Article

Application of Generation Adequacy Analysis for Reliability Evaluation of a Floating Production Storage and Offloading Platform Power System

Patricio F. Castro 1,2,†, Yuri Percy M. Rodriguez 2,3,*,† and Fabricio B. S. Carvalho 2,†

1 Petróleo Brasileiro S.A., Rio de Janeiro 20231-030, Brazil; patriciocastro@petrobras.com.br
2 Department of Electrical Engineering, Federal University of Paraíba (UFPB), João Pessoa 58051-900, Brazil; fabricio@cear.ufpb.br
* Correspondence: molina.rodriguez@cear.ufpb.br
† These authors contributed equally to this work.

Abstract: This paper proposes the application of generation adequacy analysis for reliability evaluation of an insulated power generation system that supplies a FPSO (Floating Production Storage and Offloading) oil and gas production platform. The frequency and duration method was adopted for generating system reliability evaluation. The historical reliability data of the floating production storage and offloading platform power system and the continuous Markov process are used to determine the generator’s reliability model. The load model was also based on the platform daily peak load variation curve. The system risk indexes were obtained using Monte Carlo simulation. Two system scenarios were simulated using different failure data for one of the generators and the software PowerFactory® has been used as a tool for this simulation. For a complete generation system modeling, frequency and duration methods were developed to calculate the probabilities, frequencies and duration of the system states. Numerical results are presented and discussed to demonstrate the applicability of the proposed method.

Keywords: reliability; generation adequacy; FPSO; frequency and duration method; Markov process

1. Introduction

Power systems reliability analysis can be applied to any project life cycle [1,2]. Its relevance is due to the high interruption costs that penalize customers. In oil and gas production platforms like FPSO (Floating Production Storage and Offloading) producing over 150,000 barrels per day (BPD) of oil and 7 million m³/day of gas, where the production interruption is costly [3], such evaluation can be an important tool to measure the power generation system performance and to perform actions to achieve higher platforms’ availability [4].

In Brazil, especially for pre-salt fields, production platforms FPSO are currently the most deployed production facilities. In general, these platforms’ power systems are insulated from other power systems and use gas turbine-driven generators [5]. In this context, the generation system is a core for those types of platforms given its size and the amount of load that is electrically driven.

Different reliability evaluation techniques are considered in power systems. For example, applications of Bayesian networks in reliability evaluation are presented in [6]. An Artificial Intelligence (AI) enhanced reliability assessment methodology is detailed in [7]. However, studies on offshore platform power system reliability are relatively scarce [8]. Cost reductions of an FPSO electrical installation at the project phase, where some changes in a typical configuration of the electrical network architecture for an FPSO was proposed, are detailed in [5]. Those changes had an impact on the power system reliability and...
different operational conditions were evaluated in terms of unavailability. No risk indexes or systems’ states probabilities, frequencies or duration parameters were evaluated.

In [9], the electrical components of an oil platform power system were modeled based on a multi-states approach. In this case, the platform is fed by an external power source through a submarine cable, so the generation adequacy analysis is not applicable.

A reliability evaluation performed in an offshore oil platform power system is presented in [8], where the authors applied a method based on state enumeration for modeling the power system’s components similar to a Markov process. To model the system, a statistical evaluation for each system’s state was performed. In this case, no evaluation about the power system’s risk of not meeting the demanded load or system’s states frequencies were considered. Without the knowledge of the system’s risk index, the operator cannot evaluate which is the best configuration for operating the system in terms of generation adequacy. Another point is that without systems’ states frequencies, it is not possible to know the most frequent states and identify if a low capacity state is frequent. An index of energy demanded but not supplied is also presented in this research, although for isolated systems without the characteristics of energy commercialization, this index has no application.

Generation adequacy analysis is a powerful tool to determine the ability of the power system to supply system load under different conditions and scenarios. A predictive scheme for an operation reliability evaluation for system operations planning is proposed in [10]. A reliability assessment conducted at regular and close intervals to ensure adequacy is detailed in [11]. Distribution site reliability indices from a combined system architecture with residential demand strategies and on-site photovoltaic generation units are considered in [12]. A framework to integrate wind power and energy storage models to a bulky power model is presented in [13]. Generation adequacy analysis evaluates the power system static capacity to meet the system load in global terms, that is generators and loads are concentrated in a single bus that represents the system under evaluation [14,15].

For an FPSO generation system, a combined evaluation of generation risk indexes and systems’ states frequency and duration as presented by Roy and Kumar [16] and L. D. Arya et al. [17], can guide the system’s operators and maintenance teams to identify its weaknesses and to overcome them.

Reliability evaluation applied to oil and gas platforms is an area to be explored. There are few references devoted to the reliability analysis of FPSO, and none considering the reliability evaluation of an FPSO, as well as the use of operational data to obtain the probability of states of the FPSO generators to obtain a system reliability evaluation of an FPSO. In this paper, the power generation system and the electrical load of an FPSO have been modeled to perform a generation adequacy analysis. To represent the system in terms of reliability, two approaches have been considered: risk indexes were determined for the generation system taking into account the system’s load duration curve for two operational scenarios and the capacity outage probability table was obtained using the frequency and duration method for the same operational scenarios. The exponential failure density function was used for modeling the generators in terms of reliability.

For the system risk index a Monte Carlo Simulation was implemented in DIgSILENT PowerFactory© [18]. The frequency and duration method is used to obtain each generation system state, its frequency and duration. Capacity outage probability tables were obtained for two operational scenarios that were simulated considering the cumulative performance of multi-state systems.

The main contributions of this work can be summarized as follows:

- A reliability evaluation of an FPSO main generation system, where not only the system’s risk indexes were evaluated, but also the system’s states had their frequency and duration determined;
- Cumulative states have been considered in this study to represent generation system states;
- Usage of operational data as time into operation, maintenance records data, operator’s registers, and supervisory data to obtain generators’ state probabilities.
• Real case generation capacity evaluation for an isolated oil and gas production platform power system.

The rest of this paper is organized as follows. In Section 2, the main generators are modeled according to a four states model and the system’s load curve is presented. Additionally, the generation adequacy indexes are highlighted and the capacity outage probability table indexes are presented. The experimental results are evaluated in Section 3, and the conclusions and future works derived from this paper are discussed in Section 4.

2. Materials and Methods

In reliability assessment, system risk identification checks if the system is capable of supplying energy to its customers respecting the specified operating limits [19]. The risk model for the system is based on the combination between the generation model and the load model, where the calculated indexes do not reflect the generation deficiency at any particular customer load point, but instead measure the overall adequacy of the generation system [1].

In order to calculate the system’s risk model, the generation system and load must be modeled. Figure 1 illustrates the basic approach to evaluate the generation adequacy.

![Figure 1. System modeling for generation adequacy analysis.](image-url)

Each generator capacity must be provided to run the stochastic model. This is a fundamental information since the system’s capacity to meet the load depends on its generators’ available power. Generators’ reliability model is used for defining the availability states of each generator. Probability states are assigned to the generators representing each operating
Transition rates between operating states need to be calculated to complete the generator’s model. Scheduled maintenance can reduce the available capacity of the system under a certain period of time and can also be taken into account in the model. Defining generators’ capacity and the stochastic model, the generation system is ready for the adequacy analysis.

The system’s loads are modeled based on the demanded power from the power system. The daily peak load is then used for generation adequacy analysis since the expectancy is that the generation system can meet the highest demand over the evaluated period.

The FPSO generation power system is composed of four gas turbine-driven generators with 25 MW each with a total power capacity of 100 MW at 13.8 kV and a nominal 0.8 inductive power factor. This is the system that will be used to compose the generation model. A real FPSO load duration curve will be used for modeling the load and then composing the generation risk model. Figure 2 presents the FPSO power system where the four main generators are connected to the main switchgear (tag number PN-5143001).

2.1. Generation Modeling

The generator model consists of modeling each component of the system in terms of reliability [1]. For this purpose, the four generators’ operational data obtained from maintenance records, operator’s registers and supervisory are used to determine the generator’s reliability. Table 1 summarizes the obtained generations’ operational data, which are used to calculate the generation system’s reliability data presented in Table 2.

### Table 1. System’s generators operational data.

<table>
<thead>
<tr>
<th>Operational Data</th>
<th>Generator</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unit A</td>
</tr>
<tr>
<td>Number of starts</td>
<td>70</td>
</tr>
<tr>
<td>Fails to start</td>
<td>9</td>
</tr>
<tr>
<td>Fails into operation</td>
<td>10</td>
</tr>
<tr>
<td>Time in service (h)</td>
<td>6291</td>
</tr>
<tr>
<td>Available time (h)</td>
<td>8316</td>
</tr>
<tr>
<td>Unavailable time (h)</td>
<td>444</td>
</tr>
</tbody>
</table>

### Table 2. System’s generators reliability data.

<table>
<thead>
<tr>
<th>Generators Reliability Data</th>
<th>Generator</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unit A</td>
</tr>
<tr>
<td>MTTF (h)</td>
<td>331</td>
</tr>
<tr>
<td>MTTR (h)</td>
<td>23</td>
</tr>
</tbody>
</table>

The number of starts and time into operation was obtained from the generator’s supervisory. The failure to start data were obtained by the operator’s record. Available and unavailable time were calculated based on maintenance records and operator’s information.
In Table 2, exponential failure density was considered as representative for calculating the mean time to fail (MTTF) and mean time to repair (MTTR) [21–23]. According to Equations (1) and (2), where λ and μ are the transition rates between states 2 and 3 from the four states model presented in Figure 3 [1].

$$MTTF = \int_0^\infty t.\lambda e^{-\lambda t} = \frac{1}{\lambda};$$  (1)
The option for the four states was due to the system’s operating characteristics that in some cases demand that one of the units operate under peaks of load.

Figure 3. Four-state generator model (Reproduced from [1], Plenum Press, 1996).

This model for the generators consider the following states:

0 – Reserve Shutdown: in this state the machine is stopped waiting to be demanded;
1 – Forced out but not needed: in this state the machine is unavailable but the system does not require it;
2 – In service: in this state the machine is being demanded and is supplying the system;
3 – Force out in period of need: in this state the machine is unavailable for starting or was operating and failed during the operation. In this state, the system will not get all the loads supplied.

The generators’ model can be represented as a Markov process [21], where the transition rates can be seen in Figure 3, where:

- \( P_s \): Probability of failure to start;
- \( D \): Average in-service time per occasion of demand;
- \( T \): Average reserve shutdown time between periods of need;
- \( \lambda \): Expected failure rate;
- \( \mu \): Expected repair rate.

According to [1], the probabilities of the components residing in each state in terms of the state transition rates are given by Equations (3)–(7).

The probability for the reserve shutdown state (\( P_0 \)) is given by Equation (3):

\[
P_0 = \frac{\lambda T[D\mu + 1 + D(\mu + \frac{1}{T})]}{A}, \tag{3}
\]

where \( A \) is given by Equation (4):

\[
A = [(D\lambda + P_s)(\mu T + 1) + (\mu + \frac{1}{T})D] + [(1 - P_s) + (\mu + \frac{1}{T})D](\mu(T + D)). \tag{4}
\]

Equation (5) gives the probability of Forced out but not needed state (\( P_1 \)):

\[
P_1 = \frac{D\lambda + P_s}{A}. \tag{5}
\]

For the in-service state (\( P_2 \)), Equation (6) gives this state probability:
\[ P_2 = \frac{D\mu (1 - P_S + D\mu + D_T)}{A}. \]  
(6)

For the blueforce out in period of need state (\( P_3 \)), Equation (7) gives this state probability:

\[ P_3 = \frac{D(\mu + \frac{1}{T})(D\lambda + P_S)}{A}. \]  
(7)

For operational scenario 1, the actual generators’ operational and reliability data were considered, which are presented in Table 3.

Table 3. Four-state probability model for FPSO generators—Scenario 1.

<table>
<thead>
<tr>
<th>State</th>
<th>States Probability (in %)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unit A</td>
</tr>
<tr>
<td>( P_0 )</td>
<td>23.43</td>
</tr>
<tr>
<td>( P_1 )</td>
<td>0.92</td>
</tr>
<tr>
<td>( P_2 )</td>
<td>69.25</td>
</tr>
<tr>
<td>( P_3 )</td>
<td>6.34</td>
</tr>
</tbody>
</table>

A second scenario was also simulated, in this case, a failure at the generator “C” that took 1528 h to be repaired was neglected, so this machine was considered in reserve shutdown during this period. In Table 4, the probabilities of the new state for generator “C” are presented. The states probabilities for generators “A”, “B” and “D” remained the same as in scenario 1.

For both scenarios, the maintenance schedule for stopped machine was taken into account according to the maintenance plan defined by engineering team, since the planned maintenance reduces the system’s capacity and should be considered in the generator’s model. This maintenance is distributed over one year and represents on average 220 h/year per machine considered in this paper.

Table 4. Four-state probability model for floating production storage and offloading generator “C”—Scenario 2.

<table>
<thead>
<tr>
<th>State</th>
<th>States Probability (in %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_0 )</td>
<td>29.47</td>
</tr>
<tr>
<td>( P_1 )</td>
<td>1.50</td>
</tr>
<tr>
<td>( P_2 )</td>
<td>61.94</td>
</tr>
<tr>
<td>( P_3 )</td>
<td>7.10</td>
</tr>
</tbody>
</table>

2.2. Load Modeling

To develop the risk model for Generation Adequacy Analysis, the load also must be modeled [1]. In Monte Carlo simulation, random probability values are generated by the simulation software and each value from the simulation is compared with the probability of each state for each generator, then the system capacity that will be available at that time is defined [18,24]. Comparing the available capacity of the generation system to the system peak load in a given day will define if the system had its demand met.

For this study, the daily peak load curve for one year had been obtained from an existing FPSO power system. The load curve was loaded to the simulation software to perform the generation adequacy analysis. For both simulation scenarios, the same load curve had been used. Figure 4 illustrates the curve used in the simulations.
2.3. Risk Indexes

The determination of available generation capacity to guarantee an adequate energy supply is an important aspect in the planning and operation of the electrical system [1,25].

The interest for static generation capacity assessment lies in the calculation of indexes that measure system adequacy, i.e., the capacity meets the load in global terms. Thus, both generator and loads are concentrated in a single bus, in which the combination of mathematical models that represent the behavior of the generation system integrated with the load model form the basic method to obtaining adequacy indexes [26].

The main objective of adequacy analysis is to evaluate the static capacity of the generation system, determining indexes that assess the risk of not meeting the system load, the frequency that it occurs and its duration [27].

Risk indexes were calculated using a Monte Carlo simulation. In the case study for two scenarios, 100,000 iterations had been performed [18]. For each iteration, PowerFactory® software generates a random value that corresponds to the generators’ states. The sum of the generators’ capacity corresponding to the selected state is made and at a random time point, the load of the system is selected. If the demand is higher than the generation the system will not meet the load. The difference between the system load and generation capacity is the demand not supplied. The ratio between the number of iterations that the system did not meet the load per the total amount of iteration is the loss of load probability (LOLP), given by Equation (8):

\[
\text{LOLP} = \frac{N_{DNS}}{N} * 100\%,
\]

where \(N_{DNS}\) is the number of iterations in which the demand exceeded the generation capacity; and \(N\) is the total number of iterations.

Another system risk index is the expected demand not supplied (EDNS), which is the ratio between the sum of the demands that exceeded the generation capacity at each
iteration in Monte Carlo simulation per the total amount of iteration [18], as presented in Equation (9):
\[
EDNS = \frac{\sum_i DNS_N}{N},
\]
where \(DNS\) is the demand not supplied at the iteration \(i\); and \(i\) is the iteration index.

2.4. Frequency and Duration Methods

Frequency and duration parameters are linked to the determination of the frequency at which the system can be found in a given state and the average duration that the system resides in that state. Frequency and duration indexes are the most useful indexes to evaluate reliability for customer or load points. The creation of similar indexes for calculating the reliability of a generation system offers additional parameters for the system’s evaluation (such as the frequency of a given state of the system and its duration) [1]. With the definition of the states of each system’s generator, it is possible to calculate the transition rates between states, as well as perform the calculation of the probability of finding the component in each state, as seen in Section 2.1.

With the generation system’s components modeled, it is possible to evaluate the complete generation system in terms of the frequency and duration of its states using the capacity outage probability table (COPT).

Equation (10) gives the frequency of finding the system in a given state \(k\):
\[
f_k = p_k \cdot \lambda_k,
\]
where \(p_k\) is the probability that the system is in a certain state; and \(\lambda_k\) is the transition rate for the exit from the state (in this case, represented by the failure rate \(\lambda\)).

The multi-state models for generators are fully determined when its states are defined in terms of its capacities, probabilities and frequencies [28], Equation (11) represents those attributes:
\[
G_i = \{c_k; p_k; f_k\},
\]
where \(G\) represents the generator, \(i\) is the index that represents the generator, \(C\) represents the generators’ states capacities vector, \(p\) is the states probabilities vector, \(f\) is the states’ frequencies and \(k\) is the component’s state index.

A generation system composed of more than one generator can be represented by a combination of multi-state components, resulting in a multi-state system as well. Equation (12) represents the combination of multi-states components creating a multi-state system.

\[
G_{sist} = G_1 \ast G_2 \ast ... \ast G_i,
\]
where \(G_{sist}\) is the representation of the resulting system.

The system states now created are represented as an individual component, i.e., in terms of their capacities, probabilities and frequencies [29], according to Equation (13):
\[
G_{sist} = \{C_j; P_j; F_j\},
\]
where \(j\) is the system state index.

For the four-state model for the generator shown in Figure 3, or for a multi-state model, it is possible to combine the component’s states that have a similar impact on the behavior of the system [1], being those states called cumulative states. The probability of finding a component in a cumulative state is equal to the sum of the mutually exclusive probabilities of each state. Since states are mutually exclusive, the probability of the cumulative state is the sum of the probabilities of each of the states that composes it is determined by Equation (14):
\[
p_k = p_i + p_j,
\]
where \(p_k\) is the probability of the cumulative state; \(P_i\) is the probability of state \(i\); and \(P_j\) is the probability of state \(j\).
The frequency of the cumulative states should include all the transitions frequencies, disregarding the transitions between the cumulative states—since they do not represent transitions outside the cumulative state. Equation (15) is used for calculating the frequency of cumulative state:

\[ f_k = f_i + f_j + f_{ij}, \]  

where \( f_k \) is the frequency of the cumulative state; \( f_i \) is the frequency of state \( i \); \( f_j \) is the frequency of state \( j \); and \( f_{ij} \) is the transition frequency between states \( i \) and \( j \).

L.D. Arya et al. [30] presented a methodology based on binomial distribution evaluation to calculate the system’s states probabilities and frequencies for four generation system, considering that all units are identical and have the same failure data. In this case, this methodology is applied only for particular conditions when all generating units have the same reliability data.

A.M.L. Silva [28] presented an algorithm based on discrete convolution for a two generator system. In that paper, the authors modeled the system having three states with different capacities and another system having two states with different capacities. In this case, the cumulative states have not been considered when both systems were evaluated together.

System states probabilities are calculated through the discrete convolution between generators’ states probabilities, according to Equation (16) in a four generator’s system:

\[ P_j = (p_1 * p_2) * (p_3 * p_4), \]  

where \( P_j \) is the vector with the system state probabilities; \( p_1 \) to \( p_4 \) are generators’ states probabilities vectors. For each term of the convolution cumulative states are grouped according to Equation (18).

The system’s states frequencies are obtained summing the resulting vector from the discrete convolution between the states probabilities of systems’ generators and generators state frequencies, as presented in Equation (17):

\[ F_j = [(p_1 * f_2 + p_2 * f_1) * (p_3 * p_4)] + [(p_3 * f_4 + p_4 * f_3) * (p_1 * p_2)], \]  

where \( F_j \) is the vector with the system state frequencies; \( p_1 \) to \( p_4 \) are generators’ states probabilities vectors and \( f_1 \) are \( f_4 \) the generators’ states frequencies vectors. For each term of the convolution cumulative states are grouped according to Equation (19).

The system’s capacities are obtained by summing the generators’ capacities for each iteration when the calculation of the state probabilities and frequencies are done.

Cumulative states can also happen when the system states are calculated, so it must also be grouped to have the representation of a practical state, so their probabilities and frequencies are combined according to Equations (18) and (19).

\[ P_k = \sum_i P_i, \]  

\[ F_k = \sum_i F_i. \]  

With the vectors \( C_j, P_j \) and \( F_j \), it is possible to generate the COPT for the generation system, as presented in Table 5.
Table 5. Capacity outage probability table.

<table>
<thead>
<tr>
<th>States</th>
<th>Capacity Outage</th>
<th>Probability</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C1</td>
<td>p1</td>
<td>f1</td>
</tr>
<tr>
<td>2</td>
<td>C2</td>
<td>p2</td>
<td>f2</td>
</tr>
<tr>
<td>3</td>
<td>C3</td>
<td>p3</td>
<td>f3</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>j</td>
<td>Cj</td>
<td>pj</td>
<td>fj</td>
</tr>
</tbody>
</table>

The average duration of a particular capacity condition can be obtained by Equation (20):

\[
D_j = \frac{p_j}{f_j}
\]

where \( D_j \) is the average state duration of the system.

3. Results

A simulation using PowerFactory© was carried out to obtain the risk indexes for the FPSO generation system. A Monte Carlo simulation was performed and the generation states were determined by this simulation based on each state probability.

System states are convolved with the load duration curve aiming to evaluate the capacity of the generation system to meet the load in a specific time, and then define the probability of the system not meeting the load demanded by the system. For this simulation, the generators’ states “0” and “2” considered 25 MW of available capacity, and states “1” and “3” considered the available capacity of 0 MW per generator. For this system, no derated states were considered since there are no records of this condition.

For the generation system, the states with an impact similar in the behavior of the system were combined. This is the case of the states “0” and “2”, which give the system the available capacity of 25 MW per generator and the states “1” and “3”, where the available capacity is 0 MW per generator. In both cases, the impact of the states for generators’ capacity is the same, so those states can be cumulative.

A new state with a new probability is obtained using the combination of states, according to the Equation (14), and a new frequency according to the Equation (15).

The system states were then defined using frequency and duration methods, where for each system state was calculated its probability, state transition frequency and residing duration.

Two operational scenarios were simulated in terms of risk indexes and COPT, explained in the following subsections. The first scenario is based on the actual failures records of the FPSO generation system and the second scenario was created disregarding a failure that had 1.528 h of repair time.

3.1. Scenario 1: Regular Operation and Reliability Data

In this subsection, the operational risk indexes LOLP and EDNS will be evaluated for scenario 1.

Using the states probabilities of generators presented in Table 3, the risk indexes calculated by the software are:

- LOLP = 6.76% (Confidence interval: 6.63 to 6.89%);
- EDNS = 889 kW (Confidence interval: 867 kW to 911 kW),

where the LOLP is the probability that the generation system does not meet the demanded load by the power system and EDNS is the expected demand not met by the generation system.
To calculate the system parameters stated in Table 6, it is necessary to determine the state transition frequencies for each generator. A program in Python was developed to calculate the COPT using the generators’ reliability data stated in Table 1.

The specific aspects of the proposed method to determine the COPT is illustrated in the flow chart presented in Figure 5.

![Figure 5. Capacity outage probability table calculation method flow chart.](image-url)
Table 6. Capacity outage probability table—scenario 1.

<table>
<thead>
<tr>
<th>State</th>
<th>$C_k$ (MW)</th>
<th>$P_k$ (%)</th>
<th>$f_k$ (occ./Period)</th>
<th>$D_k$ (Period/occ.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>60.25</td>
<td>92.31</td>
<td>57.18</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>34.58</td>
<td>132.27</td>
<td>22.90</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>4.92</td>
<td>43.57</td>
<td>9.88</td>
</tr>
<tr>
<td>4</td>
<td>75</td>
<td>0.25</td>
<td>3.70</td>
<td>5.93</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>0.00</td>
<td>0.08</td>
<td>4.03</td>
</tr>
</tbody>
</table>

The first step to calculate the COPT parameters is to get the reliability data from the generators to obtain the state probabilities and frequencies for each generator. The generators’ state probabilities can be calculated from Equations (3)–(7). Then, using the states transition rates and probabilities, the state frequencies for each generator are calculated according to Equation (10). The next step is to determine the available states’ capacity in terms of power. With generators’ states probabilities, frequencies and capacities, it is verified if there are cumulative states; if so, they must be grouped in terms of probabilities and frequencies, according to the Equations (14) and (15), respectively.

The final step is to calculate the system’s states probabilities, frequencies, and duration. This step is done using Equations (16), (17) and (20) for the generator’s states that create the system’s states. In the case that the system has cumulative states, those must be grouped according to Equations (18) and (19).

For scenario 1, the COPT is obtained using the algorithm developed in Python and stated in Table 6, where the system’s states capacities, probabilities, frequencies and duration are determined.

3.2. Scenario 2: Disregarding Generator “C” (1528 h Repair Time)

In this subsection, the same techniques detailed in Section 3.1 for generation adequacy analysis with frequency and duration method have been used. This study case neglected a time-to-failure in generator “C” that took 1528 h to be repaired to evaluate the impact of this failure over the system reliability indexes.

In this operational scenario, the available time for generator B was considered 8108 h and the unavailable time was 652 h. With those records, new states probabilities were calculated as stated in Table 4.

The new risk indexes are shown below:

- LOLP = 3.29% (Confidence interval 3.20 to 3.38%);
- EDNS = 388 kW (Confidence interval 373 kW to 402 kW).

As can be seen from the new LOLP and EDNS values, the higher availability of the generator C reduces the system’s loss of load risk and reduces the possibility of load curtailment.

For this scenario, the COPT was also calculated, and it is stated in Table 7, where it is possible to verify that the system state 1 has an improvement in its probability and frequency, which means that the system enters more frequently in this state, and it is more likely that the system can be encountered on it. Additionally, the duration of the system at this state increases due to a higher probability of its occurrence. Another analysis that can be made is that the states with higher capacity outages have a lower probability of occurrence, which decreases the duration of those states.
<table>
<thead>
<tr>
<th>State</th>
<th>( C_k ) (MW)</th>
<th>( P_k ) (%)</th>
<th>( f_k ) (occ./Period)</th>
<th>( D_k ) (Period/occ.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>76.64</td>
<td>112.21</td>
<td>59.83</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>21.18</td>
<td>135.04</td>
<td>13.74</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>2.10</td>
<td>24.28</td>
<td>7.56</td>
</tr>
<tr>
<td>4</td>
<td>75</td>
<td>0.09</td>
<td>1.48</td>
<td>5.08</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>0.00</td>
<td>0.03</td>
<td>3.68</td>
</tr>
</tbody>
</table>

### 4. Conclusions and Future Works

In this study, a generation adequacy assessment considering risk indexes based on a stochastic method and the frequency and duration method was proposed. The risk model combined with the frequency and duration method provided more robustness to the generation adequacy assessment. Besides calculating the risk of each assessed scenario, it is possible to assess the frequency of occurrences of each system state in terms of unavailable capacity, as well as the time the system remains in each state.

Risk indexes translate the probability of the generation system meeting the demand and the demand that probably will not be met. These indexes evaluate how robust the generation system is to meet the demand. System evaluations can be performed for different load profiles by varying the load duration curve or using different fixed demands. For each situation, different values of LOLP and EDNS will be obtained. In this case, the COPT will not change because it depends only on the generator’s states probabilities.

It can be seen that comparing the simulated scenarios using the frequency and duration method, when the availability of generator “C” increases, the system resides more time in higher capacity states and the generation system state “1” frequency increases. Additionally, one can verify that the system’s state 3 frequency reduces. Consequently, in this case, the components of the generation system states will define the system’s states parameters.

**Future Works**

An integrated reliability assessment considering the interdependence between the oil production process, auxiliaries systems and power system’s equipment is still a challenge for reliability evaluation.

In this context, for future works derived from this research, the authors propose a financial evaluation for both presented scenarios. Additionally, a more detailed evaluation of components’ contribution for the reliability indexes as well as the analysis of external factors contributions on reliability indexes and optimization of the scheduled maintenance to improve generators’ availability and reduce system’s risk indexes are promising lines for future research. The generation adequacy analysis presented can also be considered to be applied to other industries and scenarios to evaluate its potential and achievements.

**Author Contributions:** Conceptualization, P.F.C., Y.P.M.R. and F.B.S.C.; methodology, P.F.C., Y.P.M.R. and F.B.S.C.; software simulation, P.F.C.; validation, P.F.C., Y.P.M.R. and F.B.S.C.; writing—original draft preparation, P.F.C., Y.P.M.R. and F.B.S.C.; writing—review and editing, P.F.C., Y.P.M.R. and F.B.S.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Acknowledgments:** The authors would like to thank the Federal University of Paraíba (UFPB) and Petrôleo Brasileiro S.A. for the financial and material support in the development of this work.

**Conflicts of Interest:** The authors declare no conflict of interest.
Abbreviations

The following abbreviations are used in this manuscript:

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AI</td>
<td>Artificial Intelligence</td>
</tr>
<tr>
<td>BPD</td>
<td>Barrels Per Day</td>
</tr>
<tr>
<td>COPT</td>
<td>Capacity Outage Probability Table</td>
</tr>
<tr>
<td>EDNS</td>
<td>Expected Demand Not Supplied</td>
</tr>
<tr>
<td>FPSO</td>
<td>Floating Production Storage and Offloading</td>
</tr>
<tr>
<td>LOLP</td>
<td>Loss of Load Probability</td>
</tr>
<tr>
<td>MMTF</td>
<td>Mean Time to Fail</td>
</tr>
<tr>
<td>MTTR</td>
<td>Mean Time to Repair</td>
</tr>
<tr>
<td>P₀</td>
<td>Probability of Reserve Shutdown State</td>
</tr>
<tr>
<td>P₁</td>
<td>Probability of Forced Out but not Needed state</td>
</tr>
<tr>
<td>P₂</td>
<td>Probability of In-Service State</td>
</tr>
<tr>
<td>P₃</td>
<td>Probability of Force Out in Period of Need State</td>
</tr>
</tbody>
</table>

References


