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

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***Abstract*—In accordance with the 2030 Agenda for Sustainable Development, [1], defined by ONU, 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.**

***Index Terms*—reliability assessment, availability assessment, combined-cycle power plant, power equipment, Reliability Block Diagram, Monte Carlo Simulation**

I. INTRODUCTION

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. 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.

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: Component substitution, more specifically an upgrade of the classical mechanical circuit breakers to modern electronic circuit breakers; Component influence, where it is studied the influence of the central power equipment – the transformer; 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 where 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. These methods are further detailed.

II. METHODOLOGY

A. 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. The formulas correspondent to both basic types of functional relation, series and parallel, are detailed in the following subsections.

B. Series Functional Relation

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

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

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 (1)):

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

Regarding the MTTF – mean time to failure – for constant failure rates and exponential distribution, which is the case, the equivalent system with n components failure rate, λ_s, is given by:

$$\lambda_s = \lambda_1 + \lambda_2 + ... + \lambda_n \tag{3}$$

The MTTF of the n-series component system, $MTTF_s$ is defined by:

$$MTTF_s = \frac{1}{\lambda_s} = \frac{1}{\lambda_1 + \lambda_2 + ... + \lambda_n} \tag{4}$$

C. Parallel Functional Relation

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

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

$$R_p(t) = 1 - \prod_{i=1}^{n}(1 - R_i(t)) \quad ; \text{for } i = 1, 2, ..., n \tag{5}$$

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 (5).

2) Standby parallel: 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 (6):

$$R_{sb}(t) = P[\tau_1 > t \cup (\tau_1 < t \cap \tau_2 > t)] \tag{6}$$

Being τ_1 and τ_2 the times that the active component and the standby component fail, respectively. From (6) it can be obtained (7):

$$R_{sb}(t) = R_1(t) + \int_0^t R_2(t - \tau_1) f_1(\tau_1) d\tau_1 \tag{7}$$

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 a basic reliability equation (present in the main document of the thesis) in the later (7), it results (8):

$$R_{sb}(t) = R_1(t) + \int_0^t R_2(t-\tau_1)\frac{dR_1(\tau_1)}{d\tau_1}d\tau_1 \tag{8}$$

The equation (8) 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. Fortunately, equation (8) 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, and considering the failure rate constant, results (9):

$$R_{sb}(t) = \exp(-\lambda t) + \int_0^t \exp[-\lambda(t-\tau_1)]\frac{d[\exp(-\lambda\tau_1)]}{d\tau_1}d\tau_1 \tag{9}$$

With some mathematical manipulation, (9) can be reduced, resulting the final simplified equation to quantify the reliability of a parallel standby system:

$$R_{sb}(t) = (1+\lambda t)\exp(-\lambda t) \tag{10}$$

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.

D. Markov Chain

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 [2], showcased in the figure 1. 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.

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 1, 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.

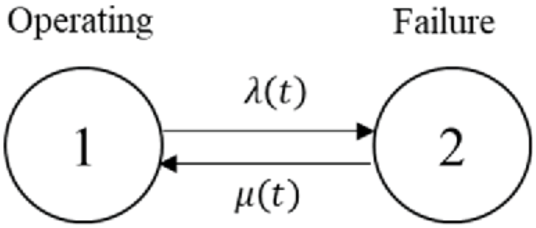

Fig. 1. Single component two-way Markov Chain representation from [2].

E. 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. 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. Thus, the Monte Carlo Simulation is used to complement the Markov Chain, to simulate the whole power plant.

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 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:

$$F(x_i) = 1 - e^{-\lambda \cdot x_i} <=> Z = 1 - e^{-\lambda \cdot X} \quad (11)$$

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 (11), results:

$$ln(1 - Z) = -\lambda \cdot X \quad (12)$$

Isolating X from the expression (12), and considering that $1-Z$ and Z have the same distribution, outcomes the following equation:

$$X = -\frac{ln(Z)}{\lambda} \quad (13)$$

The later equation (13) 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}. This is analogous to the repair rate, as X in the mathematical expression (13), instead of representing the time until failure, can represent the time until repair, t_{dwn} (the down time of a component):

$$X = -\frac{ln(Z)}{\mu} \quad (14)$$

So, in conclusion, from the expressions (13) and (14) results:

$$t_{up} = -\frac{ln(Z)}{\lambda} \quad (15)$$

$$t_{dwn} = -\frac{ln(Z)}{\mu} \quad (16)$$

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 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.

III. RESULTS

Firstly, in order to apply the methodology discussed in the section II, there was the need to choose an appropriate case-study. It was chosen an example of a 61.5kV combined-cycle power plant, with a substation and two generating groups of 14MW each. 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.

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 2, the "basic frame" is showcased and the referred two main groups identified.

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.

Regarding the objective of the Generation Group, it is ultimately, as the name indicates, to generate electric power. This generation is conceived by two turbines: 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.

The functional relation between the two referred groups is a series relation, since the Generation Group to generate power depends directly on the transformed energy from the Substation Group. The other functional relations between components are detailed on the thesis document.

Having showcased the case-study, it can now be discussed the studies performed on it. The whole method and process of reliability and availability assessment is in-dept explained in the main core of the thesis.

A. Standard Case

Firstly, with the intention of having a term of comparison, 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, the standard case, and as a matter of fact all the cases, 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 3 and 4 of reliability and unavailability over time, respectively. Additionally, the table I containing the total mean reliability and unavailability values is provided. An hourly reliability without the occurrence of events and an hourly standard deviation curves are also included in the figure 3.

Analysing the figure 3, it can be observed that the reliability starts off high, as it was expected, since the reliability formula for constant failure rates fits an exponential. Furthermore, most of the components at the beginning of the mission time have high values of reliability, making the overall power

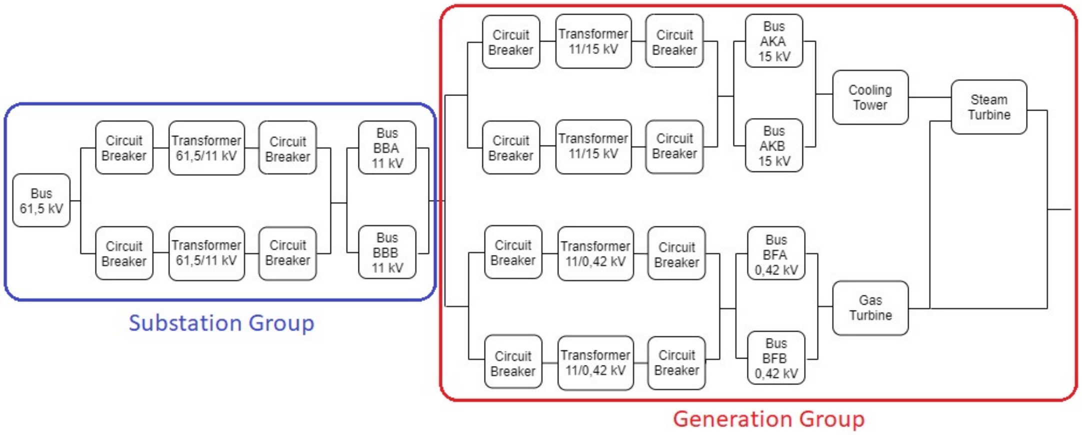

Fig. 2. Power plant's "basic frame" and main component groups. In blue the Substation Group and in red the Generation Group.

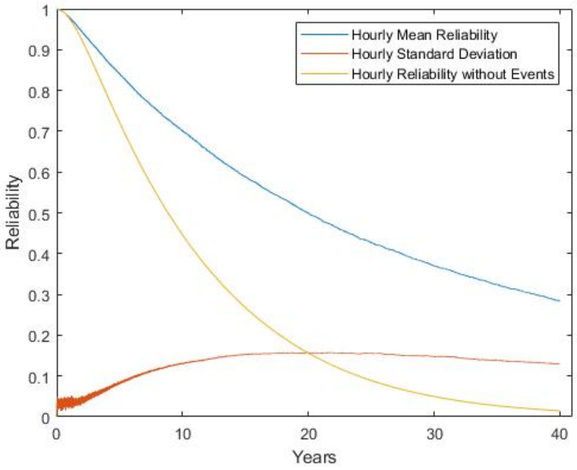

Fig. 3. Reliability of the power plant for the standard case, over 40 years.

plant's reliability also high. As it was also expected, the reliability decays over time, which makes sense: the older the components, and consequently groups of components, the less reliable they are. The total mean reliability value, present in the table I, is 0,5484.

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 I. 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 consequence 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). 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.

Regarding the availability, it was decided to express it as its opposite - unavailability - just for being more practical in terms of data display. Observing the figure 4, 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 I. 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.

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.

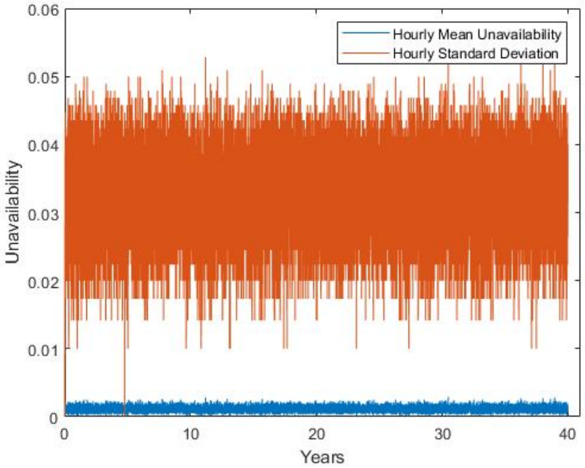

Fig. 4. Unavailability of the power plant for the standard case, over 40 years.

TABLE I
TOTAL MEAN RELIABILITY AND UNAVAILABILITY VALUES OF THE STANDARD CASE.

	Total Mean Reliability	Total Mean Reliability w/o maintenance	Total Mean Unavailability
Standard Case	0.5484	0.2824	0.00113

B. Component Substitution - Circuit Breaker Substitution

In order to evaluate if 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. The authors of the paper [3] detail in their paper information about a ”smart ultra fast acting electronic circuit breaker”. After analysing the component functions disclosed there, functional relations were defined and the failure and repair rates of the electronic circuit breaker computed. The whole complete process in more detail can be found in the thesis document.

The reliability and unavailability results over time (40 years) are represented in the figure 5 and in the table II, along with the standard case counterparts, in order to compare both cases.

TABLE II
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

Starting with the analysis of the figure 5, there are some points that immediately stand out when comparing both standard and circuit breaker substitution cases. Firstly, the hourly mean reliability increased, which can be visually confirmed in the figure 5, and by comparing the values of the total mean reliability of the power plant between the standard and this case, present in the table II. 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. This was already expected as the failure rate of the electronic circuit breakers are lower than the classic ones. In regard to the unavailability of the power plant with electronic circuit breakers, there are also some notes to share. Comparing the total mean unavailability values of both cases, present in the table II, 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 is due to the fact that the disparity between the repair rate of the classic circuit breaker and the electronic one cancels the discrepancy between their failure rates.

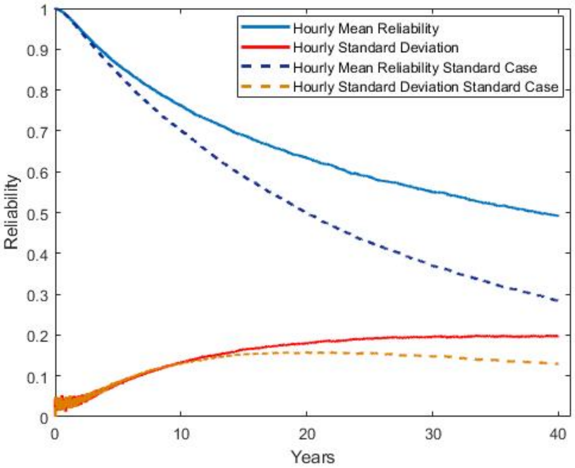

Fig. 5. Reliability of the power plant with the electronic circuit breaker comparison with the standard case, over 40 years.

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. 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 when compared with the classical ones.

C. Component Influence - Transformer Influence

The power plant, figure 2, has always 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. In order to determine the influence of the parallel transformer in the reliability and unavailability of the power plant, two different studies were undertaken: Simulation of the power plant without the parallel transformer and with the parallel transformer in standby, named ”No Redundant Transformers case” and ”Standby Case”, respectively.

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 6. The same procedure was conducted regarding the unavailability, where the total mean unavailability values of the three cases are present in the table III. The total mean reliability values can also be consulted in this table.

Starting with the comparison between the No Redundant Transformers and the standard cases, 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 III: 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.

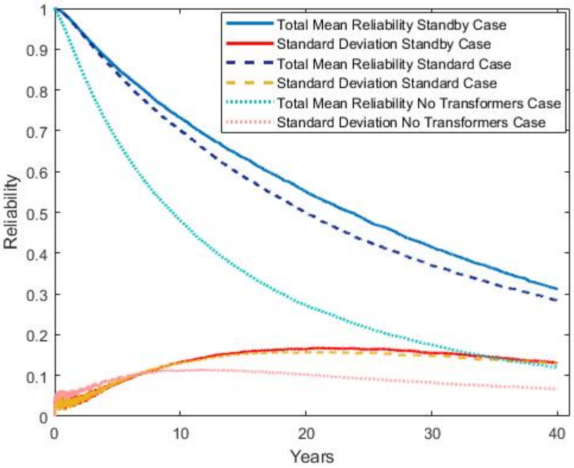

Fig. 6. Reliability of the power plant for the no redundant transformers, standard and standby cases, over 40 years.

TABLE III
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	-

In regard to the unavailability results, the total mean reliability 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 III. 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.

The Standby Case was performed using the equation (10) for the parallel transformers, instead of (5). 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 (6) to (10).

Comparing the standby and the standard case reliability simulations, making use of the figure 6 and the table III, 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. Comparing the standby and the no redundant transformers reliability studies, dashed and point lines of the figure 6, 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 redundant 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.

D. Component Addition - SVC addition

In order to implement the SVC in the scheme of the basic-frame, there was the need to determine where it should be placed. After an in-dept analysis on how it would functionally relate to the rest of the power plant's components, it was concluded that it would be placed in series with the 61,5 kV bus and consequently with the remain of the power plant. However, a SVC failure, in normal conditions, does not affect the rest of the power plant, so, 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. This was done by completing the basis of the work performed by the authors of [2]. Then, consulting [4], work which consists in a survey on forced outages of four different structures, it was possible to associate a percentage of occurrence of catastrophic events. The catastrophic cases failure rate, expressed in the equation (17) as $\lambda_{catastrophic}$, was then determined by the product between the percentage of occurrence of catastrophic incidents(3%) and the normal condition SVC failure rate, λ_{normal}.

$$\lambda_{catastrophic} = \%_{occurance} \times \lambda_{normal} \tag{17}$$

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. Regarding the repair rate, it was suggested in [4] that it should be around the same as the repair rate in normal conditions. All these deductions are in more detail in the thesis document.

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 7 and in the table IV, 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 7 and the table IV. For instance, the total mean reliability of the power plant is at 0.5259, whereas in the standard case it is at 0.582, 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.

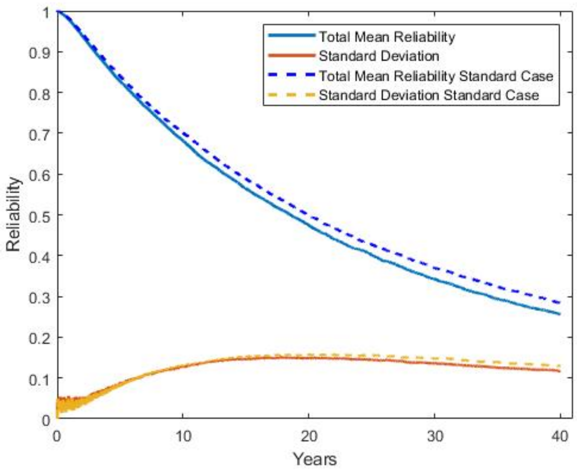

Fig. 7. Reliability of the power plant with the SVC in catastrophic cases, over 40 years.

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 IV, 0.002214 of total mean unavailability, which is approximately the double of the unavailability

TABLE IV
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

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.

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.

E. Preventive Maintenance

In the preventive maintenance study, it is intended to simulate a scheduled maintenance in the original power plant (standard case). 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 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 were grouped in frequency: annual, biennial, 5-in-5 years and 10-in-10 years, but only the annual is showcased here, in the figure 8, for the rest of the frequencies consult the main thesis document.

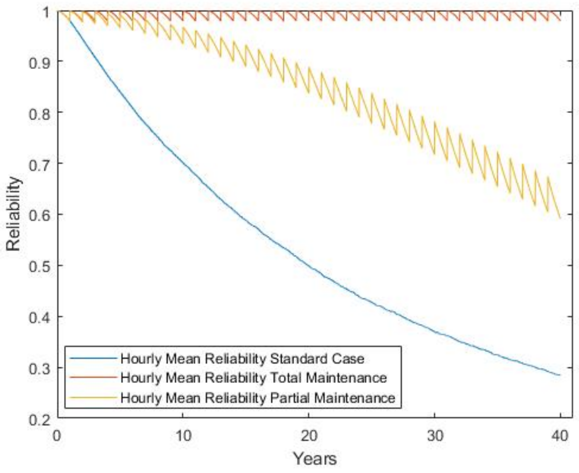

Fig. 8. Reliability of the power plant comparison between annual total & partial maintenance and the standard case, over 40 years.

As can be observed, both total and partial maintenance present sawtooth-like curves. 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 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. Regarding the availability, it stays approximately the same as the standard case. This is due the fact that the failure and repair rates were not altered in this study of preventive maintenance. So, it is only natural that the availability did not change significantly in comparison with the standard case. 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% e 28%, for annual, biennial, 5-in-5 years and 10-in-10 years, respectively.

IV. CONCLUSIONS

The motivation of this thesis was to address a goal defined by the ONU in their 2030 Agenda for Sustainable Development, [1], 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. 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.

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. In terms of unavailability, the no redundant transformers case is greatly outperformed by the standard case, as the percentual difference between the two is 366%. The study of unavailability was not possible to perform for the standby case. Concerning the component addition study, where a SVC was added to the original power plant scheme, it is outperformed by the SC in total mean reliability and unavailability by 4% and 96%, respectively. 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.

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