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A Combined Stochastic Approach for Enhancing Power Supply Reliability and Availability of Critical Users, Using Petri Nets Model, Monte Carlo Simulation and Fuzzy Logic

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ABSTRACT

Power supply interruptions and outages constitute a highly significant concern for industrial and critical users, especially in the oil and gas sector, where any interruption means a substantial economic impact. This study aims to assess the reliability and the availability of power supply within an oil and gas company located in southern Algeria, which is a region known by its harsh and severe environmental conditions such as high temperatures, strong winds, and geographical constraints. This work focused on evaluating these constraints and their impact on energy availability using dynamic reliability approach: Petri nets model PNM and Monte Carlo simulation MCS coupled with fuzzy logic to assess dynamic variables. Three different power networks were evaluated, and the results indicated that environmental constraints have a significant impact on power supply availability resulting from the occurrence of common cause failures, delays time, and the probability of failure on demand. These results emphasize the necessity of dynamic evaluation of power networks rather than relying solely on static data, which may lead to incorrect decisions regarding the choice of backup energy sources.

Keywords: Power supply, Reliability and availability, Petri Nets, Monte Carlo, Fuzzy logic, Critical users

INTRODUCTION

Ensuring an acceptable level of power supply reliability, availability and resiliency in restoring energy after disruptions is a major preoccupation for industrial and commercial facilities [1]. The critical nature of their operations and products justifies the high importance placed on the reliability, stability, and resiliency of their electrical power systems. Many of these facilities operate continuously (24/7), and any power interruption can result in significant production and financial losses. [2]

Due to the mentioned challenges and the complexity of power supply systems in industrial and commercial context, they adopt a set of methods that serv to enhance and optimize power supply reliability indices [3]. These strategies are often based on probability theories and rely on various metrics to assess and evaluate the reliability of electrical grids since the early design phase. This approach is essential due to the unpredictable nature of events that can disrupt power supply and the severity of their consequences, events are often divided into categories: the first one are those predictable events such as the increase of load demand, and the second category is those events which occur randomly without prediction like the natural disasters [4], common cause failures and major risks (fires, high temperature and extreme wind storms) [5]. Thus, probability studies serve as powerful tools in identifying and managing risks that could compromise the grid's stability.

One of the most widely used strategies in reliability assessment is the principle of redundancy. Industrial plants and critical facilities often implement backup systems such as alternative power lines, generators, or multiple sources of power to ensure uninterrupted power supply[6]. However, designing such systems requires careful analysis during the design phase to obtain the most optimal network configuration [7] and avoid any risk underestimation. Therefore,

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it is recommended to integrate the probability theories in this context to achieve the best accuracy results with different choices of reliability indices such as Probability of losing power supply (POLPS), Expected Energy not Supplied (EENS) and many other metrics related to the power supply reliability assessment. Different common methods are often used widely due to their easy principles of application and the accuracy of the results in terms of reliability assessment in different sectors, such as: The reliability Block Diagrams RBD, Fault Tree Analysis FTA; Markov Chains, Petri Nets…. Etc. [8].

The economic aspect always plays a crucial role in the design phase of electrical networks for any electricity user, particularly industrial users. This aspect is not only related to the investment cost of building a robust electrical network, it concerns also to the economic losses generated if a low-efficiency[9] electrical configuration is adopted [10].

Industrial users are always looking for the lowest financial losses in the case of a blackout. These losses are commonly related to the delayed time of restoring power availability which is affected commonly by harsh environmental constraints and logistic delays. Thus, this work takes into account this side to be studied as a crucial aspect within reliability studies by integrating dynamic evaluation using fuzzy logic, moreover, two other important aspects are widely discussed in this work which are common cause failure CCF and probability of failure on demand PFD, the objective of studying these aspects is to give an illustrative overview for each reliability enhancement proposition in order to make analysis based on priorities, advantages and constraints. among the different existing methods in this context this work has adopted only the dynamic reliability methods to address the realistic evaluation of grid's reliability and availability, that integrates the strength of fuzzy logic with the stochastic tools of reliability analysis PNM and MCS.

This paper consists of the following parts where the section 2 following the introduction presents previous works conducted in the framework of improving the reliability of complex electrical systems using probabilistic analysis methods in several fields, focusing on critical industries. The third section proposes a methodology for improving the reliability of electrical systems for industrial users during the design phase by choosing the PNM, MCS and FIS. The fourth section provides a real case study of an electrical network for an oil and gas company in Algeria, where this network is studied as a vulnerable network that has to be improved using the methodology proposed in the third section, and finally the work is finished by discussions and conclusion.

RELATED WORKS

Several approaches have been used to assess the reliability of electrical systems in various sectors, notably: the public sector, the industrial sector, and many other sectors that use continuous electricity. The most common approaches used in this field are often deterministic or probabilistic approaches. In the [11], two common probabilistic methods (Markov chain + RBD) were used to evaluate the reliability indices of a complex electrical system with a very large number of generators; the combination of the two methods succeeded in calculating different reliability indices for the studied system.

As reported in the [12], reliability block diagrams were used to evaluate the reliability indices of an interconnected network containing different sources in an isolated region in Algeria; the results showed the effectiveness of this method in modeling and performance of the reliability index calculations in the case of integrating different sources into the same network. Another work in the [13], where the FTA method was used to assess the unavailability of a protection circuit of a 132 KV line; the method was applied with a redundancy arrangement to evaluate the improvement achieved through redundancy on the studied network. According to the [14], a reliability-centered maintenance algorithm was developed to select the best maintenance intervals in electrical installations; the RCM strategy was proposed for industrial clients and electrical installations that could face long outage periods even though they have redundancy systems. The [15] discussed, a semi-Markov process was used to evaluate the reliability of autonomous sources in the oil and gas industry; the adopted method offers several selection opportunities by comparing certain characteristics in the design or extension phase. In the [16], an industrial site was studied to modernize its electrical scheme to minimize recovery time during random events; the proposed solution based on the automation process contributes significantly to improving the reliability of power supply by reducing downtime MDT, especially under severe weather conditions. As analyzed in the [17], a common probabilistic method was used to

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assess the reliability of a simple electrical system, the method based on PNM was used to simulate the behavior of the studied network with the MCS method, the results showed the effectiveness of PNM in this context, where all reliability indices of the power supply were successfully calculated using this method. In the [18], another aspect of reliability was addressed to assess the reliability of a repairable electrical system using the FTA method combined with importance factors to identify critical components in the studied system; the study highlights the importance of redundancy, inspection time, and source diversity to improve the reliability of electrical systems. For critical users the [19] used: the FTA and RBD methods were used to evaluate the reliability indices of a critical nuclear power plant, the two methods have been used to evaluate the reliability of an emergency system that uses diesel energy to produce electricity, the study showed some specific differences between the two techniques in terms of flexibility of the chosen events modeling, where the FTA method demonstrated some advantages compared to the RBD.

Other important concepts in the context of improving the reliability of electrical supply, particularly for industrial users, have been discussed in several research studies, such as the effect of independence (EI) between redundant systems and the effects of common cause failures (CCF). The authors discussed in the [20], a strategy that minimizes the dependence between redundant energy sources in emergencies, and the results provide specific methods to optimize the selection of excitation systems, especially for distributed generation DG installations. Another contribution in the [21], where they developed a new approach that integrates CCF with independent failures via the dynamic fault tree (DFT), the developed method provides a high-precision interpretation of the likelihood of failures occurring in complex systems. The authors used minimal cut sets (MCS) and root cause analysis to simplify how different root causes could contribute to system failures. In the [22], they employed a new method called multiple Greek letters model (MGL) dedicated to studying reliability and availability within electrical networks that may simultaneously share the same failure. The method successfully demonstrated the impact of considering common cause failures on reliability results, making it an effective tool for assessing the reliability of electrical supply.

Given the financial impacts of power supply losses, the concept of economic losses becomes an indispensable concept that must be studied in the evaluation of electrical supply reliability. Several studies have been conducted in this regard using different methods to calculate the cost indices related to electricity supply losses. The economic side is often discussed in the context of enhancing the reliability of power supply grids either by studying investment costs or losses cost reduction. Another work [23], has used mathematical methods and a simulation of 1 million hours for a redundant system with duplication and tripling of different power sources. The study focuses on the impact of investments in improving power grids and outage durations, and the results show how multiplexing power sources can enhance the reliability of electric supply while considering the economic implications. In [24], they focus on the economic aspect of power interruptions due to uncertainty events. The article discusses the concept of events with high-impact low-probability (HILP), where they employed a quantitative methodology that provides a description of the potential socio-economic risks induced by a power outage during HILP events. In [25], the authors discussed the concept of vulnerability in power grids in the event of extraordinary events. Several aspects of vulnerability were addressed in the article to conduct vulnerability assessment during extraordinary events; the proposed methodology begins with identifying critical consequences and ends with identifying existing and missing barriers in the power grid in case of contingencies to determine the lack points of the systems. The authors in the [26] suggested a reliability assessment model based on analytical method with an algorithm for coupled devices of electricity, they specifically research to enhance power supply reliability in coupled devices that integrate natural gas with a case study that integrates a gas turbine in different scenarios and the results show a significant I improvement in terms of reliability through the multi-state model.

Based on the previous studies and lessons learned from power grid's reliability assessment, this work aims to highlight key criteria that can help stakeholders during the design phase of electrical grids of industrial users. Standards such as IEEE-STD493-2007 have been specifically developed to guide this process, emphasizing the importance of power supply reliability. In such way, power supply stability it could directly equates the production stability, and its disruption results in production and financial losses.

Many previous studies have proposed strategies to improve electrical grids reliability such as the integration of new technologies, advanced prediction methods, and better load demand forecasting[27], [28], while this work aims to assess the reliability and availability since the design phase through dynamic evaluation of different variables (the

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expected availability of the configuration based on dynamic evaluation) in a single study that takes into account the design phase as a crucial phase to choose the relevant redundant power grid configuration for industrial and critical users.

METHODS AND METHODOLGY

The process of ensuring the reliability of the power supply for critical users, where any power interruption is intolerable, passes on a deep and hard evaluation of potential threats, where it is essential to implement barriers that take into account random and unforeseen events as well as the difficulties that may interrupt or hinder the quick restoration [29]. To meet these challenges, it is very important to establish a redundant configuration that offers a certains degree of flexibility and resilience in case of contingencies to minimize the negative impacts, as it is shown in figure (1) that visualizes a generic relationship between the blackouts and the resulted severity which is often related to economic losses, thus it is very essential to adopt the principle of defense in depth that matches the reliability robustness with the efficiency, independence and diversification of the barriers [30], as it shown in figure (2).

Considering the criticality of the power supply for critical installations, we propose a practical methodology that combines the strengths of fuzzy logic, PNM and MCS to determine the best redundancy of the network since the design phase[30].

The proposed methodology aims to integrate PNM with MCS and FIS to facilitate decision-making during the design phase to choose the best configuration of the power supply network based on various reliability indicators. The strength of this choice is that it allows us to model any factor or element that can influence the optimal reliability of the supply. The proposed method relies on studying different factors as (constraints/advantages) in a dynamic way based on probabilistic approaches commonly used to address reliability issues in electrical networks, where the advantage of this method is that it allows decision makers to simulate various schemes and configurations, each one with its own properties and constraints, thus enabling them to make decisions with a high degree of accuracy[31].

There are many problems that may affect the reliability of the network, such as random events, environmental constraints, the availability of the repair crew team, failures due to common causes and delay times etc. By modelling each configuration with its own characteristics, we will be able to conduct a structured prioritization assessment among the proposed configurations, where decision makers can choose the most relevant configuration based on the results obtained, whether for reliability indicators such as POLPS (unavailability), MTTF, and MTTR, or for the expected negative impacts that may result from the loss of power supply reliability. This gives the method a distinctive feature compared to the other methods used to assess the reliability of systems.

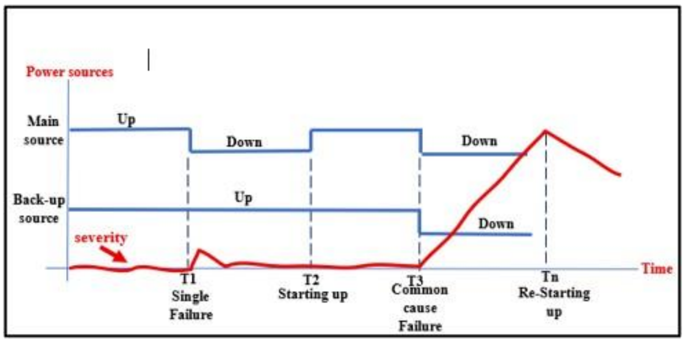

Fig. 1: illustrative generic model between power outage and its severity

Additionally, the proposed method can be very beneficial and useful in terms of system life cycle monitoring, it offers the simulation of a large number of hours with the MCS method. This feature highlights the strength of the method for carrying out an accurate assessment [32]. The PNM and MCS, when combined, provide us with a powerful tool that allows us to model all constraints and advantages with a long period of simulation while this degree of details may not be possible with the other reliability methods to take into account all factors that affect the reliability of the studied network.

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In reality, losing power supply reliability is a risk, which is defined in its common shape as the product of probability and severity, where severity is also defined as the product of vulnerability of the threatened area and the intensity of the threat, any risk study has to be conducted in the frame of studying causes and consequences where the figure 3 gives an illustrative bowtie model related to losing power supply as a central unwanted event.

The risk indicators can all be studied and modelled through the coupling of PNM and MCS. The severity of losing power supply reliability will become increasingly severe with the non-availability of the repair team, spare parts and maintenance infrastructures, and this is very feasible to be modelled with PNM, while the probability of losing reliability in power supply is directly linked to the failure rates of overhead distribution or transmission lines or any other component among the grid, which can also be done with PNM, once the PNM is prepared we can run a MCS for any desired period.

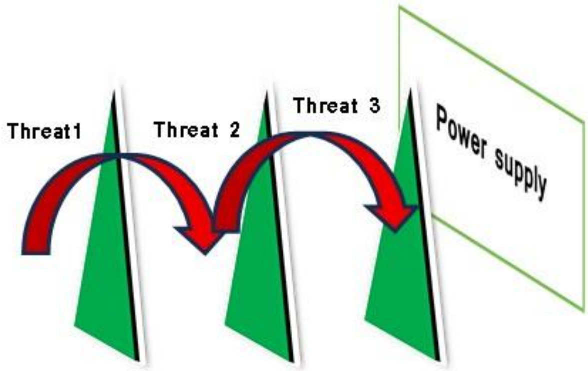

Fig.2: scheme of the defense in depth

These aspects of severity and probability play a crucial role in ranking risks in order to prioritize recommendations. In the context of designing a reliable power supply network, they can also play the same role, precisely in making relevant decisions based on an accurate quantitative assessment. The proposed method could cover all these aspects through the accuracy of its results due to the arithmetic characteristics and its ability to simulate any system over a long period.

To enhance and consolidate (MCS) results, it is essential to use accurate data within the (PNM). However, in dynamic reliability studies, we often face various forms of uncertainty where static data derived from databases cannot be treated as an absolute truth due to differences in operating environments. For example, overhead lines implemented in desert areas face much more severe constraints compared to those in urban areas[33], as well as maintenance interventions under extreme heat stress could not be usually positive [34]. To address this issue, this work introduces a Fuzzy Inference System (FIS) designed to rectify the chronic underestimation of critical reliability parameters specifically logistics delay times, common-cause failure factors, and the start-up refusal probability of engine-driven backup systems. While conventional static data often leads to erroneous assumptions that misguide stakeholder decision-making, integrating dynamic, real-world variables into the simulation engine ensures highly robust selection criteria. The inherent strength of a FIS lies in its unique mathematical capacity to interpret vague, uncertain, and highly fluctuating data. This makes it an invaluable framework for reliability assessments under stochastic conditions, where harsh environmental stressors and random operational events cannot be accurately captured by rigid, fixed averages.

The following equations explain one of the used methods of adapting the MCS method with concepts of reliability and maintainability that follow the exponential distribution, which is recommended by the IEEE STD 493-2007.

All reliability metrics related to power supply assessment could be calculated through the mentioned set of equations, moreover the maintenance equation can also be used to determine the damages resulting from the loss of power reliability by calculating downtime and maintenance time in relation to the lost production hours of the critical facility. The latter could play a crucial role in determining the expected amounts of any investment in order to build a robust power supply grid by conducting a cost effectiveness assessment[35].

$$F(\delta) = P(T \le \delta) = 1 - e^{-\lambda\delta} \quad (1)$$

$$M(\mu) = P(T\_repair \le \mu) = 1 - e^{-\gamma\mu} \quad (2)$$

Where 1 is the unreliability equation and 2 stands to the maintainability equation. With:

$F(\delta)$: unreliability function, $M(\mu)$: maintainability function, λ: failure rate and the γ: repair rate, δ: time to failure, μ: time to repair., T: time of 1st failure

The two equations (1 and 2) would be adopted to the MC formula as follows in the 3 and 4:

$$\delta = \frac{-\ln(1-z)}{\lambda} \quad \text{and} \quad \delta = \frac{-ln(z)}{\lambda} \quad (3)$$

$$\mu = \frac{-\ln(1-z)}{\gamma} \quad \text{and} \quad \mu = \frac{-\ln(z)}{\gamma} \quad (4)$$

where: δ: time to failure (TTF), μ: time to repair, Z: random number ($0<z\le1$),

Then the down time represents in 5, and the confidence interval is shown in 6 as follows:

$$T\ unavailable = \sum_{i=1}^{n} \mu i \quad (5)$$

$$CI\% = \bar{x} \pm z(\alpha/2).\frac{s}{\sqrt{n}} \quad (6)$$

Where the: $\bar{x}$: sample mean, s: sample standard deviation, n: number of simulations (samples) and the α: significance level.

For the failures due to common cause failures, the failure rate is given as follows:

$$\lambda ccf = \lambda.\ (total)\ x\ beta\ factor \quad (7)$$

where:

The λccf is the failure rate related to common cause failures. The λ is the total failure rate and beta factor β.

The unavailability equation is given as follows:

$$\hat{U} = \frac{\lambda}{\lambda+\mu} \quad (8)$$

Where the $\hat{U}$ is the asymptote unavailability

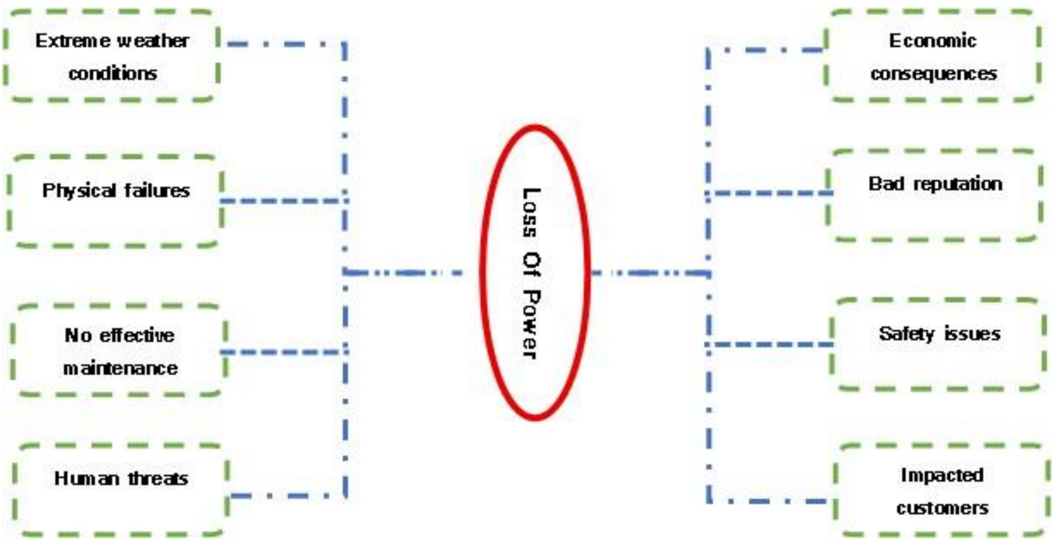

Fig.3: Bow tie model related to loss of power supply

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CASE STUDY

Work area description:

To concretely illustrate the aspects developed in the previous sections, we have chosen as a case study a critical industrial site (petroleum plant), located in the south of Algeria, dedicated to the production of crude oil and gas. The facility in question is a processing unit that manages both crude oil (10000 barrels per day), and gas (2 million cubic meters per day of lift gas, natural gas, and LPG). The power supply for this site is provided by a 60 kV high voltage line that provides more than 14MW, connected to a transformer station belonging to the Algerian national company of gas and electricity SONELGAZ. This substation is located at 8 kilometers from the site, while the power generation. plant is situated in Hassi Messaoud, approximately 60 kilometers away. The figure (4) below presents the scheme of this supply line.

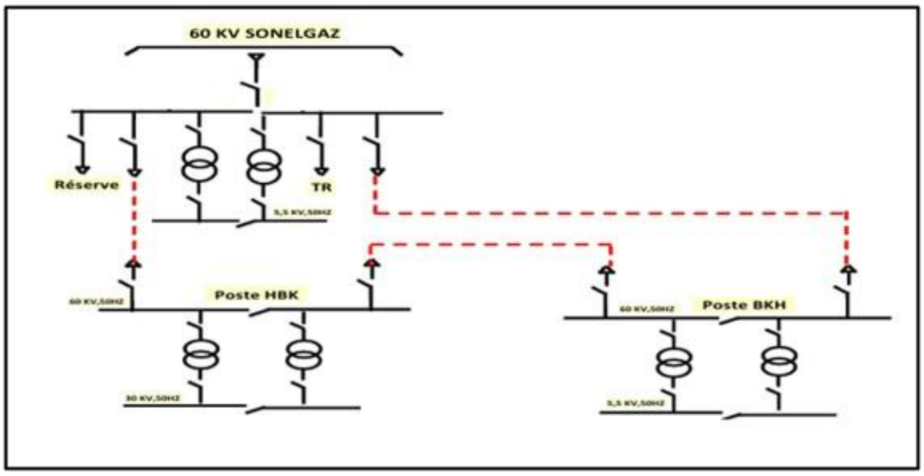

Fig. 4: The unifilar scheme of the plant

The chosen site for this study is the GLA production center (oil and gas production), which serves as the central hub connecting two other oil facilities, HBK and BKH, which collectively produce over 25,000 barrels of crude oil per day. As illustrated in Figure 5, a single 60 kV high-voltage overhead line supplies these three installations through GLA, with an interconnection establishing a loop topology between the sites. Because the GLA hub distributes power to the other two facilities, it represents a critical node requiring an uninterrupted power supply, any failure at GLA inherently propagates and affects the remaining two locations

The objective of this section is to assess the reliability and availaibility of the main transmission line supplying this industrial complex. To accomplish this, a vulnerability analysis of the existing infrastructure is conducted in accordance with IEEE STD-493-2007 guidelines to identify threats capable of compromising line integrity.

The adopted approach integrates several critical operational parameters into the design phase of a redundant power system: 1) the probability of common-cause failures simultaneously affecting both the primary and backup sources (due to harsh desert conditions characterized by extreme winds and temperatures); 2) the availability of maintenance crews during contingencies, which poses a significant challenge given the harsh geographical terrain of the overhead lines; and 3) the potential economic losses incurred during a total blackout. To address these challenges, three distinct configurations based on unique redundancy philosophies are proposed. This demonstrates that selecting a redundant system must rely on precise, measurable criteria that directly influence critical facility power reliability.

To rigorously evaluate the reliability and availability of each configuration, Stochastic PNM are utilized for precise modeling. Calculations and simulations are executed using GRIF (Interactive Graphs for Reliability) software, leveraging MCS to analyze system behavior. This section applies the methodology outlined in Section 3 to propose a secondary power source that minimizes the vulnerability of the existing infrastructure. Consequently, this study focuses only on external stochastic events, such as random events leading to lines failures driven by environmental constraints or physical threats, as well as delay times. Conversely, stationary components like transformers, switch

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breakers and busbars are assumed to be fully available due to strict adherence to periodic preventive maintenance schedules.

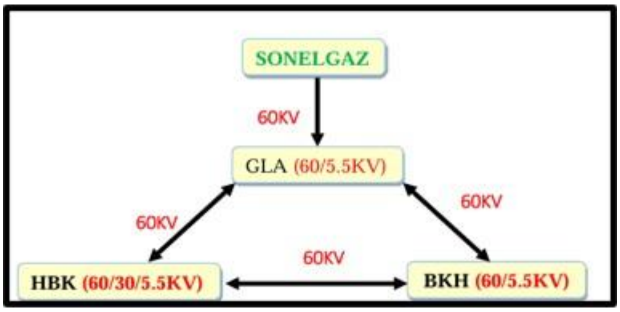

Fig. 5: The interconnection-grid between the supplier and the oil Plant

The Proposed Configurations:

First configuration: This configuration proposes adding a second overhead line from the same electrical substation located at 8 km from the petroleum plant. This solution is economically appealing, as the implementation cost is kept low due to the close proximity between the site and the transformation station. To assess the availability of this configuration, it is crucial to identify the associated threats and opportunities, along with its potential economic impacts in the event of a failure. Indeed, for this type of industrial user, cost reducing is the primary concern.

The block diagram shown in Figure 6 highlights two of the threats listed in the table 1, with particular emphasis on common-cause failures and the availability of maintenance teams. These factors are considered to be very critical, as they can significantly affect the continuity of the power supply, especially during major incidents when the entire petroleum facility depends on the only electrical substation. The table 2 summarizes the inspired data from IEEE-STD-493 used for the PNM.

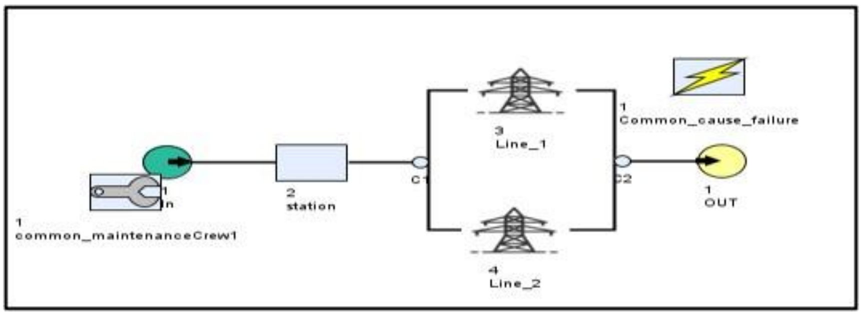

Fig.6: First configuration diagram

Table-1: First configuration properties

Constraints	Opportunities
✓ Unplanned shutdowns at the substation. ✓ Incidents at the power generation station located 60 km away ✓ Simultaneous failure of both lines due to common-cause events such as natural disasters. ✓ Limited immediate availability of maintenance teams in the event of massive environmental events.	✓ Acceptable implementation costs ✓ No high Joule effect losses ✓ Quick fault location and intervention

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As it is shown in Figure 7, PNM was applied model the defined specifications of the 1st configuration, which includes two redundant lines supplied by the same substation located 8 km away. The Failure and repair rates for both lines were assumed to be identical

Table-2**:** First configuration parameters

	Substation	Existing overhead line/mile	2nd overhead line/mile	Law	Source of Data
Failure Rate λ (h^{-1})	4.840182E-5	4.692E-7	4.692E-7	EXP	IEEE-STD 493
Repair Rate μ (h^{-1})	0.029	0.3937	0.3937	EXP	IEEE-STD 493
Beta factor for β_{CCF} common cause failure	0.05 (affects the two lines)			/	Historic data
Maintenance team availability	Only one team shared between substation and the two lines with delay time of 2 hours for the lines and 0 hour for the substation				

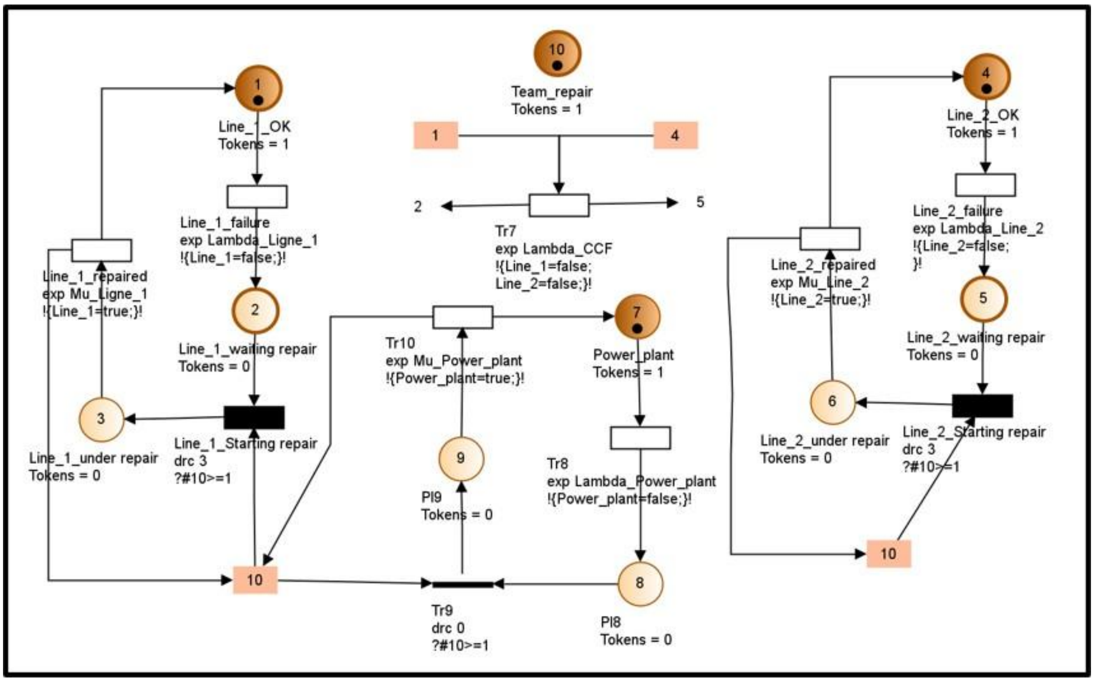

Fig. 7: Petri nets model related to the first configuration

Second configuration: The second configuration entails the deployment of a redundant feeder connected to an alternative power source (Substation 2), with the objective of mitigating common cause failures and enhancing operational reliability as shown with the block diagram in figure 8. This step enables the allocation of a separate maintenance crew specifically assigned to fault restoration on the secondary line. However, it introduces certain technical issue in terms of time to detect the failure as well as the economic constraints due to the significantly greater distance of Substation 2 compared to the primary station, these properties are resumed in table 3, while the table 4 highlights the used data for this configuration.

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Table-3**:** Second configuration properties

Constraints	**Opportunities**
✓ Cost constraints. ✓ Difficulties of detecting and localization of second line's failures. ✓ Over-dependency on two different suppliers.	✓ Availability of two separate maintenance teams ✓ Common cause failures are neglected

The failure rate of the two overhead lines is expressed by number of Km between the industrial plant and the supplier station, then the receiver equipments such transformers and busbars within the facility are alla assumed to fulfill their missions.

Failure rate/mile = 4.692E-7, and for 8km = $\frac{4.692E-7}{1.69}$ x 8 = **2.332E-6** (for the nearst overhead line).And for the second overhead line the fraction is multiplied by 200 km .

Table-4: Second configuration parameters

	Substation ½	Existing overhead line/ mile	2nd overhead line /mile	Law	Source of Data
Failure Rate λ**(h^{-1})**	4.840182E-5	4.692E-7	4.692E-7	EXP	IEEE-STD 493
Repair Rate μ**(h^{-1})**	0.029	0.3937	0.3937	EXP	IEEE-STD 493
Beta factor of common cause failure $\boldsymbol{\beta_{CCF}}$	Ignored				
Maintenance team availability	Two independent team: the first is for substation_1 and line_1 with delay time of 2 hours and the second for substation_2 and line_2 with delay time of 8 hours.				

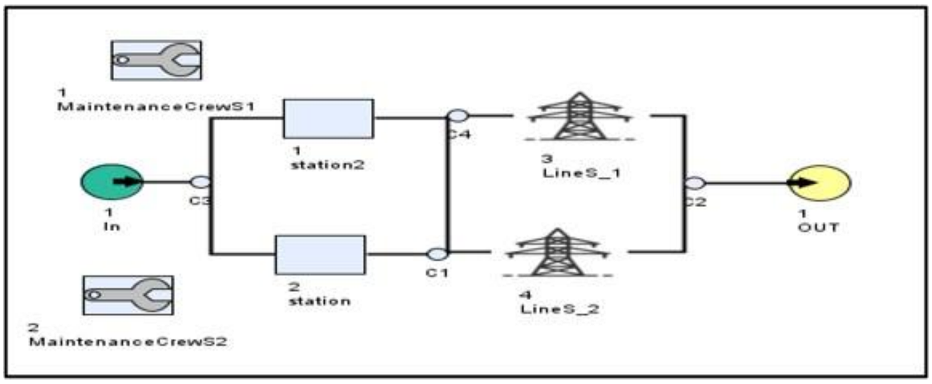

Fig8: Second configuration diagram

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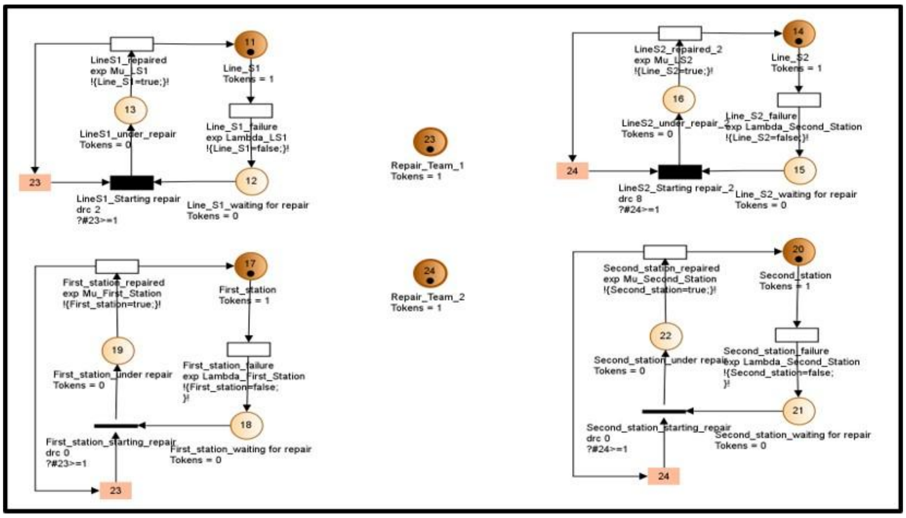

Fig. 9: Petri nets model related to the second configuration

As it is modeled in figure 9, the PNM has been used to visualize the specifications of the second configuration, where the second added source is located at 200 Km away from the plant, it's the only nearest choice to implement an independent source separated to the existing source, the major constraint in this proposition is that it implies a certain delay time to detect and repair failures, which is assumed to be 7 hours in the simulation process, where the nearest existing line takes only 3 hours as a delay time with an ignored CCF in this configuration.

Third configuration: The third configuration involves installing an autonomous power source by adding a gas turbine that will generate electricity alongside the existing overhead line as shown in figure 10. This solution is intended to reduce dependency on external substations and provide greater operational flexibility for maintenance activities, without causing any production downtime. Since the gas turbine's primary fuel source is already available on site, implementing this solution would make it possible to have an efficient redundant system which could meet the most reliability and availability requirements (efficiency, independence and diversification), as well as contribute significantly to minimize lost production hours and the expected flared gas due to black outs. In this configuration the gas turbine is assumed to be available provided that the preventive maintenance is carried out in its required durations, thus the probability of its failure depends only on certain environmental constraints that may delay the starting time. The table 5 and 6 summarize the properties of this configuration and the used data respectively.

Table-5: Third configuration properties

Constraints	Opportunities
✓ Manufacturing cost ✓ Maintenance cost	✓ Availability of in-house maintenance teams ✓ common cause failure is neglected ✓ No loss production hours/ no flared gas due to blackout

Table-6: Third configuration parameters

	Substation 1	Existing overhead line/mile	Gas Turbine	Law	Source of Data
Failure Rate $\lambda(h^{-1})$	4.840182E-5	4.692E-7	2.1343E-5	EXP	IEEE-STD 493
Repair Rate $\mu(h^{-1})$	0.029	0.3937	0.1618	EXP	IEEE-STD 493
Starting attempts probability γ	/	/	0.95	/	Historic data
Beta factor for β_{CCF} common cause failure	Ignored				
Maintenance team availability	Two independent teams: "the first for substation_1 and line_1 with delay time of 2 hours" and the second for gas turbine with delay time of 0 hours.				

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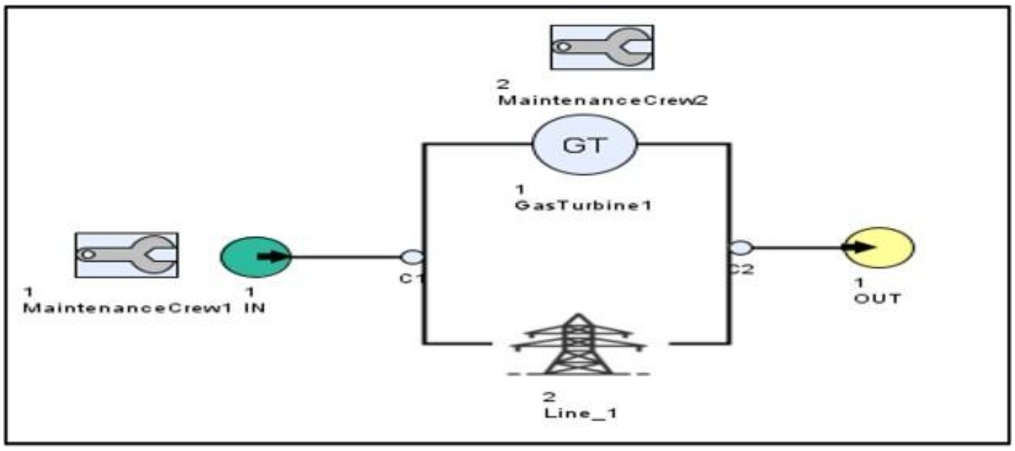

Fig.10: Second configuration diagram

The figure 11 demonstrates the backup system added to the existent line, which is a gas turbine that will use the natural gas produced by the facility to generate electricity, the biggest feature of this solution is that it allows more flexibility and more independence to carry out inhouse maintenance of the gas turbine, which makes it a robust backup source of power compared to external sources, another advantage of this proposition is the neglected CCF probability as well as it gives the lowest delay time to start maintenance of the gas turbine after any outage, due to the availability of crew teams in the facility during the night and day shifts,.

For the three configurations the MCS will be run for 30 years (262800) hours with a confidence interval of 90%, through the GRIF software this simulation offers us different reliability metrics as results with high accuracy such as: MTTF, availability and many other metrics.

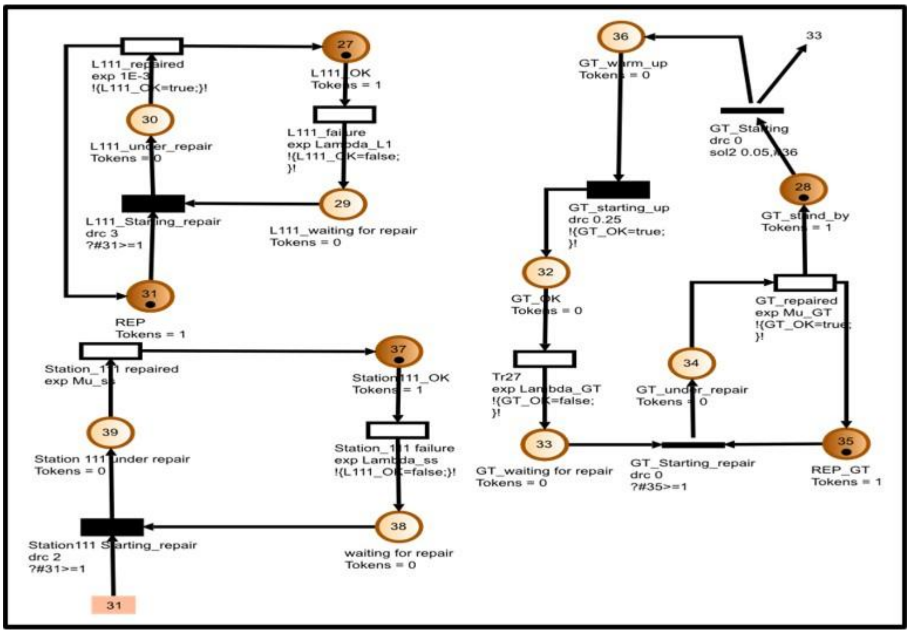

Fig.11: petri nets model related to the third configuration

RESULTS AND DISCUSSION

First configuration: the figure (12), shows the evolution of the POLPS over time, the obtained curve depicts an exponential behavior of this configuration, where the curve starts at 0 and rises in an exponential shape to its maximum value of 0.0961with a mean value of 0.039. Another aspect related to reliability assessment of this configuration is shown in the figure 15, which depicts the comparative evolution of the three MTTF, where the mean

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value of the first configuration registered the lowest value with 17789 hours, this metrics affirms that this configuration may start facing failures after only 2 years.

The shape of the curve can be explained by cumulative probabilities of failure over time, where the existence of only one repair team that supervises the two lines and the station creates a major operational bottleneck, in cases of multiple failures occur or in harsh environmental circumstances, a single team cannot fix all failures at once. This factor impacts directly the mean time to repair and delay time to start repair.

Although the mean value did not exceed 0.039 which looks like a minor value for systems reliability, but for critical users it leads to severe negative consequence in terms of economic losses, this configuration adopts two overhead lines, which looks like a classical redundancy but in reality the lack of diversification and geographical area affects the availability of this configuration and lead directly to the loss of load due to common cause failure.

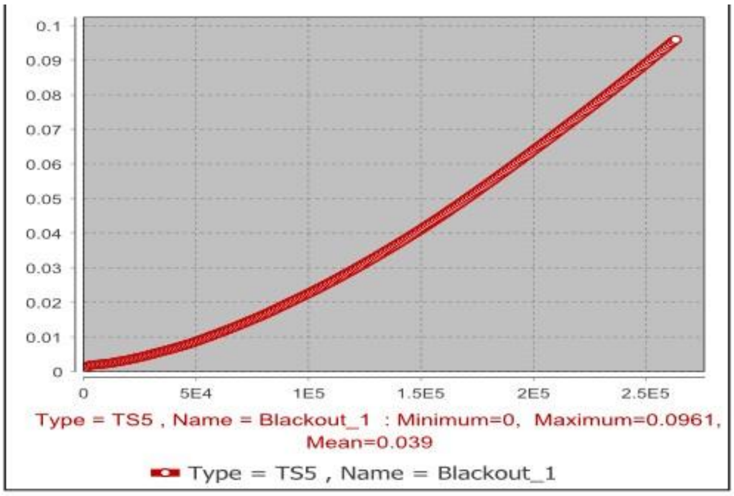

Fig.12: POLPS evolution of First configuration

Second configuration: Regarding the second configuration, Figure 13 shows a highly significant improvement in system availability, where the maximum value of the (POLPS) did not exceed 8.E-6 and an average of 2.5394E-6. Moreover, the MTTF evolution curve related to the second configuration has also registered the highest value, with a mean value of 68805 hours, as it is shown in the figure 15. These results affirm the robustness of this architecture and highlight the high degree of resilience provided by the diversification of power sources and the use of two separate repair teams. Even with the extended logistics delay time required for the second line, the overall configuration remains highly reliable. This outcome proves that a separation strategy successfully outweighs the drawbacks of extended travel times, effectively eliminating the vulnerabilities of common-cause failures and shared maintenance crews.

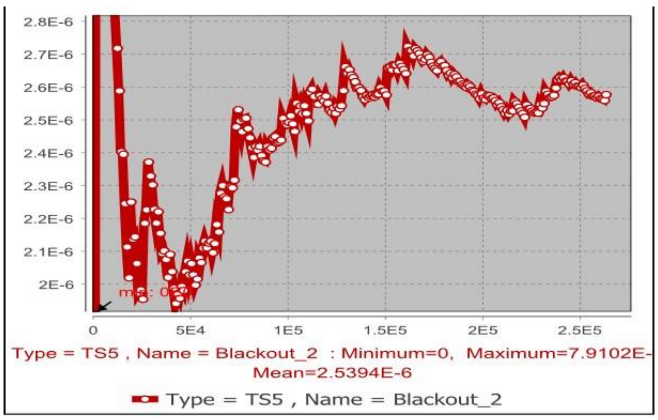

Fig.13: POLPS evolution of the second configuration

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Third configuration: The results obtained from the third configuration (figure 14) reveal a very interesting dynamic. As observed, the curve takes some time to stabilize before eventually capping at a maximum POLPS of 1.22E-4.

Unlike the first configuration, it is clear that the gas turbine acts as a genuine and highly effective safeguard against prolonged outages. This is mathematically demonstrated by the curve flattening out and stabilizing after reaching its ceiling. In addition to these promossing results this configuartion achieved a significantly higher MTTF value with 48672 hours.

One of the most prominent advantages of this setup is that the turbine instantly takes over by utilizing the gas already available on-site, which drastically minimizes the threat of a total blackout. It is true that its average unavailability is slightly higher than that of the second configuration caused by the starting time of the turbine. However, it introduces a crucial operational benefit,true physical and technological diversification. While the parallel overhead lines in the second configuration could still be wiped out simultaneously by a severe storm, the on-site gas turbine completely breaks this vulnerability, ensuring power continuity even under extreme environmental threats.

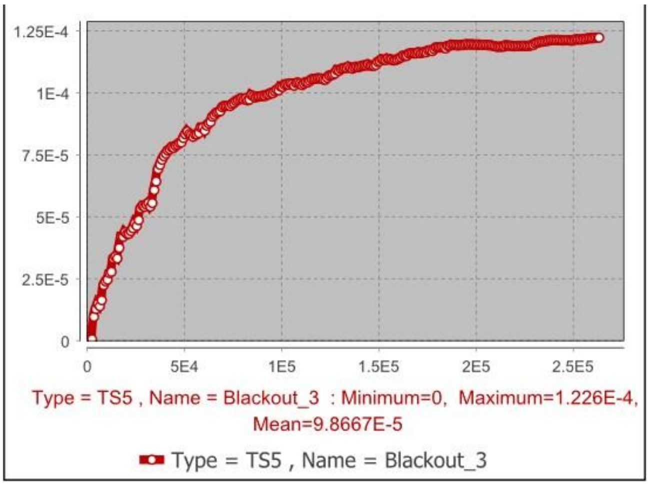

Fig.14: POLPS evolution of the third configuration

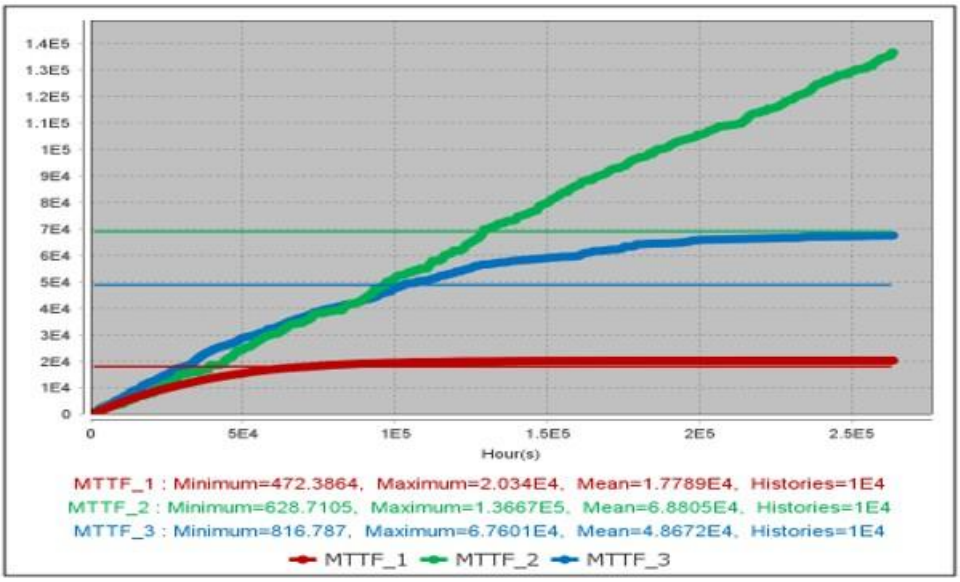

Fig.15: Mean Time to Failure related to each configuration

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After simulating the three systems using the MCS method via GRIF software over a 30-year period, it is very clear from the obtained results that the differences in performance involve several factors, such as common causes, travel time for maintenance teams, and start-up times for the gas turbine.

However, it is not enough to rely solely on these obtained results because they are based on static values. These values can actually change due to dynamic variations that might occur in each of the three systems. Therefore, conducting an additional study to analyze these factors and understand their true impact on grid reliability will be very useful in the decision-making process for stakeholders.

Integration of Fuzzy logic inference system:

Given the Saharan nature of the studied site and its geographical conditions, which can affect restoration times and sometimes increase the probability of common-cause failures, a fuzzy logic-based model is proposed in this section to overcome these uncertainties and align with the dynamic constraints of each configuration. The Mamdani inference model provides an ideal mathematical framework to translate human experience and meteorological data into logical rules. Thus three fuzzy inferenece systems (FIS) are proposed in the study.

In this part three different FIS are developped distinctly to address the dynamic constraints in the aim of adjust the vulnerabilities of each configuration, the three FIS are respectively as follows:

FIS1: Delay logistique time; FIS2: evolution of Bccf; FIS3: GT starting up constraints. (the tables below (tables 7,8 and 9) give the inputs and outputs of each FIS).

For each FIS membership functions are used with logic rules, the figures16,17 and 18 depict respectively the membership function of each configuration.

Table-7: related variables to FIS1

Variable	Type	Fuzzy Term	Ranges
Ambient Temperature	Input	Moderate	0°Cto 35°C
		High	30°C to 48°C
		Extreme	45°C to 60°C
Wind Speed (Vwind)	Input	Low	0 to 30 km/h
		Moderate	25 to 65 km/h
		Strong	60 to 100 km/h
Distance Km	Input	Near	0 km to 110 km
		Moderate	80 km to 320 km
		Far	280 km to 500 km
Logistic Delay (DT)	Output	Short	0 to 3 hours
		Medium	2 to 7 hours
		Long	6 to 12 hours

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Tables-8: related variables to FIS2

Variable	Type	Fuzzy Term	Ranges
Wind Speed	Input	Low	0 to 30 km/h
		Moderate	25 to 65 km/h
		High	60 to 100 km/h
Structural Condition (RS)	Input	Robust	60% to 100%
		Normal	30% to 70%
		Vulnerable	0% to 40%
Beta Factor (β) of CCF	Output	Low	0 to 0.03
		Medium	0.02 to 0.08
		High	0.07 to 0.15

Tables-9: related variables to FIS3

Variable	Type	Fuzzy Term	Ranges
Lubricating Oil Temperature (Tlube)	Input	Cold	0°C to 22°C
		Nominal	20°C to 55°C
		Hot	50°C to 80°C
Starter Stress (STstarter)	Input	Low	0% to 35%
		Medium	25% to 75%
		Critical	65% to 100%
Startup Time	Output	Fast	0 to 15 min
		Normal	12 to 30 min
		Penalized (+15 min)	30 to 60 min
Probability of Failure to Start (PFD)	Output	Low	0 to 0.02
		Medium	0.01 to 0.06
		High	0.05 to 0.12

The numerical ranges for each FIS variable were derived from historical meteorological profiles typical of desert regions, as well as field data provided by maintenance teams operating under identical environmental conditions, thereby ensuring that the fuzzy membership functions closely reflect real-world operational realities.

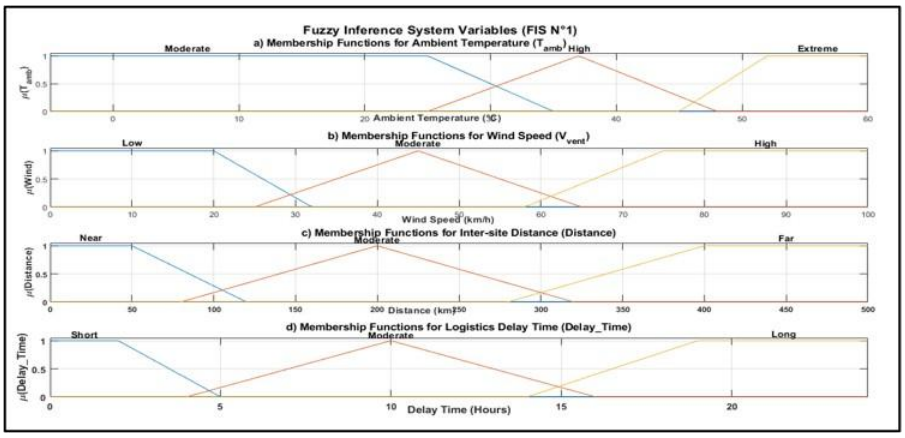

Fig.16: membership functions of FIS1

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Based on the established overall structure of each Fuzzy Inference System (FIS) specifically the definition of input/output variables and membership functions a logical rule base was implemented using MATLAB to evaluate the dynamic behavior of these models. This section aims to highlight and analyze the results generated by the Mamdani inference approach.

To accurately capture the harsh desert environment and its geographical constraints, a set of 3D control surfaces was derived from the fuzzy inference rules. These 3D surface plots provide a clear visual representation of the non-linear interactions among the selected variables.

Ultimately, the resulting surfaces are used to examine specific critical scenarios that may occur randomly with a high degree of severity. This approach makes the reliability studies significantly more realistic and dynamic, moving far beyond the conventional static simulation of reliability indices.

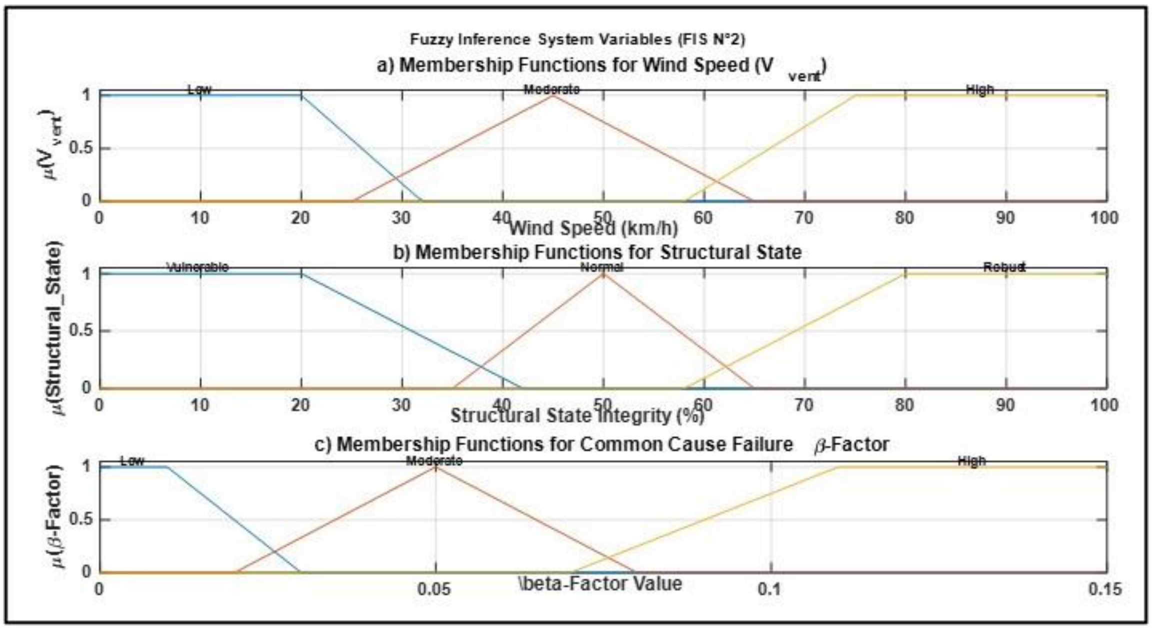

Fig.17: membership functions of FIS2

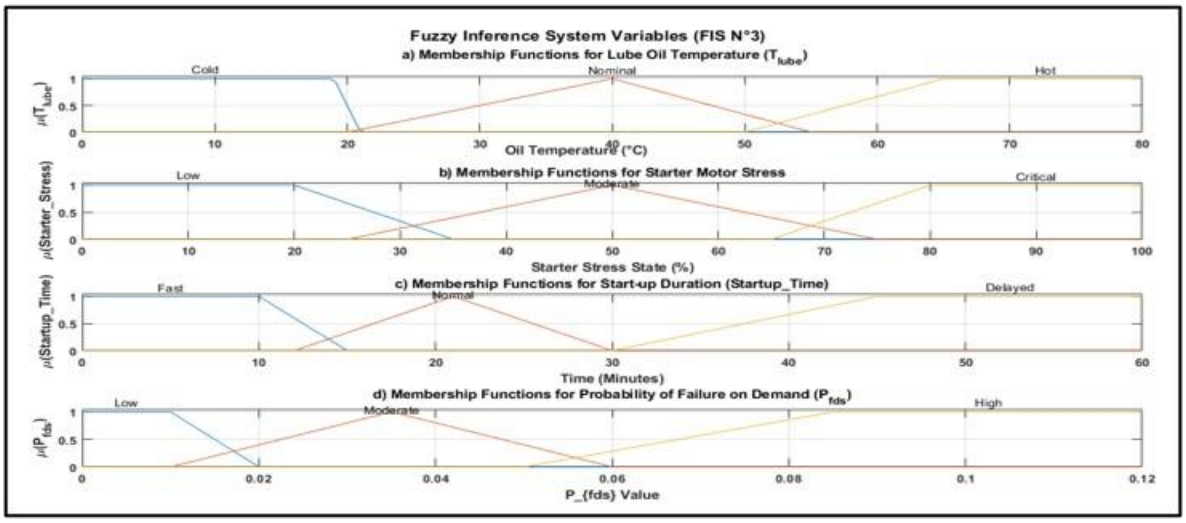

Fig.18: membership function of FIS3

Based on the obtained 3D surfaces, we extracted the maximum values of each output for each configuration, in order to input them into the GRIF software to evaluate the expected changes from each modification.

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For the first configuration, a change was applied to the logistic delay parameter (delay time), which reached its maximum value of **12.5 hours**, as well as to the beta factor, which was set at **1.1**.the extracted results are shown in figure 19 and 20 respectively.

Regarding the second configuration, the modifications concerned the logistic delays of each line: for the first line, we applied a delay of **12.5 hours**, while for the second line, we set a delay of **18.5 hours** to correspond to a distance of approximately **300 km**. Additionally, the failure rate (lambda) of the second line was adjusted by multiplying it by this new distance (i.e., 300 km × the nominal rate of line 2).

For the third configuration, the modifications concerned the probability of refusal to start, which reached a critical value of **0.07**, as well as the starting time, which was extended to **40 minutes.** (figure 21 a and b)

The results of these simulations are shown in Figure 22. It is clearly observed that the second configuration maintains its overall advantage, despite an obvious degradation of its average value under these severe environmental constraints where it takes a mean value of **(8.85E-5)**, The same behavior was observed for the other two configurations. The first configuration recorded a relative increase in its average value, reaching a mean value of **0.044** while the third configuration displayed an average value of **1.05E-4.**

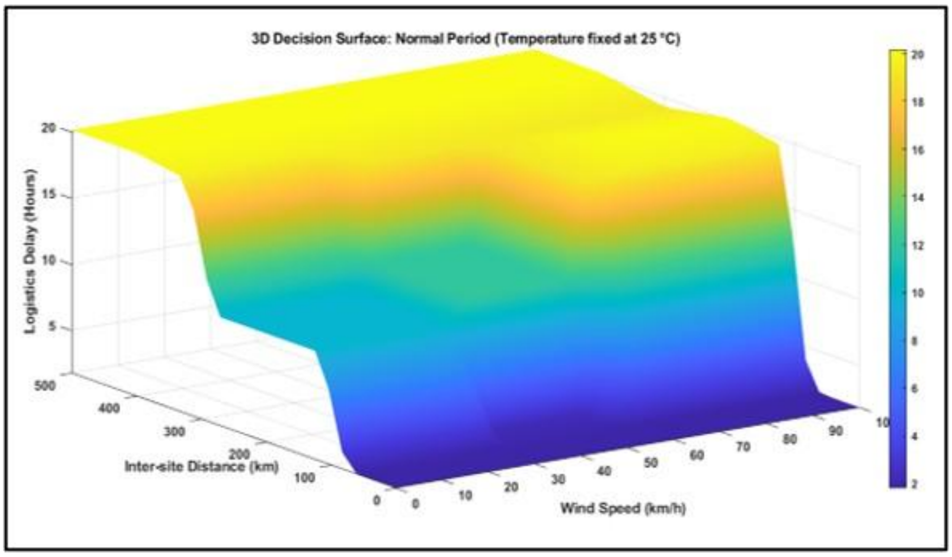

Fig.19: FIS (1) evolution of delay time VS Wind speed and Distance

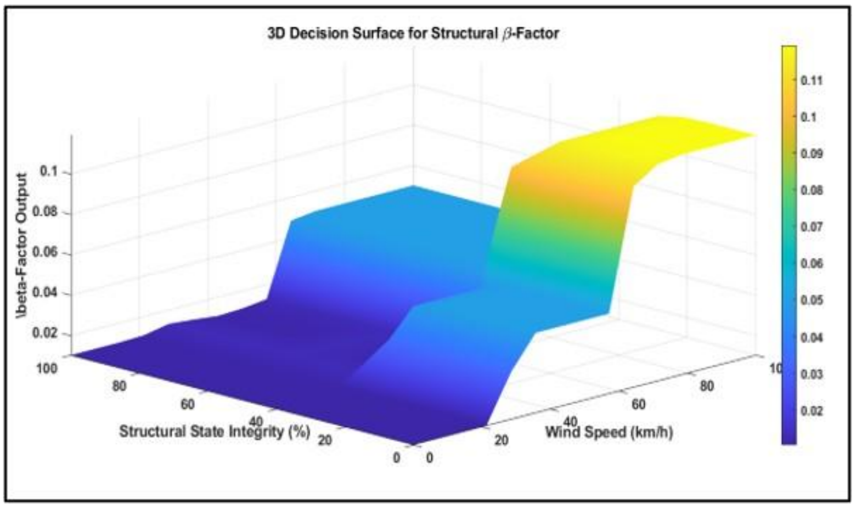

Fig.20: FIS (2) evolution of Beta factor VS Wind speed and Structural integrity

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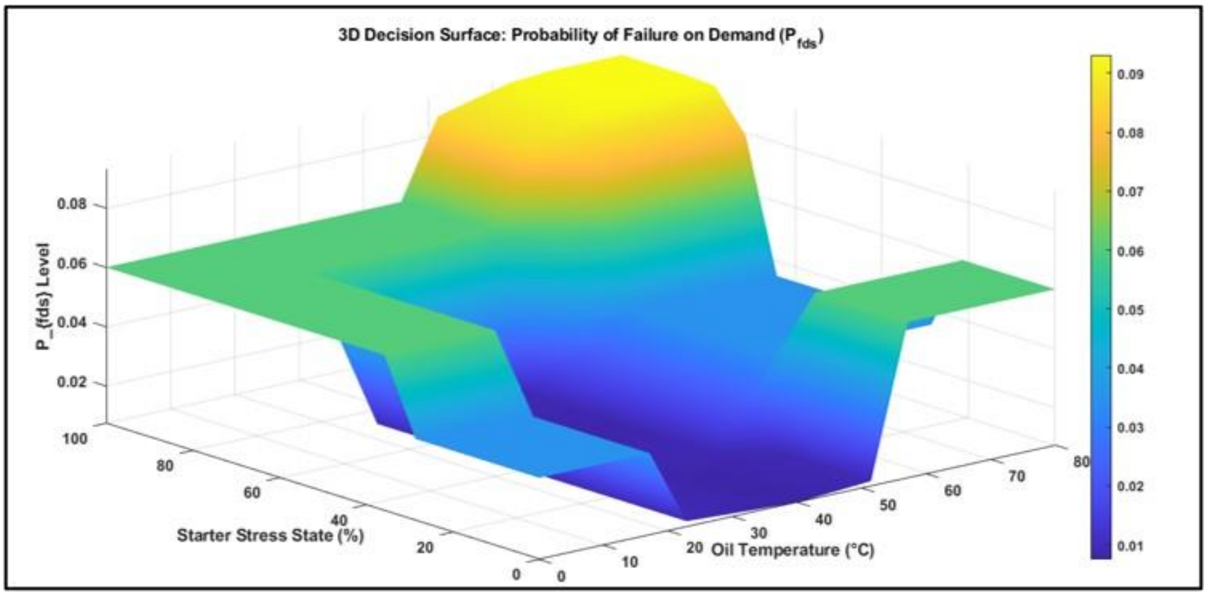
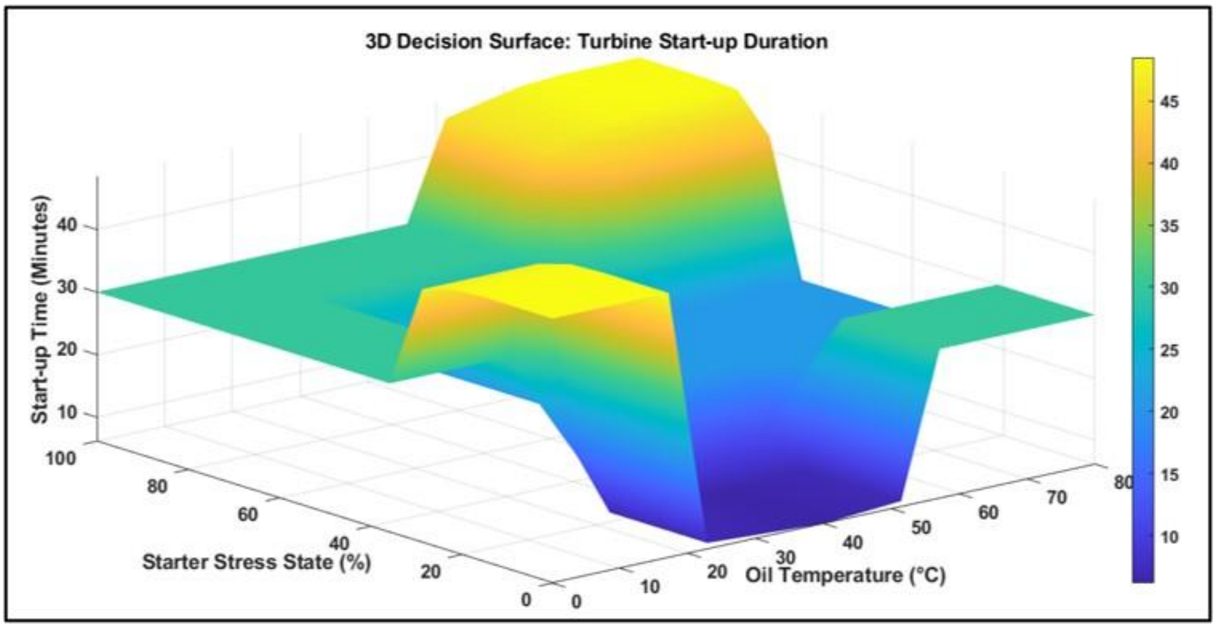


a)



b)

Fig.21: FIS (3). GT (Failure to Start probability and starting up time)

Although these values remain dependent on adjustments and variations of the variables within the FIS, they offer a highly realistic and dynamic illustrative perspective for decision support. This confirms the crucial importance of dynamic approaches when evaluating the reliability of critical systems. Nevertheless, the final choice of architecture could be reconsidered in light of cost-benefit ratio analysis for each configuration. Ultimately This step demonstrates the crucial importance of rationalizing reliability studies, which proves capable of influencing critical engineering decisions.

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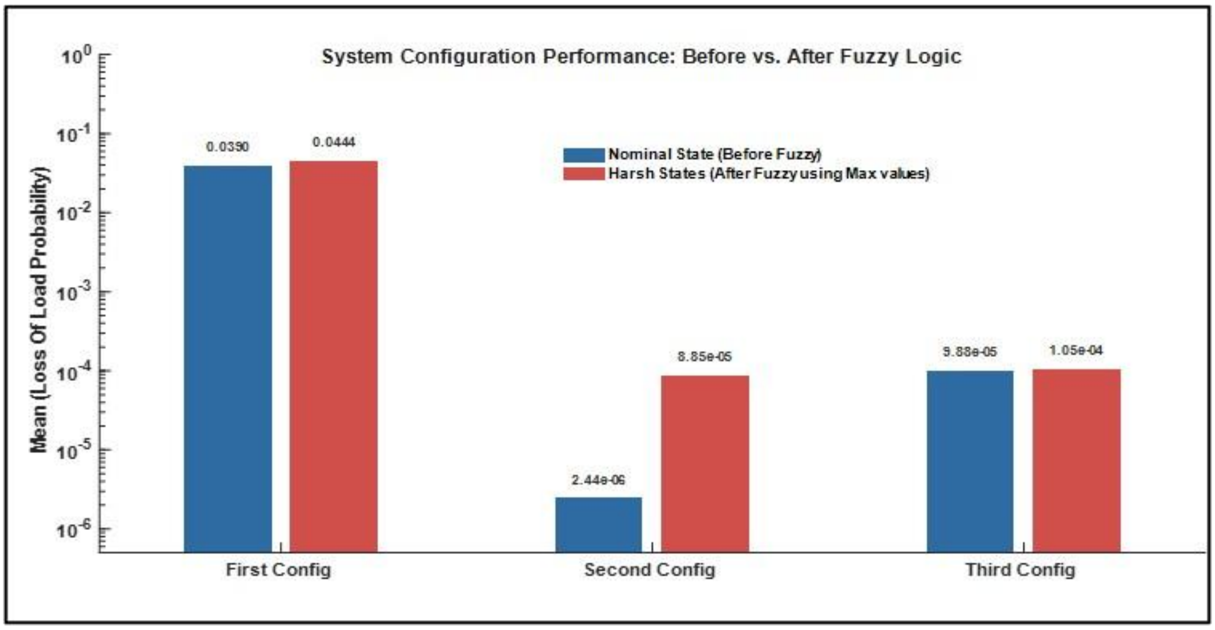

Fig.22: comparison of results before and after FIS

CONCLUSION

This paper treats the power supply system of an Algerian oil plant by studying the reliability of its existent network and proposing solutions to improve it, based on a methodology that begins by identifying threats and then modeling them using PNM integrated with the MCS. The paper presents a case study that proposes three different backup configurations to improve the existent network, each characterized by different properties. A set of essential criteria emerged from the three configurations, which are: common cause failures, availability of the maintenance team, the delay duration in starting maintenance operations and the probability of failure on demand, where each of these criteria contributed to noticeable changes in the results obtained during the simulation period. The results indicated that the second proposal represents the highest level of availability compared to the other two proposals, featuring by its: independent maintenance team, absence of common cause failures, as well as to the separation of supplier stations.

This paper provides a valuable and realistic methodology by integrating PNM, MCS, and FIS to assess the reliability and availability of the power supply for critical users. By relying on realistic operational conditions and available data sources, the adopted methodology can play a crucial role in the decision-making process for such engineering studies. However, incorporating a comprehensive cost-benefit ratio analysis remains highly recommended in this context, as evaluating the technical trade-offs alongside investment factors is essential for making the most relevant deployment decision.

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