance	0.8213	-
5-in-5 year Total Maintenance	0.9249	-
5-in-5 year Partial Maintenance	0.7658	-
10-in-10 year Total Maintenance	0.8461	-
10-in-10 year Partial Maintenance	0.7025	-

Chapter 5

Conclusions

The motivation of this thesis was to address a goal defined by the ONU in their 2030 Agenda for Sustainable Development, which consists in ensuring access to reliable energy for the whole world. In order to contribute in improving the reliability of energy, complying with the expectations and resolutions set by the United Nations to help the development of the society in general, reliability (and availability) studies were performed to a combined-cycle power plant. These studies were divided in three distinct types: component substitution; component influence and component addition. A preventive maintenance study was also accomplished. Moreover, the reliability of the original standard case was computed and used as term of comparison to the referred studies. In this work, considering the available resources and limitations, a combination of three methods was chosen as the methodology for this thesis: RBD, Markov Chains and Monte Carlo Simulation. In order to implement the chosen methodology, the case study was identified and deconstructed to fit a reliability (and availability) computation, i.e, the components were gathered in groups and subgroups by function and the relations between themselves were defined and exhaustively justified, with the intention of serving as an example for future studies on how to initially approach a reliability case study. Then, the reliability and availability evaluation processes were detailed step by step. It is hoped that this will serve as a basis for potential future reliability studies, as it can greatly facilitate the implementation and save precious time in further reliability evaluations. Having the implementation fulfilled with the researched failure and repair rates, it was then possible to perform the simulations of the planned and already referred studies. Firstly, it was simulated the standard case to serve as a term of comparison to the other studies. The approach and conclusions taken on those studies are further resumed:

1. Component substitution

   In this study it was tested how much the reliability of the power plant would change when the classical mechanical circuit breakers were exchanged by electronic ones. After defining the component relations that compose the electronic circuit breaker, the failure and repair rate of the electronic circuit breaker were computed and validated. Then, the simulation of the system was performed with the electronic CB, whose results outcome that the total mean reliability of the power plant is improved by 0,12 of absolute reliability value, which corresponds to an increase of 22% when compared to the values obtained in the standard case. In terms of unavailability, the results are approximately the same as the standard case.

2. Component influence

   In the studied power plant, there are present redundant transformers, so it was decided to evaluate their actual influence on the system reliability. Two different simulations cases were done – the no redundant transformers case and the standby case. From the undertaken simulations it outcomes that the difference of total mean reliability between the standard and the no redundant transformers cases is around 0.2 of absolute reliability value, being the standard case value higher, corresponding to 35 % of variation, while the total mean unavailability differs 366 % from the value of the standard case. Regarding the standby case the results regarding the total mean reliability were 7% and 39% higher, comparing with the standard and no redundant transformers case, respectively. With this study, it could be concluded that the standby case outperforms slightly the standard case and heavily the no redundant transformers case. Thus, it was proved the importance of the redundant transformer in this type of applications. The study of the standby case demonstrated that it increases the reliability of the power plant, even though just by 7%, but the key on that study is that it is expected that the transformers in standby use less energy than in full operation, which meets the motivation of complying with 2030 ONU expectations of a more sustainable and reliable energy.

3. Component addition

   After investigation of the state-of-the-art, it was determined that the only way the SVC could influence the power plant is if it catastrophically failed, i.e, if the failure in the SVC causes some kind of fire or explosion which obliges the shutdown of the whole power plant. In those cases, it can be considered that the SVC is in series with the 61.5kV bus and, consequently, with the rest of the power plant. Based on works developed by the authors of [24] and [38], it was possible to define the failure rates of the SVC related to these catastrophic events. Regarding the repair rate of these type of cases was provided by [38] and used in this work. Finally, it was possible to add the SVC to the power plant simulation and compute the reliability and availability of the altered system. The simulation results return a slightly worst total mean reliability, when compared with the standard case, being this difference 4 %. Regarding unavailability, the difference is more significant, as the SVC addition case doubles the total mean unavailability value of the standard case. Thus, the introduction of the SVC has negative effects on both reliability and unavailability, so, it is of the upmost importance to undertake a trade-off study to determine if the implementation of the SVC is worth, i.e, if the compensation of reactive power is advantageous knowing that it will negatively influence the reliability and the availability/unavailability of the power plant.

4. Preventive Maintenance

   Aiming to test the influence of a planned preventive maintenance, simulations of the standard case for two types of maintenance – total and partial – and for different frequencies of maintenance – annual, biennial, 5-in-5 years and 10-in-10 years – were performed. Note that the total maintenance is expected to not be economically feasible, so it is used only as a reference, and only the partial maintenance is taken in consideration as a an actual possible solution. The results of this study suggest that the preventive maintenance for the partial maintenance greatly improves the reliability of the studied power plant for every frequency, having increased the total mean reliability in 54%, 50%, 40 % and 28%, for annual, biennial, 5-in-5 years and 10-in-10 years, respectively. Regarding unavailability, the maintenance does not affect it effectively, since it approximately maintains the standard case total mean unavailability values. It is hoped that awareness towards preventive maintenance was raised as this study proves that it positively influences reliability.

Notice that for all these studies it is important to refer that an economical study is needed to evaluate either or not the reliability improves are worth cost wise. This economical study was not within the scope of this thesis.

5.1 Future Work

One of the main difficulties found in this thesis was to acquire valuable data to a reliability study – failure and repair rates. A series of databases were utilized to have the necessary data to compute the simulation studies. The problem is that a single database was not enough, as none of them was complete to the point to be the only consulted. A lot of factors condition the reliability of a component, so, the same component can have a different response if tested in distinct environments. This means that the failure/repair rate of the same component can differ according to where and how they were tested. It is then suggested, for future work, to try to standardise the databases regarding failure and repair rates, in order to obtain the most accurate result possible. Another possible solution to this problem is to perform this type of work in cooperation with a company that has the required data only available internally.

Another suggestion to refine this work would be to undertake a more complete study regarding the maintenance of equipment. In this work it was only tested maintenance with fixed frequencies. It is thought that it would be interesting to have a maintenance study that evaluates when a certain component actually needs maintenance, and ”performs” it only when it is necessary. This would ultimately minimize the cost of maintenance, while still improving the reliability of the given system.

As has been mentioned previously, it is also suggested an economical study, as it is of extreme importance to determine conclusively if the studied approaches are in fact worth cost wise. From this adjacent study would outcome more definitive conclusions regarding the trade-off between reliability/unavailability and cost.

An additional suggestion would be to develop/use a multi-state system, i.e, a system in which individual components can possess more than two states, as it would be a even more realistic way to model the components' states, leading to more accurate reliability assessment studies.

Finally, as an ultimate suggestion for future work, it would be interesting that other types of equipment, not only power equipment, were inserted in the basic-frame developed in this thesis, in an effort to have a more complete scheme of an actual power plant. Thus, it would be possible to further understand the relation between all the components comprised in the power plant, and how their relations effectively affect the reliability and availability of the power plant.

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