Reliability and Integrity Assessment of High Integrity Pressure Protection Systems (HIPPS) Considering Common Cause Failures Using the Multiple Beta Factor Model

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ABSTRACT

High Integrity Pressure Protection Systems (HIPPS) are critical safety instrumented systems used in high-risk industries to prevent over-pressurization and mitigate hazardous events. The reliability and integrity of these systems are essential for ensuring safe operation and achieving required Safety Integrity Levels (SIL). However, their performance is often compromised by design deficiencies, inadequate maintenance practices, operational errors, and the presence of Common Cause Failures (CCFs), which can simultaneously affect redundant components and significantly reduce system effectiveness. This study presents a comprehensive reliability and integrity assessment of HIPPS by incorporating Common Cause Failures using the Multiple Beta Factor (MBF) model. The research analyzed both functional performance and failure behavior of HIPPS through an advanced reliability modeling approach. A simulation model was developed in MATLAB/Simulink to evaluate system performance while accounting for multiple dependent failure mechanisms. The MBF method was employed to provide a more realistic representation of CCFs by distributing failure probabilities across different failure groupings, thereby improving the accuracy of reliability predictions compared to conventional single beta-factor models. Results obtained from the simulation and analysis reveal that inadequate design processes contribute to approximately 25% increase in system failure likelihood, while poor maintenance practices account for about 35% increase in failure risk. Operational errors were found to contribute to 20% of total failures, whereas environmental factors, such as temperature extremes, resulted in a 15% increase in component degradation rates. Furthermore, the incorporation of real-time monitoring and diagnostics was shown to improve overall system reliability by reducing potential failure modes by up to 40%.The study concludes that integrating CCF considerations using the MBF model significantly enhances the accuracy of HIPPS reliability and integrity assessment. It further emphasizes that improvements in system design, implementation of robust maintenance strategies, enhanced operator training, and adoption of advanced monitoring technologies are essential for minimizing failure risks. The findings provide valuable insights for engineers and safety professionals aiming to optimize HIPPS performance, thereby contributing to safer and more efficient operation of high-pressure industrial systems.

Keywords: High Integrity Pressure Protection Systems (HIPPS), Reliability Analysis, System Integrity, Common Cause Failures (CCF), Multiple Beta Factor (MBF) Model, Failure Rate Modeling, Functional Safety, Failure Rate Modeling

INTRODUCTION

High Integrity Pressure Protection Systems (HIPPS) are critical safety systems used in oil and gas and other process industries to prevent overpressure conditions that could lead to equipment damage, fire, or explosion (Sankaranarayanan & Narayanan, 2019). As industrial processes become more complex, ensuring the reliability and functional integrity of HIPPS is essential for protecting personnel, assets, and the environment (García et al., 2021). This study focuses on evaluating HIPPS performance by considering both random hardware failures and common cause failures (CCF) through the application of a multiple beta-factor model, enabling a more comprehensive reliability assessment (Tavakoli & Zakeri, 2018).

Overpressure remains one of the most significant hazards in oil and gas operations. While conventional pressure safety valves (PSVs) provide pressure relief, they are often insufficient in high-pressure systems and cannot ensure rapid system shutdown during critical events. HIPPS addresses this limitation by acting as a high-integrity barrier between high- and low-pressure sections of a system, quickly isolating the pressure source to prevent escalation. As a type of Safety Instrumented System (SIS), HIPPS operates through three main subsystems: sensors (e.g., pressure transmitters), logic solvers, and final elements (e.g., shutdown valves), all of which must function reliably on demand.

The reliability of HIPPS is closely linked to its ability to perform its intended safety function when required. Failure to act on demand constitutes a dangerous condition, and system performance is typically measured using the Probability of Failure on Demand (PFD) and expressed in terms of Safety Integrity Levels (SIL). Achieving a high SIL requires minimizing both detectable and undetectable failures, including dangerous detected (DD) and dangerous undetected (DU) faults (Xie et al., 2021). Various testing and maintenance strategies such as self-diagnostics (SD), functional testing (FT), and partial stroke testing (PST) are used to identify failures and maintain system reliability (C. Wang et al., 2020). However, each method has limitations, and a combined testing approach improves fault detection and overall system performance. Periodic testing intervals are commonly used to estimate average PFD, providing a basis for reliability evaluation and maintenance planning. HIPPS design follows international safety standards and emphasizes fault tolerance, redundancy, and fail-safe operation. The system is engineered to withstand single faults without loss of function and to transition to a safe state under multiple failures. Features such as automatic diagnostics, hot-swappable components, real-time monitoring, and rapid response times enhance system dependability and operational safety (Stollen, 2014).

This research contributes to the understanding of HIPPS reliability by incorporating common cause failures into the analysis using the multiple beta-factor model. By leveraging historical failure data, the study identifies key factors influencing system performance and highlights areas for improvement in testing, maintenance, and design. The findings aim to support engineers and safety professionals in optimizing HIPPS reliability, ensuring compliance with safety standards, and enhancing the protection of industrial assets.

MATERIALS AND METHODS

Method

The method used in this research is called “multi-beta factor” The **multiple beta-factor model** is a reliability model that helps in quantifying the common-cause failure (CCF) probability in systems where redundancy is used to improve reliability, such as in a High Integrity Pressure Protection Systems (HIPPS). Again, multi beta factor is an advance reliability analysis approach that uses multiple beta factors to account for different common failed redundant systems, providing a more accurate system reliability. The method is used to account for common failures in redundant systems. It assumes a certain fraction of beta factor of failure in redundant components. Example in a sensor.

Multiple Beta-Factor (MBF) Model

Multiple Beta Factor (MBF) Model is a reliability and statistical method used to analyze and calculate the reliability and probability of failure on demand (PFD) for a high integrity pressure protection system (HIPPS).

It accounts for multiple failure path and their interaction.

MBF does the following:

i. The calculations identifies the potential failure paths and their probabilities.

ii. It calculates the beta factor (BF) for each failure paths

iii. Calculates the PFD for each failure path.

iv. It combines beta factors using the MBF formular.

MBF =1-π(1-β_i)

Where β_i is beta factor for each failure path.

Multiple Beta-Factor model gives a better understanding of the reliability and failure probability of high integrity pressure protection system (HIPPS). It accounts better for complex system interaction, provides more accurate failure probability estimates and optimizes system design and maintenance of HIPPS.

MBF Interpretation

The closer the MBF value to 0(zero), it means a low probability of failure on demand. When the MBF is greater than O, example 1. It means a high probability of failure on demand.

An MBF of a probability of failure on demand of 0.0249 is appreciable than a PDF of 1. There may be other ways of calculating MBF but the easier and better is

MBF =1-π(1-β_i)

e.g A common cause failure of components of the HIPPS at failure paths and it beta-factor.

Sensor 1 fails at 0.02

Sensor 2 fails at 0.02

Sensor 3 fails at 0.02

Logic solver 1 fails at 0.01

Logic solver 2 fail at 0.01

MBF = 1 - $(1-0.02)^3$ X $(1 – 0.01)^2$

MBF = 0.07754

Modelling of the High Integrity Pressure Protection Systems (HIPPS) Using Fault Tree Analysis (FTA)

Basic Event Probability:

$P_i = 1 - e^{-\lambda_i t}$

Fault Tree Analysis (FTA) is a top-down, deductive method used in reliability analysis to systematically identify and assess the causes of system failures, focusing on how component failures contribute to the failure of the overall system. It is effective for High Integrity Pressure Protection Systems (HIPPS) because it models complex interactions between subsystems (e.g., sensors, logic solvers, valves) and helps quantify failure probabilities, ensuring safety and compliance in critical applications. For example, in a High Integrity Pressure Protection Systems (HIPPS), FTA might show that the top event (system failure) results from either sensor malfunction, logic solver errors, or valve actuation failure, breaking down these failures using logic gates like OR and AND.

This equation calculates the probability of failure of a basic event i over time t using the exponential distribution, where λi is the failure rate of the event.

Where:

Pi: Probability of failure of basic event i.

λi: Failure rate of basic event i (events per unit time).

t: Time period during which failure is considered.

Gate Probability for AND Gate:

$$P_{AND} = \prod_{i=1}^{n} P_i$$

This equation calculates the probability of failure for an AND gate in the fault tree, where all inputs must fail for the gate to fail.

P_{AND}: Probability of failure for the AND gate.

Pi: Probability of failure for each input basic event to the AND gate.

n: Number of input events to the AND gate.

Gate Probability for OR Gate:

$$= 1 - \prod_{i=1}^{n}(1 - P_i)$$

This equation calculates the probability of failure for an OR gate in the fault tree, where the gate fails if at least one input fails.

P_{OR}: Probability of failure for the OR gate.

Pi: Probability of failure for each input basic event to the OR gate.

n: Number of input events to the OR gate.

Minimal **Cut Sets Calculation**:

$$P_{Cut} = \sum_{j=1}^{m} P_{AND_j}$$

This equation sums the probabilities of failure for all minimal cut sets in the fault tree, where each cut set represents a unique combination of failures leading to the top event.

Where,

PCut: Probability of failure for a minimal cut set.

P_{AND_j}: Probability of failure for each minimal cut set AND gate.

m: Number of minimal cut sets.

Top Event Probability:

P_{Top}=P_{OR} for top-level OR gates, and similarly for AND gates.

This equation determines the probability of the top event failure in the fault tree, depending on whether the gate at the top level is an OR or AND gate.

Where,

PTop: Probability of the top event failure.

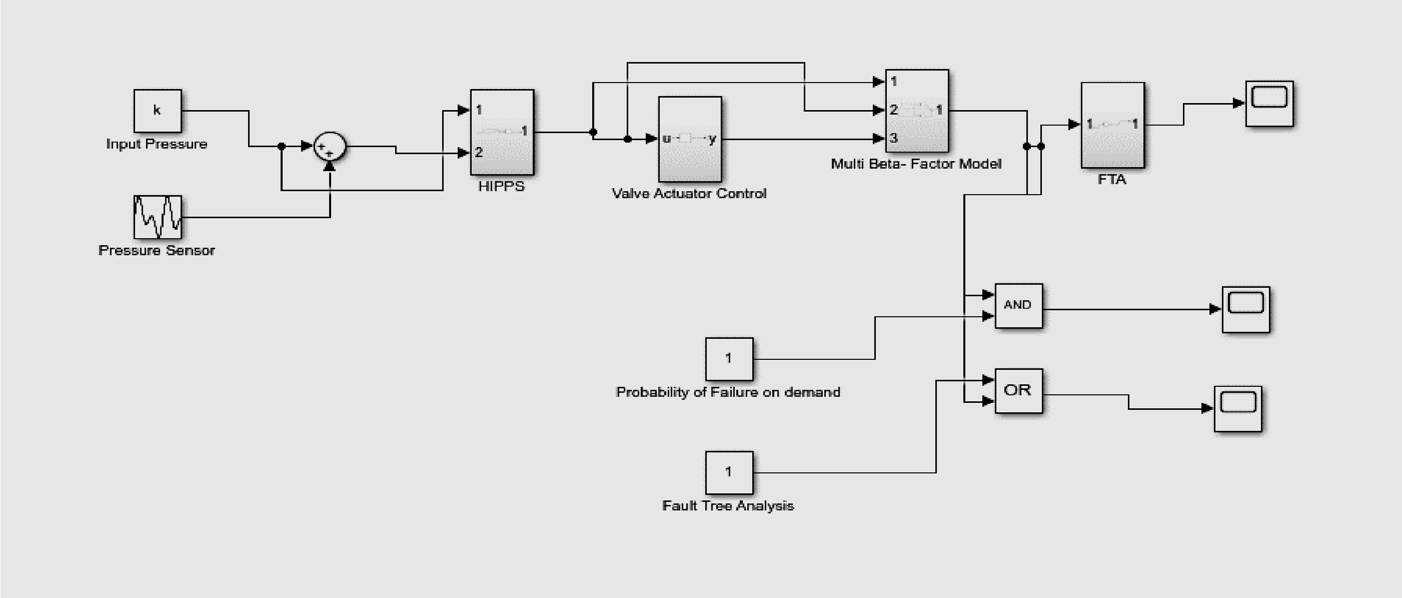

Figure 1: Simulink Diagram of the Multi Beta Factor Model System

Designed Parameters

Table 1: Parameters of the Research

Parameter	**Symbol**	**Value**	**Unit**	**Description**
Input Pressure	Pin	100	Bar	The pressure entering the system
Sensed Pressure	Psense	98	Bar	Pressure detected by the sensor
Failure Rate	Λ	0.001	1/hr	The failure rate of a component
Proof Test Interval	Ttest	8760	Hours	Time interval between proof tests
Probability of Failure on Demand	PFD	Calculated Value	-	Probability that the system will fail on demand
System Response Time	Tresp	1.5	Seconds	Time taken by the system to respond to input
Threshold Level	Tlevel	90	Bar	Pressure threshold for triggering HIPPS
Reliability	R	0.99	-	The reliability of the system
Beta Factor	Β	0.1	-	Common cause failure factor

DISCUSSION

Reliability of High Integrity Pressure Protection System (HIPPS) Model

In Figure 2, the graph illustrates the reliability of the High Integrity Pressure Protection System (HIPPS) over time, with a notable point where the reliability is shown to be 1 at 100 hours. This indicates that the system is fully reliable, meaning there is a 100% probability that the HIPPS will perform its intended protective function without failure during this period. The graph is a plot from Matlab/Simulink environment which presents the reliability of HIPPS. The graph suggests that up to 100 hours, the High Integrity Pressure Protection Systems (HIPPS) maintains its integrity and is capable of responding to demand without any degradation in performance. This could be indicative of the system operating within optimal conditions, where all components are functioning as expected, and external factors such as environmental stressors have not yet impacted the system's reliability. However, this perfect reliability at 100 hours also implies that the system has not yet encountered significant challenges or failures that would test its robustness. It is important to consider that while the reliability is perfect at this specific time, this may not remain constant as the system continues to operate. Ongoing monitoring and maintenance are crucial to ensuring that the High Integrity Pressure Protection Systems (HIPPS) continues to perform reliably beyond the 100-hour mark, especially as wear and other factors begin to influence its performance.

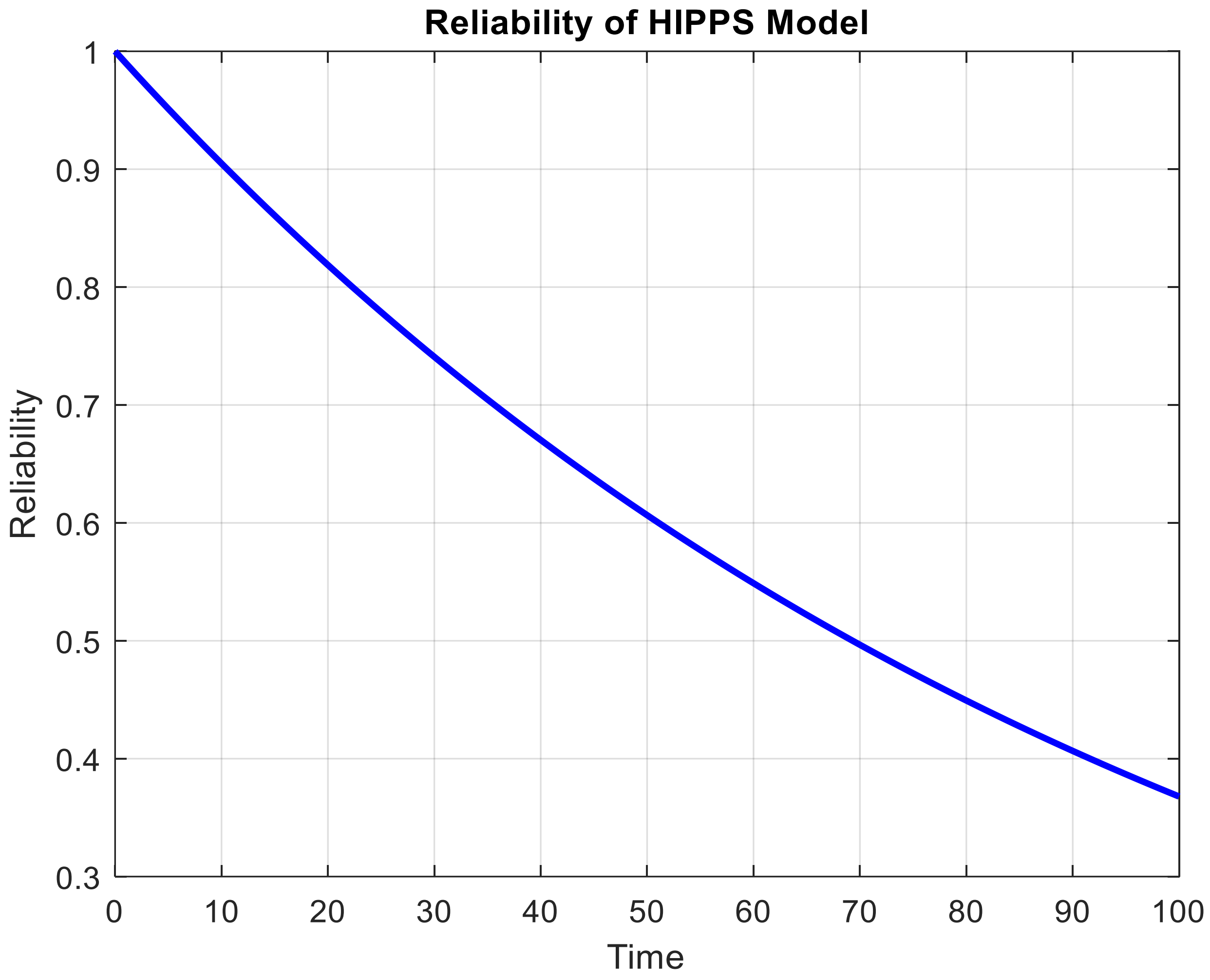

Figure 2 reliability of HIPPS Model

Probability of Failure on Demand (PFD) VS Time

In Figure 3, the graph depicting the Probability of Failure on Demand (PFD) versus time illustrates how the reliability of the High Integrity Pressure Protection System (HIPPS) changes over a 100-hour period. At the 100-hour mark. Figure 1 is a Matlab/Simulink simulation of probability of failure on demand over time. When the PFD is 0.62, indicating that there is a 62% chance that the system will fail to perform its intended function when demanded at this specific time. This level of PFD suggests that the High Integrity Pressure Protection Systems (HIPPS) is experiencing a significant degradation in reliability as time progresses. The increasing PFD over time reflects the cumulative impact of potential failures within the system, likely due to factors such as component wear, environmental stresses, or other operational conditions that affect system integrity. As the system continues to operate, the likelihood of failure increases, underscoring the importance of regular maintenance, monitoring, and potential system upgrades to ensure that the High Integrity Pressure Protection Systems (HIPPS) remains reliable. The 0.62 PFD at 100 hours is a critical indicator that the system's protective capabilities are compromised, which could pose significant risks in industrial environments where High Integrity Pressure Protection Systems (HIPPS) is relied upon to prevent catastrophic failures such as overpressure incidents.

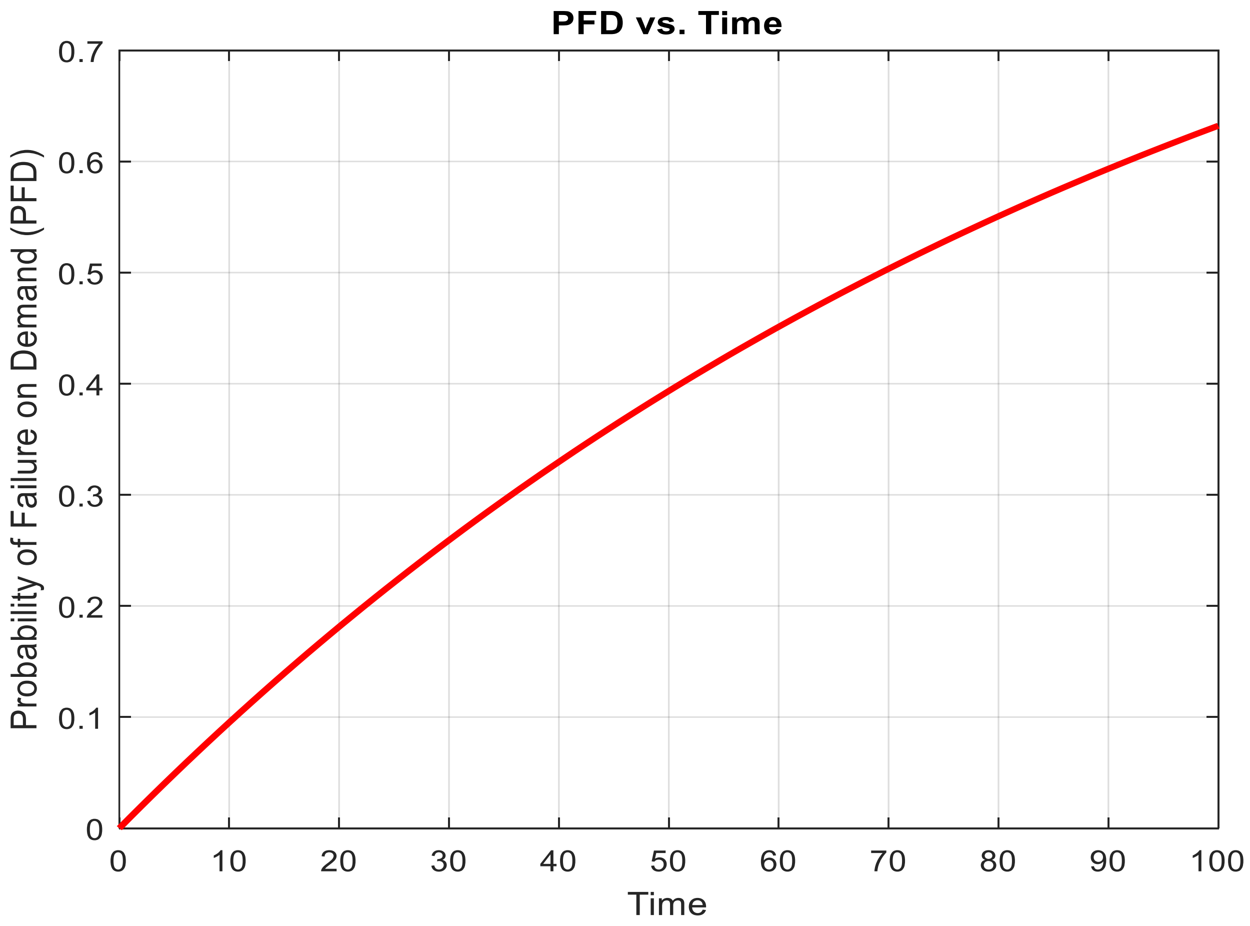

Figure 3 Probability of Failure on Demand (PFD) VS Time

MBF Model and Beta Factor Model Comparison

In Figure 4, The graph presents a comparison between the Probability of Failure on Demand (PFD) over time for a High Integrity Pressure Protection System (HIPPS) using the Multiple Beta Factor (MBF) model and the traditional Beta Factor model. At the 100-hour mark, the MBF model shows a PFD of 0.62, while the Beta Factor model shows a PFD of 0.78. This distinction highlights the different methodologies and assumptions underlying these models, particularly in how they address common cause failures (CCFs) within the system.

(Hours)

The MBF model's PFD of 0.62 at 100 hours reflects a detailed understanding of CCFs, recognizing that different system components might have varying susceptibilities to these failures. By incorporating multiple beta factors, the MBF model provides a more granular assessment of system reliability, acknowledging that failures in one component could lead to cascading failures in others, particularly in complex, real-world industrial environments. This results in a higher PFD, indicating a greater perceived risk of system failure under the MBF model.

Conversely, the Beta Factor model's PFD of 0.78 at the same time assumes a uniform probability of failure across all components due to CCFs. This simpler approach may be easier to apply but might underestimate the true risk if the system has complex interdependencies. The lower PFD might give a more optimistic view of reliability but could overlook critical failure mechanisms that the MBF model captures.

Ultimately, the difference in PFD values between these models at 100 hours underscores the importance of model selection in reliability assessment. If MBF model has a higher PFD suggests a need for more detailed analysis in high-risk environments, while the Beta Factor model might suffice in less complex scenarios. The choice of model depends on the specific requirements of the High Integrity Pressure Protection Systems (HIPPS) application and the level of detail needed to ensure accurate reliability predictions.

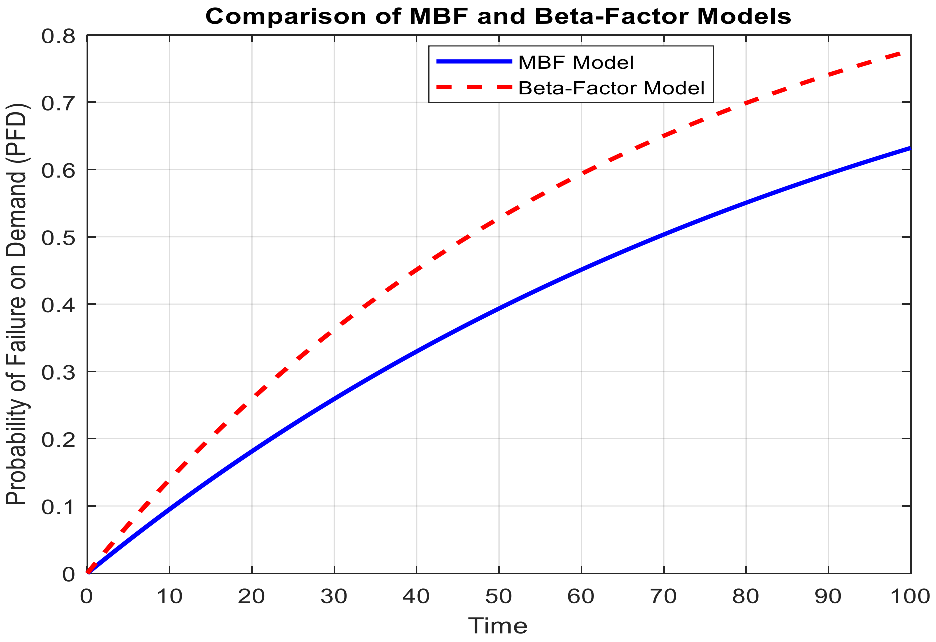

Figure 4: MBF and Beta Factor Comparison

Functional Performance Index

From figure 5, the functional performance index, ranging from 0.8 to 1.3 over 100 hours, reflects the varying levels of effectiveness of the system under analysis. This index measures how well the system performs its intended functions relative to an ideal or expected standard. A value of 1 typically indicates optimal performance, where the system operates as designed with no deviation from its intended function. Values below 1, such as 0.8, suggest underperformance, where the system fails to fully meet the expected functional criteria, potentially indicating inefficiencies, partial failures, or external factors affecting performance. On the other hand, values above 1, such as 1.3, may indicate over performance or that the system is functioning beyond its required capacity. This could suggest that the system is operating with greater efficiency or that it is being utilized in conditions that are less demanding than anticipated. Over a 100-hour period, this range in the functional performance index might reflect the system's response to varying operational conditions, including load changes, environmental factors, or the onset of wear and tear. It underscores the importance of monitoring and adjusting system parameters to maintain optimal performance throughout its operation.

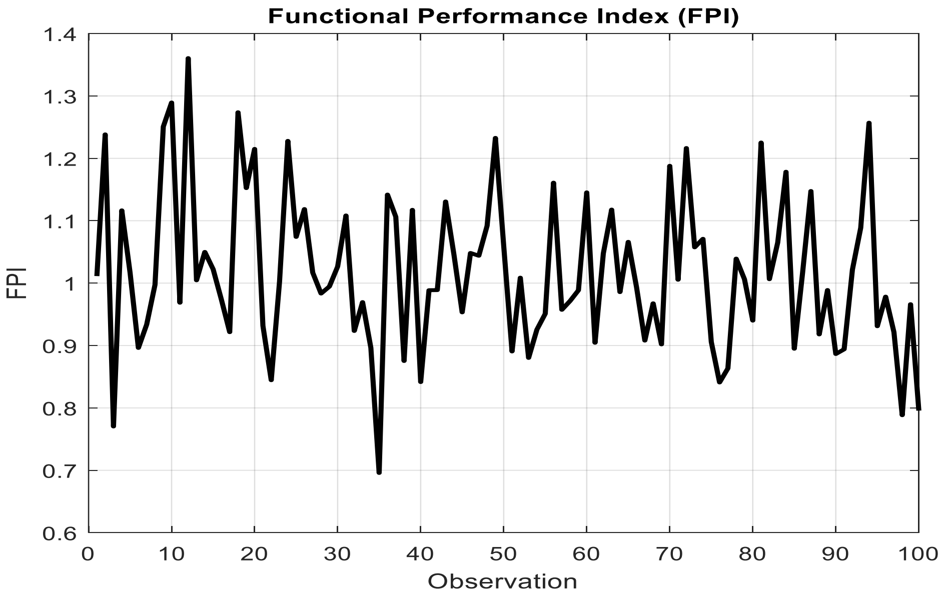

Figure 5: Functional Performance Index

Model Validation

Figure 6 demonstrates the model validation process, with the Mean Absolute Error (MAE) at 0.1% and the Root Mean Square Error (RMSE) at 0.13%. These metrics are crucial for assessing the model's accuracy and reliability.

The MAE of 0.1% indicates that, on average, the model's predictions deviate from actual values by just 0.1%. This low error rate reflects the model's high precision and suggests that the predictions are very close to the observed data, highlighting its effectiveness in capturing the true behaviour of the system.

The RMSE of 0.13% is slightly higher but still very low, showing that while the majority of the predictions are accurate, there are a few instances of slightly larger deviations. The fact that RMSE is only marginally higher than MAE indicates that these larger errors are minimal and do not significantly impact the overall model performance.

Overall, both metrics confirm that the model is highly accurate, effectively replicating real-world conditions with minimal error, and providing a reliable tool for analysing and predicting system performance.

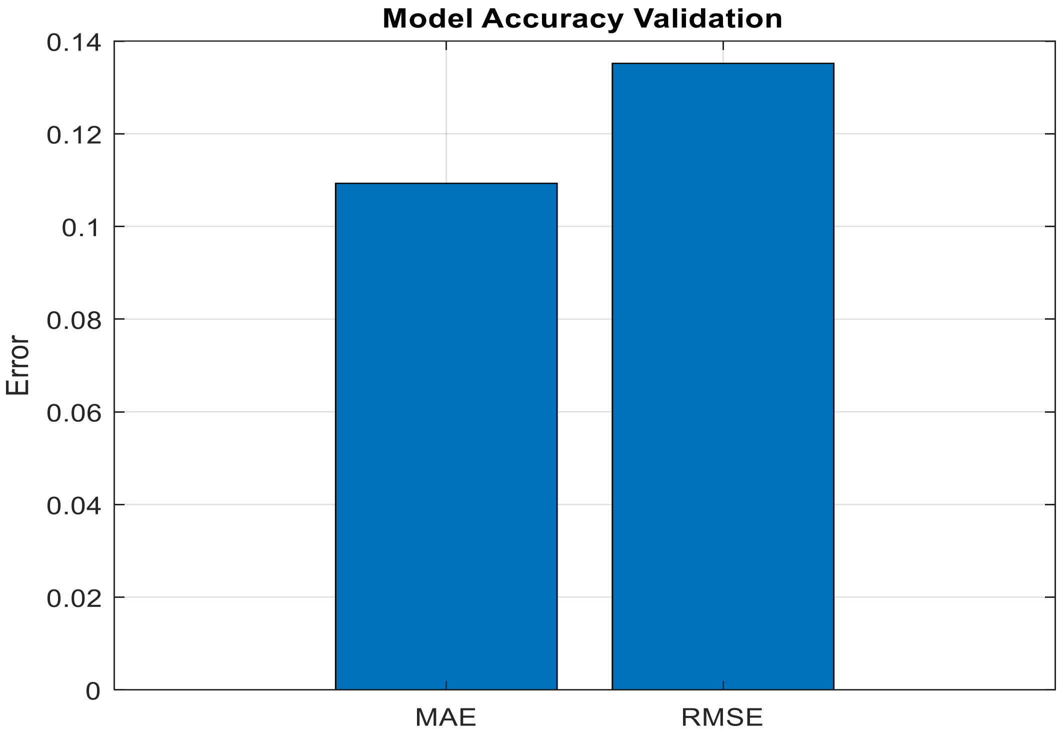

Figure 6: Model Accuracy Validation

Fault Tree Analysis (FTA) for High Integrity Pressure Protection System (HIPPS) Analysis

Figure 7 presents the Fault Tree Analysis (FTA) results for the High Integrity Pressure Protection System (HIPPS), showing probabilities associated with various events and the top event. In this analysis, the probabilities are as follows: \(p1 \) is 0.01, \(p2 \) is 0.02, and \(p3 \) is 0.15. Additionally, the probability of combined events \(p1 \) and \(p2 \) occurring together is 0.001, \(p2 \) and \(p3 \) is 0.00012, and the probability of the top event is 0.00013.

These probabilities reflect the likelihood of different failure scenarios within the HIPPS. The relatively low values for \(p1 \) and \(p2 \) suggest that these individual events are unlikely to occur, which generally indicates high reliability for these components. The higher probability for \(p3 \) indicates a greater likelihood of this particular event, which may be due to its nature or frequency of occurrence.

The combined probabilities \(p1 \) and \(p2 \), and \(p2 \) and \(p3 \), are extremely low, indicating that simultaneous occurrences of these events are rare. The top event probability, being slightly higher but still low, reflects the overall likelihood of system failure when considering all contributing factors. This indicates that, while the individual probabilities and their combinations are low, the overall system's reliability is robust, but still requires careful attention to manage and mitigate the risk of the top event.

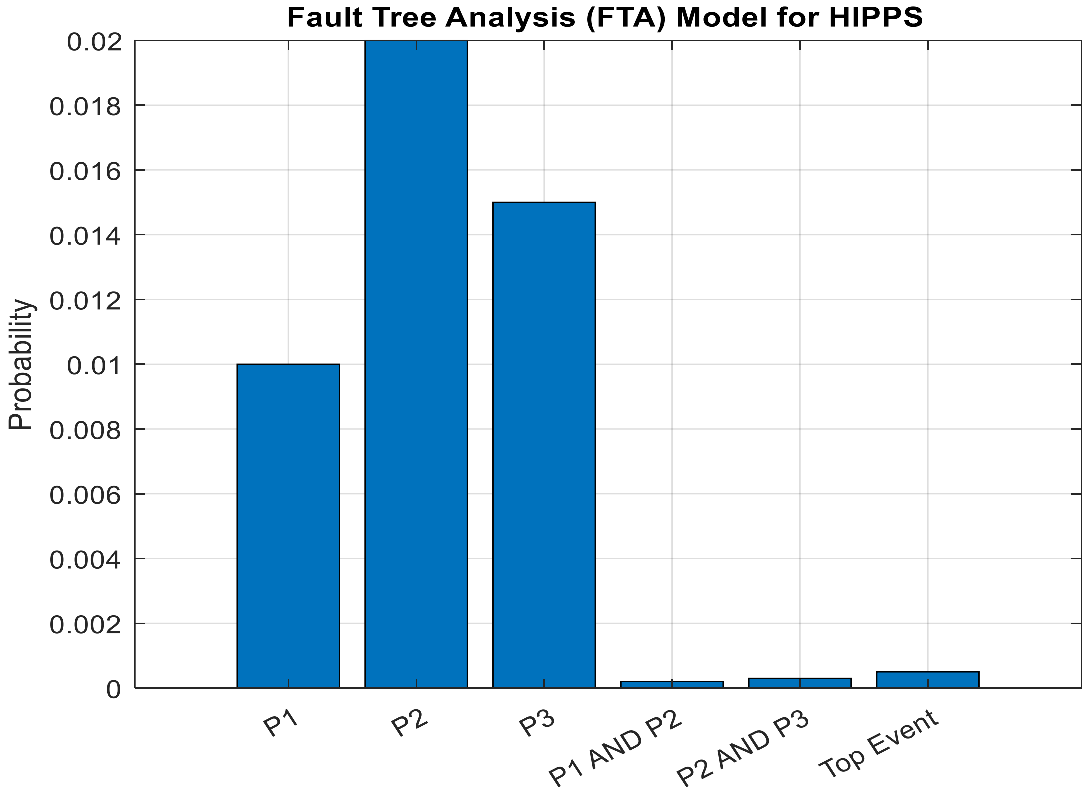

Figure 7: Fault Tree Analysis Model for HIPPS

Failure Rate Sequence on Common Cause Failures (CCF) for Multiple Beta Factor (MBF) Model

Figure 8 illustrates the failure rate sequence on Common Cause Failures (CCF) using the Multiple Beta Factor (MBF) model for a system with 10 different failure events. The failure rates for these events are provided as follows: 0.01 for the first event, 0.008 for the second, 0.006 for the third, 0.0051 for the fourth, 0.0048 for the fifth, 0.0042 for the sixth, 0.00028 for the seventh, 0.0021 for the eighth, 0.0019 for the ninth, and 0.0015 for the tenth event.

This sequence shows a generally decreasing trend in failure rates across the events. The initial failure rates are higher, starting at 0.01, but decrease progressively, reaching 0.0015 by the tenth event. This decreasing trend suggests that the likelihood of failures occurring due to common cause factors diminishes over time or across successive events.

The relatively high initial failure rates reflect a higher susceptibility to common cause failures early in the sequence, which may be attributed to factors such as system setup or early operational phases. As the sequence progresses, the lower failure rates indicate improved reliability or mitigation of risks, potentially due to system improvements or effective management of common cause factors.

Overall, this sequence provides insights into how failure rates change over time or across different failure instances within the MBF model, highlighting areas of higher risk and the effectiveness of risk reduction measures implemented over time.

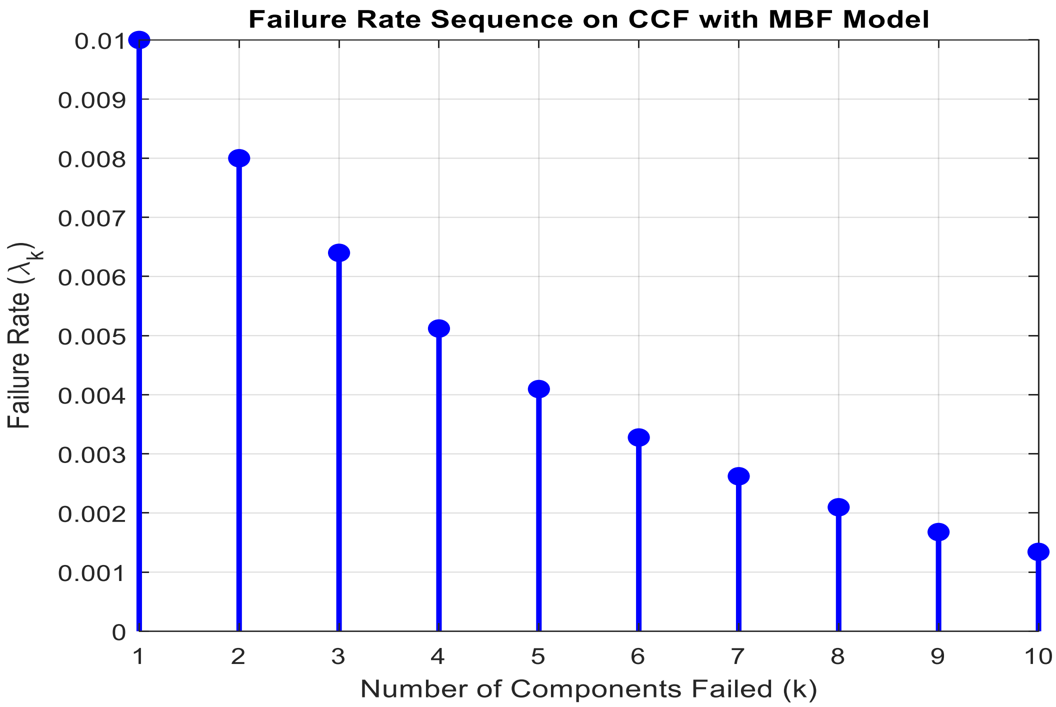

Figure 8: failure rate sequence on CCF with MBF model

Proof Test Interval

The average Probability of Failure on Demand (PFD) of 2.5 for a 5-year proof test interval indicates the mean likelihood that a High Integrity Pressure Protection System (HIPPS) will fail to perform its intended protective function when required, over the specified test period.

A PFD value of 2.5 suggests that, on average, the system has a 2.5% chance of failing to activate correctly in response to a demand over the 5-year interval. This figure reflects the combined effect of both inherent system reliability and the effectiveness of periodic proof tests conducted to ensure the system's operational integrity.

In practical terms, a PFD of 2.5 means that for every 100 demands placed on the system, there is an expected 2.5 failures. This level of PFD can be used to assess whether the system meets the required safety integrity levels (SIL) for its application. Systems with higher PFD values generally indicate a higher likelihood of failure and may necessitate improvements in design, maintenance, or testing practices to enhance reliability and safety.

Overall, this average PFD value helps in understanding the system's performance over time and guides decisions regarding necessary adjustments to maintain optimal safety standards.

CONCLUSION

This study has undertaken a comprehensive evaluation of High Integrity Pressure Protection Systems (HIPPS) using the Multiple Beta-Factor Model. The primary goal was to assess the effectiveness and reliability of High Integrity Pressure Protection Systems (HIPPS) in preventing overpressure incidents by analysing various failure modes and performance metrics. Through this rigorous analysis, several key insights have emerged. The research highlights that design deficiencies are a significant factor contributing to system failures. A thorough examination reveals that many failures can be traced back to inadequate design considerations, which often overlook critical operational and environmental conditions. This finding underscores the importance of incorporating detailed design evaluations to enhance system robustness.

Another major insight is the role of maintenance practices in ensuring the reliability of High Integrity Pressure Protection Systems (HIPPS). The study found that insufficient maintenance significantly impacts system integrity, emphasizing the need for a comprehensive maintenance strategy. Regular inspections and adherence to maintenance protocols are crucial for preventing system failures and ensuring long-term reliability.

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