Enhancing Reliability of Fuel Gas System at Combined Cycle Power Plant

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***Abstract* — This paper presents a methodology to boost the reliability of a combined natural gas and associated petroleum gas system (fuel gas system, FGS) for a gas turbine unit in a combined cycle power plant. The use of failure mode, effects, and diagnostic analysis (FMEDA) is proposed to avoid unplanned shutdowns of the power plant. This method identifies and evaluates potential types of failures, develops measures to reduce them, and establishes a new protection system. The system includes a gas analysis system (GAS), a shut-off valve system (SVS), a fuel gas controller (FGC), and workstations for an engineer and operator. The gas analysis system has two automatic subsystems with different measurement methods. One of them includes three gas chromatograph analyzers that operate according to the 2-out-of-3 voting. The results of gas chromatography and the diagnostic archive of alarms serve as the basis for analyzing the causes of possible failures. Reliability models were developed to confirm the effectiveness of using diagnostic data from gas analyzers within the gas subsystem. They employ a gas chromatography and a common fuel gas controller. The FMEDA findings demonstrate that a new safety interlock can be implemented without any additional financial outlay for software and hardware.**

***Index Terms* — Combined cycle power plant, diagnostic alarm, failure detection, associated petroleum gas supply, safety interlock, gas chromatography, reliability.**

I. INTRODUCTION

There is a growing interest in using reliability theory to enhance the availability, profitability, and safety of power generation. This is due to the unexpected production shutdowns caused by equipment failures at power plants leading to adverse events and their negative consequences for all stakeholders.

Combined cycle power plants (CCPPs) powered by gas and steam turbines are gaining significant traction. In regions with active oil production, associated petroleum gas (APG) is a byproduct, making its utilization particularly challenging. A viable solution to this problem is to use the CCPP running on APG.

Flaring gas is an inefficient utilization method, while burning it in gas turbine engines is a more environmentally friendly and cost-effective approach. This process involves cleaning the gas and connecting it to the system. In this paper, we consider the Brayton cycle, where associated petroleum gas is used in conjunction with a traditional fuel such as natural gas. The gas mixture is fed into the combustion chamber. APG is the primary fuel in this system, while natural gas plays a crucial role in stabilizing operational parameters when the APG composition fluctuates. This is essential, as compositional instability is the key challenge when using APG. In this method, the amount of APG and natural gas can be varied depending on demand. The basic operating principle was previously presented in [1].

The use of this mixture as a fuel, however, poses a number of challenges related to the quality of the gas supplied from different sources. The composition of APG, unlike that of natural gas, varies significantly depending on

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the field. The production process also influences the quality.

Therefore, gas analyzers are essential to monitor impurities in APG and prevent potential component failures in the gas turbine, which could negatively impact operational safety. This paper proposes a method for enhancing the reliability of a fuel gas system with gas chromatograph analyzers that enable failure diagnosis.

The method relies on diagnostic data obtained from gas analyzers, including gas chromatographs, and the history of alarms. The protection system, using FMEDA, prevents the unplanned equipment and plant shutdowns.

II. LITERATURE REVIEW

Enhancing the reliability of fuel gas systems at thermal power plants is critical for ensuring uninterrupted equipment operation, minimizing emergency situations, and extending service life.

Studies on automated control, preventive maintenance, and system redundancy made a significant contribution to the development of this field. A primary emphasis is placed on the implementation of automatic monitoring systems for gas pipelines and equipment.

According to [2], the use of intelligent diagnostic systems enables the early detection of failures and reduces the risk of emergency situations. Particular attention is also paid to the advanced materials and sealing technologies to ensure tightness and corrosion resistance, as confirmed by scientific studies.

In reliability management, predictive analytics algorithms and risk assessment models play a pivotal role, enabling the early detection of potential failures and the implementation of corrective measures [3, 4].

Of particular importance is the automation of the pressure and fuel flow monitoring systems, contributing to the stabilization of system operating parameters [5, 6]. Redundancy and automated system recovery significantly enhance overall resilience [7]. The implementation of backup components and automatic gas re-feeding helps prevent downtime and reduce the energy losses.

A number of studies emphasize the importance of integrated solutions that include the modernization of technical equipment, implementation of the automatic control systems, and the predictive maintenance [2, 6]. The modeling and artificial intelligence methods in the predicting system are instrumental in increasing the reliability and operational efficiency [8].

III. PROPOSED RELIABILITY IMPROVEMENT BASED ON FAILURE MODE, EFFECTS, AND DIAGNOSTIC ANALYSIS

Failure mode and effects analysis (FMEA); failure mode, effects, and criticality analysis (FMECA); and failure mode, effects, and diagnostic analysis (FMEDA) are important tools for analyzing the reliability and safety of systems, processes, and products. Each of them is considered in more detail in [9].

1. FMEA is a systematic method used to identify potential failure modes in a system, process, or product and to evaluate their consequences [10].

The main steps of FMEA include:

– identifying the possible scenarios (modes) through which the system could fail;

– assessing the consequences of each failure mode for the system and users;

– identifying the causes that could lead to each failure mode;

– assessing the risk levels using criteria such as the probability of failure, the severity of its consequences, and the possibility of its detection.

2. FMECA is a more complex method that incorporates all the steps of FMEA, as well as a criticality assessment of each failure mode [10]. Criticality is determined based on the probability of failure, its consequences, and the ability to detect it.

FMECA is an extended version of FMEA that includes the criticality analysis. This method complements the FMEA process with a step evaluating the importance of each failure mode in terms of its impact on the system or process. This evaluation enables the identification of the most critical failure modes that require special attention.

3. FMEDA is another extension of FMEA [10]. This method includes an analysis of the system diagnostic capabilities, including its capacity to detect and diagnose failures. This analysis enables the assessment of the system's response effectiveness regarding potential failures and the mitigation of their consequences.

FMEA, FMECA, and FMEDA are widely used in managing risk and ensuring operation reliability. These methods enable the identification of potential problems early in the development and implementation of products or processes, which, in turn, contributes to improved quality and safety.

To validate the methodology, FMEDA was additionally conducted. This analysis is a key tool for assessing functional safety and reliability in power systems, particularly in the critical areas.

Leading global power equipment suppliers such as Siemens, ABB, and General Electric (GE) actively use FMEDA to ensure compliance with stringent industry standards such as IEC 61508 [11, 12].

FMEDA is applicable to a wide range of power equipment and systems. It is used to analyze sensors and transmitters, such as pressure and temperature sensors, which play a pivotal role in the control and protection systems. FMEDA is also applied to actuators, valves, control systems, and controllers, as well as high-voltage equipment, including switchgear and transformers. Furthermore, FMEDA is in demand in the realm of process automation, embracing automated process control systems (APCS) and programmable logic controllers (PLC), particularly within the nuclear and thermal power industries [13].

The leading manufacturers widely use this method. In particular, ABB employs this method to assess the functional safety of its devices, certifying them according to the IEC 61508 standard [13].

Based on FMEDA, the company calculates safety metrics such as the safe failure rate and the probability of failure on demand. Specifically, for pressure transmitters used in critical systems, FMEDA determines the failure rate, failure modes (safe or dangerous, detected or undetected), and the capability for self-diagnosis.

Siemens, in turn, develops automated FMEDA processes to reduce the time and effort required for analysis. The company applies this method to assess the safety of chips, boards, and integrated circuits, enhancing the reliability of control systems, particularly in automotive applications according to the ISO 26262 standard [12]. In the context of larger-scale solutions, FMEDA serves as an integral component of verification and validation procedures, ensuring operational safety throughout the product lifecycle.

While industrial giant GE does not publicly disclose detailed information about its FMEDA reports, the company is known to employ similar methods to improve the reliability of equipment such as turbines and generators. Specifically, GE uses advanced analytics and software tools to predict and prevent failures directly related to FMEDA concepts. By analyzing potential failures and their consequences, GE optimizes the maintenance strategies and minimizes the unexpected downtime.

The FMEDA process in the energy sector involves the collection of component data from a variety of sources, including failure rate databases such as OREDA, supplier inputs, and operational metrics. Then a failure mode is analyzed, identifying all potential causes of failure, such as short circuits or open circuits. The effects of each failure on the overall system operation are subsequently assessed.

FMEDA is therefore an integral component of the power equipment design and operation lifecycle, particularly at leading companies such as Siemens, ABB, and GE. This tool ensures a high level of safety and reliability, minimizing the risk of failures and ensuring compliance with stringent safety standards in this critical area.

Based on the methods studied, we selected FMEDA to calculate the failure rate for end systems, including single devices or a group of devices that perform a more complex function.

FMEDA was originally developed to analyze electronic devices. Currently, it is applied to the mechanical and electromechanical systems.

The main steps in calculating mean time between failures (*MTBF*), safety integrity level (*SIL*), and availability using FMEDA involve creating a FMEDA table. This table contains the data on effect, criticality, diagnosis, alongside warning, and is compiled for each system component.

First, the failure rate (λ) of a component is categorized based on consequences and diagnostics: λ^{DUC} is the detected unavoidable critical failure; λ^{DUN} is the detected unavoidable non-critical failure; λ^{DDC} is the detected dangerous critical failure; λ^{DDN} is the detected dangerous non-critical failure.

The overall failure rates for each category for the entire system are calculated by summing the corresponding failure rates for all components:

$$\lambda_{total}^{DUC} = \sum \lambda_i^{DUC}\,, \tag{1}$$

$$\lambda_{total}^{DUN} = \sum \lambda_i^{DUN}\,, \tag{2}$$

$$\lambda_{total}^{DDC} = \sum \lambda_i^{DDC}\,, \tag{3}$$

$$\lambda_{total}^{DDN} = \sum \lambda_i^{DDN}\,. \tag{4}$$

The *MTBF* for a system is calculated using formula (5):

$$MTBF = \frac{1}{\lambda_{total}} = \frac{1}{\sum \lambda_i}\,, \tag{5}$$

The safe failure fraction (SFF) is the proportion of safe and diagnosable dangerous failures relative to all failures that affect safety. It is calculated as follows:

$$SFF = \frac{\sum \lambda^{DUN} + \sum \lambda^{DDN} + \sum \lambda^{DDC}}{\sum \lambda^{DUC} + \sum \lambda^{DUN} + \sum \lambda^{DDC} + \sum \lambda^{DDN}}\,. \tag{6}$$

The probability of demand average failure (PFD_{avg}) is the average probability of failure on demand for systems that operate under low demand. It is calculated as follows:

$$PFD_{avg} = \lambda^{DUC}\left(\frac{T_1}{2}\right) + \lambda^{DDC}\left(\frac{MTTR + T_{nc}}{T_1}\right), \qquad (7)$$

where T_1 is the interval between regular tests, $MTTR$ is the mean time to recovery, T_{nc} is the time spent in an inoperative state due to a failure.

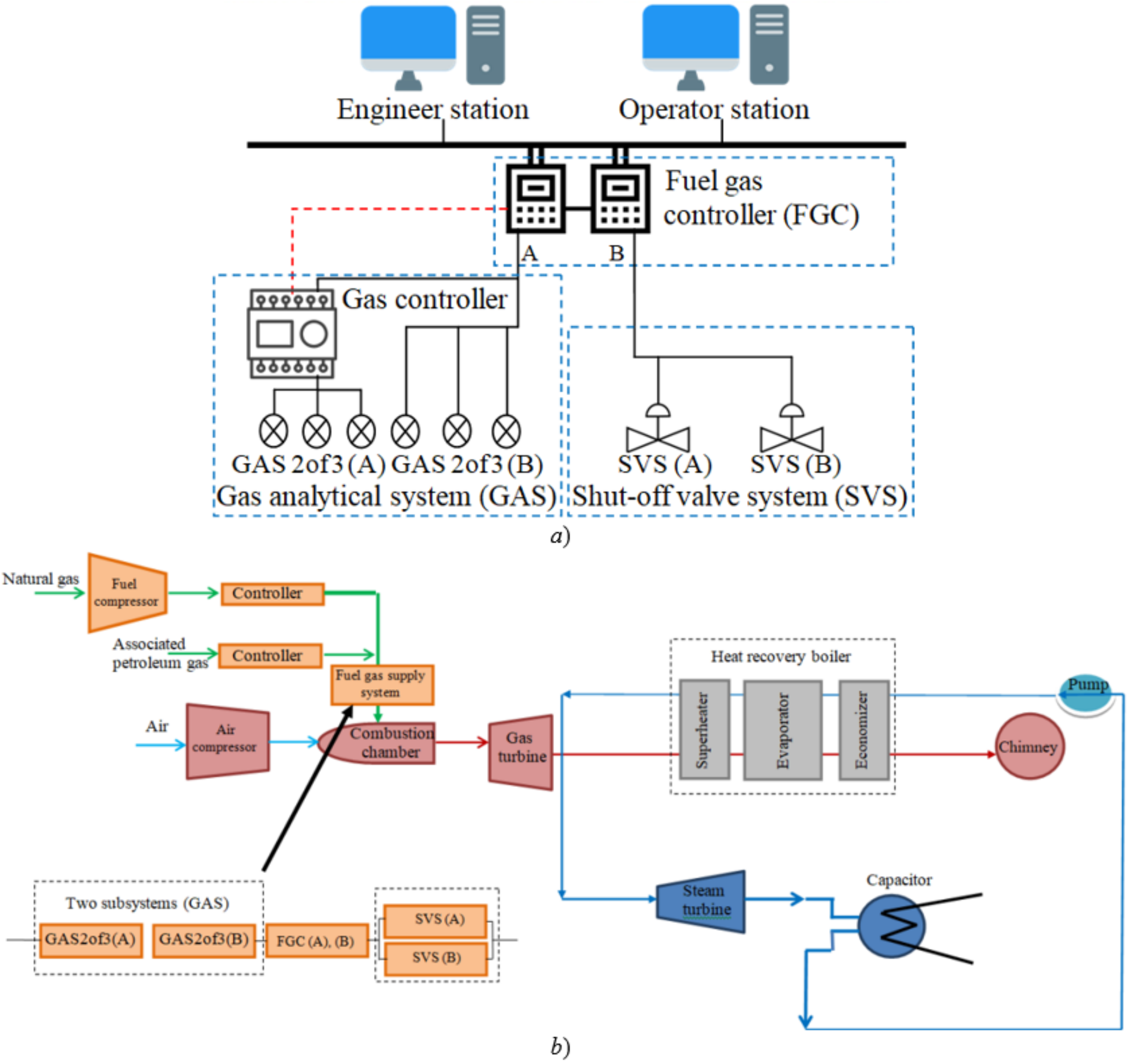
The calculated SFF and PFD_{avg} values are used to determine the achievable SIL, which depends on the system architecture and its operating mode.

The system is designed to operate using a Brayton cycle configuration and utilizes a dual-fuel combustion process that blends associated petroleum gas (APG) and natural gas.

The gas turbine unit (GTU) parameters are based on the specifications of a SIEMENS SGT-1000F gas turbine. In the nominal operating mode, the inlet temperature is 1583 K, the outlet temperature is 856 K, and the pressure rise is 15.8.

Several operating modes are considered by varying the gas flow rate, with the exhaust gas temperature ranging between 700 and 873 K. Efficient gas mixing depends on the uniform levels of temperature and pressure, which is why natural gas is additionally supplied by a compressor.

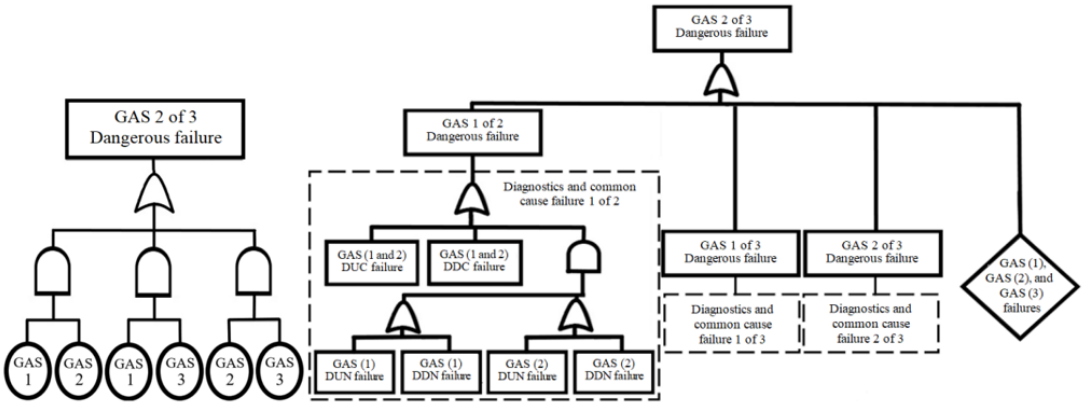
Full utilization of APG (1.48 kg/s) eliminates the need for natural gas. If the thermal parameters exceed the normal level, natural gas is supplied and regulated according to the parameters monitored by the Wobbe index sensor.



a)

b)

Fig. 1. Diagrams of the structural reliability (a) and the gas turbine system architecture (b) for the studied FGS.



a) *b*)

Fig. 2. Fault tree of the GAS subsystems in the 2-out-of-3 voting algorithm without failure diagnostics (a) and with failure diagnostics (b).

The air flow rate is up to 188 kg/s, ensuring the system operability in various modes. As gas volumes increase to 1.46 and 1.48 kg/s, respectively, and at an air flow rate of 150 kg/s, the inlet temperature remains below the permissible limits [1].

Based on the initial data, we investigate the system architecture presented in Fig. 1(a). It includes a gas analysis system (GAS), a shut-off valve system (SVS), a fuel gas controller (FGC), and engineer/operator stations.

The system has two GAS subsystems operating based on a 2-out-of-3 voting algorithm. The first subsystem, the 2-out-of-3 GAS (A), uses three remote gas analyzers of the gas chromatograph. The second subsystem, the 2-out-of-3 GAS (B), utilizes integrated gas analyzers operating with non-dispersive infrared (NDIR) sensors [14].

Gas chromatograph analyzers provide failure diagnostics, while NDIR gas analyzers do not. A reliability block diagram for the system under study is presented in Fig. 1(b) for the purpose of reliability analysis. Implementation of the fuel gas system primarily requires monitoring the system load and mandatory coordination of supply parameters for both natural and fuel gas at the point where both fuels are already mixed. The probability of success for the studied FGS ($P(t)_{\mathrm{FGS}}$) can be expressed using an exponential distribution as follows:

$$P(t)_{\mathrm{FGS}} = P(t)_{\mathrm{GAS}} P(t)_{\mathrm{FGC}} P(t)_{\mathrm{SVS}}, \tag{8}$$

$$P(t)_{\mathrm{GAS}} = P(t)_{\mathrm{GAS}(2of3)(\mathrm{A})} P(t)_{\mathrm{GAS}(2of3)(\mathrm{B})}, \tag{9}$$

$$P(t)_{\mathrm{FGC}} = P(t)_{\mathrm{FGC(A)}} P(t)_{\mathrm{FGC(B)}}, \tag{10}$$

$$P(t)_{\mathrm{SVS}} = P(t)_{\mathrm{SVS(A)}} + P(t)_{\mathrm{SVS(B)}} - P(t)_{\mathrm{SVS(A)}} P(t)_{\mathrm{SVS(B)}}, \tag{11}$$

$P(t)_{\mathrm{GAS}}$, $P(t)_{\mathrm{FGC}}$, and $P(t)_{\mathrm{SVS}}$ represent the probabilities of successful execution of the failure diagnostic functions for the GAS, FGC, and SVS, respectively.

The capacity of the GAS subsystem to effectively detect component failures is a key factor in improving system availability and safety.

In the 2-out-of-3 voting, there are two main types of fault trees for the GAS subsystem: with failure diagnosis and without it. These diagrams in Fig. 2(a) and 2(b) are true representations of reality.

Reliability models of the GAS subsystem with failure diagnostics must consider two key aspects: common cause failures (CCF) in the 2-out-of-3 voting lists and failures of automatic diagnostic functions.

Since any component can be either successful or unsuccessful, $P(t)$ is the complement of $F(t)$ to unity. The analytical reliability estimate $P(t)$ for the system and the probability distribution of random time-to-failure variables are assumed to be exponential.

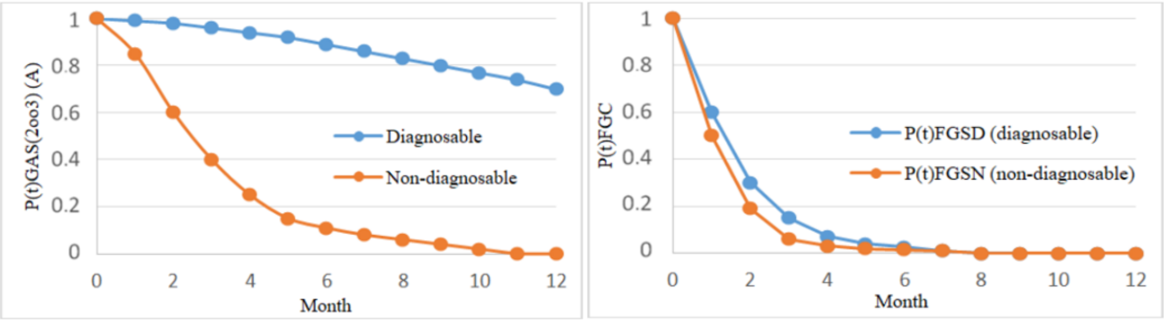
The success probabilities for the GAS subsystem without failure diagnosis, the fuel gas controller, and the shut-off valve system are formulated as follows [15]:

$$P(t)_{GAS(2of3)(\mathrm{A}),w/0,\mathrm{Diag}} = 3e^{-2\lambda^{D} t_{ti}} - 2e^{-3\lambda^{D} t_{ti}}, \tag{12}$$

$$\begin{aligned} P(t)_{GAS(2of3)(\mathrm{A}),w,\mathrm{Diag}} = 1 - 3\Big[&(1 - e^{-\lambda^{DUC} t_{ti}}) + (1 - e^{-\lambda^{DDC} t_{at}}) + \\ &+ ((1 - e^{-\lambda^{DUC} t_{ti}}) + (1 - e^{-\lambda^{DDC} t_{at}}))^{2} \Big], \end{aligned} \tag{13}$$

$$P(t)_{FGC(A)} = P(t)_{FGC(\mathrm{B})} = e^{-2\lambda^{D} t_{ti}}, \tag{14}$$

$$P(t)_{SVS(A)} = P(t)_{SVS(\mathrm{B})} = e^{-2\lambda^{D} t_{ti}}, \tag{15}$$



a) *b)*

Fig. 3. Reliability models (a) for the GAS subsystem with/without failure diagnostics; (b) for the FGC with/without failure diagnostics.

where t_{ti} is the time interval between tests or checks of the system or component condition. It can be established for regular reliability monitoring and the identification of potential problems before failures; t_{at} is the mean time required to repair a system or component after its failure. This indicator is important for assessing system availability and planning its maintenance [16].

These parameters are often used in reliability analysis and maintenance management to optimize diagnostics and repair processes, while minimizing equipment downtime.

This study examined reliability models of the GAS subsystem, as well as the FGS, operating with and without failure diagnostics. Graphs illustrating these models are presented for clarity.

Figure 3(a) shows the graphs corresponding to the reliability models of the GAS subsystem with and without failure diagnostics.

Substituting equations (12), (14), and (15) into equation (8), as well as equations (13), (14), and (15) into equation (8), we can obtain the reliability models for the FGS with and without failure diagnostics.

The results show that the failure diagnostic information provided by the gas chromatograph analyzers enhances the reliability of both the 2-out-of-3 GAS (A) and the FGC.

Design optimization relying on the FMEDA results enables the estimation of the initial *MTBF* based on statistical data and operating experience. Following the FMEDA, critical failure points were identified, facilitating modifications, the use of more reliable components, or the incorporation of redundancy.

The calculations demonstrated a 20% increase in *MTBF* and the system's upgrade from *SIL*2 to *SIL*3, exhibiting higher safety and reliability. Increased diagnostic coverage was achieved through the development of new diagnostic algorithms that detect a greater number of potentially dangerous failures, thereby reducing the frequency of undetected dangerous failures.

Optimization of maintenance is a key factor in ensuring the reliability and efficiency of systems. Before the integration of FMEDA, maintenance followed prescriptive regulations rather than actual operational state of the equipment. However, after conducting FMEDA and investigating the most probable failure modes and their possible origins, more effective maintenance strategies were formulated considering the equipment condition. This approach reduced the mean time to restore (*MTTR*) and

TABLE 1. FMEDA for the Studied Fuel Gas System

Case	Gas analysis system		Fuel gas composition		Gas turbine effect	Criticality	Diagnosis	Remark
	Normal	Error	Normal	Abnormal				
1	O	–	O	–	Normal state	–	Detectability	Correct state
					Triggering	Safe	Detectability	Impossible state
2	O	–	–	O	Normal state	Dangerous	Detectability	Impossible state
					Triggering	Safe	Detectability	Correct state
3	–	O	O	–	Normal state	Safe	Detectability	Diagnosis usage
					Triggering	Safe	Detectability	Correct state
4	–	O	–	O	Normal state	Dangerous	Detectability	Impossible state
					Triggering	Safe	Detectability	Correct state

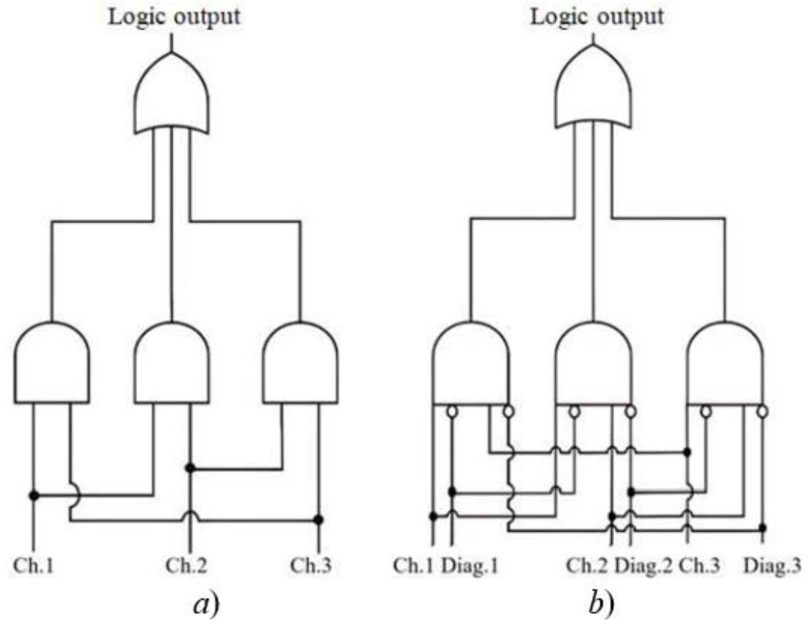


Fig. 4. Logic schemes of the existing safety interlock (a) and newly designed safety interlock (b). Ch.1, Ch.2, and Ch.3 are FGC input channels for the primary signals from the three gas analyzers. Diag. 1, Diag. 2, and Diag. 3 represent the FGC input channels designed to receive diagnostic information from the three gas analyzers.

increased the system availability.

System availability is defined as the ratio of the *MTBF* to the sum of the mean time between failures and the *MTTR*. The obtained results of FMEDA are presented in Table 1.

The analysis revealed the potential to improve the reliability of GAS and ensure the normal operation of the fuel gas composition in case 3. However, the standard protection system of the existing FGS would fail to activate in the absence of adequate failure diagnostics.

During project implementation, this model undergoes validation, a multi-stage process confirming that the model's reliability metrics correspond to actual operational data. This enables the model to be used for safety assessment.

At this stage, the model is verified by comparison with existing FMEDA systems (e.g., the project conducted by United Electric Controls in Watertown, MA, USA, under contract no. Q20/06-041). The project report, prepared by Brad Hitchcock, is available under UEC 20/06-041 R001, version V1, revision R1, November 20, 2020. This report confirms that the system has become more reliable due to the inclusion of factors that minimize the likelihood of overlooking errors that could lead to undetectable, dangerous failures [17–19]. To prevent an unwanted shutdown, a new protection system was developed without

TABLE 2. Results of Checking the Logic Operation of the Existing FGS Safety Interlock without Failure Diagnostics

Situation	Ch.1	Diag. 1	Ch.2	Diag. 2	Ch.3	Diag. 3	Logic Output
Operating	0	–	0	–	0	–	Normal
Ch. 1 error	1	–	0	–	0	–	Normal
Ch.1 and Ch. 2 error	1	–	1	–	0	–	Shutdown

*Operating = 0, Error = 1

TABLE 3. Results of Testing the Logic Operation of the Newly Designed FGS Safety Interlock with Failure Diagnostics

Situation	Ch.1	Diag. 1	Ch.2	Diag. 2	Ch.3	Diag. 3	Logic Output
Operating	0	0	0	0	0	0	Normal
Ch.1 error	1	1	0	0	0	0	Normal
Ch.1 and Ch.2 error	1	1	1	1	0	0	Normal

*Operating = 0, Error = 1

additional software and hardware modifications for the LNG plant with a failure diagnostic system (Fig. 4) [20].

IV. RESULTS

Table 2 presents the results of testing the logic operation of the existing FGS safety interlock without failure diagnostics. Table 3 shows the results of testing the logic operation of the newly developed FGS safety interlock using failure diagnostics.

Channels 1-3 (Ch. 1, Ch.2, and Ch.3) represent the FGC input channels designed to receive output signals from the three gas analyzers of the GAS subsystem. The FGC input channels designed to receive diagnostic information from the three gas analyzers are denoted by Diag. 1, Diag. 2, and Diag. 3.

The developed protection system successfully adapts to the operating conditions of the GAS subsystem in a 2-out-of-3 configuration, providing reliable protection against potential failures. Therefore, the new safety interlock based on the failure diagnostic capabilities of the gas chromatograph analyzers enhances the reliability of the tested FGS.

V. CONCLUSION

The study revealed the importance of FMEDA for the reliability analysis of complex systems, such as gas analysis and fuel gas control systems in power systems.

The use of a mixture of associated petroleum gas and natural gas in combined cycle gas turbines is instrumental in boosting the efficiency, environmental safety, and fuel diversification, while facilitating flexible fuel management, cost reduction, and enhancement of operational efficiency. The utilization of APG reduces oil production waste, lowers emissions, and contributes to sustainable development. Technologies for controlling the mixture composition are essential for stabilizing operation of turbines, extending their service life, and mitigating risks. The use of APG is also conducive to the expansion of the domestic fuel market and reduces dependence on imports, especially in the oil-producing regions of Russia. Overall, combining natural and associated petroleum gas boosts the efficiency, safety, and eco-friendliness of power plants.

This methodology allows for both the assessment of component failure rate and the identification of key aspects affecting the overall reliability of the system. The analysis shows that the implementation of diagnostic functions using gas analyzers significantly enhances failure detection efficiency, as well as availability and safety of the entire system.

The developed protection system, based on failure diagnostic capabilities, is an important step toward minimizing unplanned downtime and improving the reliability of the power plants. A comparative analysis of the existing and new safety interlocks confirmed the advantages of the diagnostic functions, creating promising avenues for optimizing maintenance and reliability management processes.

Thus, the findings from the study demonstrate the necessity of integrating advanced diagnostic methods into design and operation of complex technical systems to enhance their reliability and safety.

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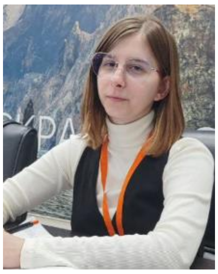

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