Analysis and Diagnosis of Control and Protection System of Gas Turbine Using the Fault Tree and Bayesian Network

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Abstract – *This paper presents a model for predicting the risk of failure of gas turbine control and protection system. Using a traditional analysis method and an artificial intelligence method, we combined Fault Tree Analysis (FTA) with a Bayesian Network (BN) to obtain accurate results for system failures. While the Fault Tree Analysis allows us to know the causes that lead to the system failure, by listing the information available in the fault tree in addition to the data previously stored by the experts, the Bayesian Network method allows us to quantify the impact of each cause on the gas turbine control and protection system, to take corrective actions to prevent them from happening in the future.*

***Keywords**: Bayesian Networks, Fault Tree, Control and Protection System of Gas Turbine, Diagnosis*

I. Introduction

Gas turbines play an essential role in the industry. It is a type of internal combustion engine that converts the energy of fuel into mechanical energy drive machinery such as gearbox, compressors and generator that produces the electrical energy. Gas turbines are also commonly used in other fields such as aviation. However, gas turbines are subject to various failures and malfunctions that can impact their efficiency and safety. therefore, it is important to implement a robust control and protection system to ensure its reliability and integrity. We can apply certain analysis methods (traditional and artificial intelligence analysis methods) to simplify this system and discover the problems it encounters during its operation. A traditional analysis method can be applied in all industrial fields such as aeronautics, nuclear energy, chemical manufacturing, etc. These methods are generally used to analyze simple systems and determine the type of possible failure modes, such as Fault Tree Analysis (FTA) which works on a top-down deductive approach that starts from a top level event (e.g., a system failure) and works backwards to identify the contributing factors and underlying causes (representing a series of intermediate and main events) through a graphical representation of the fault tree, the FTA method is more appropriate for identifying possible failure modes (in qualitative terms). However, this method needs more support to obtain logical and close to reality results, while Bayesian network BN is more suitable for modeling conditional probabilities of events in a probabilistic framework, as they allow us to predict the impact of each event on the system (in terms of quantity) based on raw data from experts, BN can offer greater flexibility and accuracy, especially when dealing with large volumes of complex systems and contexts.

Many previous studies have analyzed gas turbine control and protection system failures by conventional methods such as Failure Mode and Effect Analysis FMEA [1], Root Cause Analysis RCA [2], and fault tree analysis FTA [3]. These methods have been widely used in the industry to identify the causes of faults and develop appropriate mitigation strategies. Some studies have also analyzed the failure of the gas turbine control and protection system by means of artificial intelligence such as machine learning algorithms such as neural networks analysis [4, 5], fuzzy logic [6, 7, 8]. have been used to develop fault detection and diagnosis models and Bayesian Network [9], and a predictive control algorithm [10]. Also, recent research has focused on combining traditional methods with AI-based methods to develop more robust and accurate models for fault detection and diagnosis such as FMEA/FTA and Bayesian Network

[11], FMECA and the FT [12], Fuzzy FMEA [13], fault tree analysis and Markov chains [14], fault tree with BN [15]. These hybrid models can leverage the strengths of both approaches to achieve better performance.

Manufacturers such as General Electric, Baker Hughes and Siemens have also worked to develop a control and protection system consisting of several interconnected subsystems, where the failure of one of them leads to failure of gas turbines such as the system Bentley Nevada system, lubricating oil system, cooling and sealing air system, Turbine enclosure ventilation system, etc. which allows us to know the increase in temperature, high vibration, rotational speed, oil pressure and others, by using a different sensors such as thermocouple, RTD, etc. To measure and alert on each defect that exceeds the permissible limit in the system and send it to the control room to take preventive measures. It also relies on the strategy of renewal and component engineering according to the latest research and the results obtained through the tests that it conducts in its industrial laboratories and workshops to are aimed at improving the efficiency of the gas turbines.

This study, we can predict and know the potential faults and their impact on the system before they occur. This is done by studying all the subsystems that would help us to know all the sequential events that cause gas turbine failure. Through integrate one of the traditional methods, represented by the fault tree (FT), and the artificial intelligence (AI) method, represented by the Bayesian network (BN). This approach also allows us to analyze all systems, whether simple or complex, and to obtain better results in terms of identifying the quality and quantity of possible causes of system failure. This integration can improve the accuracy of fault diagnosis, enable more effective mitigation strategies, and make decisions.

II. Control and Protections Systems Description of Gas Turbine

Modern gas turbines protection and control systems use several systems to provide the necessary protection to the unit such as Ethernet based computer networks to provide paths for data flow between controllers, Human Machine Interfaces (HMI), input/output devices, timers, etc. Are used to monitor and provide operator commands to the control system, also are used as data archiving systems to store, and display power plant data. Many plants have hardware systems to protect such as lube oil, hydraulic oil, control oil, filter house system, etc. It acts as an on-site monitor (OSM) to transmit data between the controller and input/output circuit boards via UDH and also between HMIs, Distributed Control System (DCS), etc. With this huge amount of monitoring and protection systems, gas turbines remain vulnerable to failure due to several unknown factors.

The Control System Networks is an integration of a gas turbine components and network adapters (computers, time machines, etc.). Each component of system has a limited or recommended upgrade cycle life by the manufacturer, to mitigate undesirable events through product updates in the form of corrective actions and recommendation such as deploy end of Life equipment or update them due to technology maturity.

Therefore, the analysis and diagnostic of gas turbine control system network are important to reduce it failure. Through put an effective plan uses a combination of robust maintenance procedures, employee training, awareness, and modern technology.

We recommend this approach to manage the risks faced by gas turbines and include a proactive assessment based on our stock of information about the control and monitoring system network. This includes monitoring and planning for short- and long-term actions to protect the system from all unwanted risks.

Proposed actions include basic examination of control and protection system components such as hardware and software, including patch status, future protection plans, and development of long-term plans for upgrading through a variety of products and services.

III. Research Tools and Methodology

III.1. Fault Tree Analysis (FTA)

FTA is a technique used to analyze and evaluate the causes of an undesired events that lead to the system failure (identifying the quality of potential defects). It involves the creation of a diagram called a fault tree, which represents the logical relationships between various events and conditions that could lead to the undesired event or failure. The fault tree consists of two types of nodes: events and gates. Events represent the basic causes or conditions that can lead to the undesired event or failure, while gates represent logical operators that combine events or gates. FTA can be used to identify and evaluate potential failures or safety hazards and to identify the most effective ways to prevent or mitigate the effects of a potential failure or hazard.

III.2. Bayesian Network Analysis (BNA)

BNA is a probabilistic graphical model that represents the relationships among different variables and their conditional probabilities. It can be used to estimate the likelihood of a particular event or outcome based on different variables or parameters. It involves constructing a Directed Acyclic Graph (DAG) where nodes represent variables and edges represent the probabilistic dependencies between them. BNA is based on the Bayes' theorem, which allows for the computation of the posterior probability of a variable given its observed evidence and prior knowledge (data). BNA can be used for various tasks such as prediction, classification, and decision making, and has applications in fields such as medicine, finance, and engineering, etc. The Bayesian formula is a powerful tool for probabilistic inference that allows for updating prior beliefs or knowledge based on new evidence or observations.

- If A and B are any two events with P(B) > 0, the probability of A conditional on B is denoted P(A|B) and equals: P(A|B) =P(A ∩ B) / P(B)
- If events A and B are independent and P(B) > 0, then P(A|B)= P(A).

According to the definition of conditional probability, we have: P(A ∩ B) = P(A|B).P (B) = P(B|A).P (A).
So,

$$P(A|B) = P(B \cap A) / P(B). \quad (1)$$

Bayes theorem follows from the generalization of equation (1) to sets of events A and B:

$$P(A|B) = P(B|A).P(A) / P(B). \quad (2)$$

IV. Pratical Application on Control and Protection System of Gas Turbine

The Fault Tree Analysis (FTA) and Bayesian Network (BN) are two popular methods used for risk assessment and reliability analysis. They can be applied to various systems, including control and protection systems of gas turbines. this study allows to know the practical applications of these methods on gas turbine systems, in the first, fault tree analysis (FTA) can be used to identify potential faults and failure modes in a gas turbine system, starting with the identification of the top-level undesired event (e.g., control system of gas turbine shutdown) and then uses a logical diagram to break down this event into its contributing causes and events. then listing all undesirable events in Table 2 and 3 based on data previously stored by operators and maintenance experts, finally we use the combined approach based on Bayes method BN and fault tree FTA to model the probability of gas turbine control system failure based on different variables, the purpose of this method is to identify the most critical variables that affect system, reliability and determine the root causes of its failures and to develop effective risk mitigation strategies.

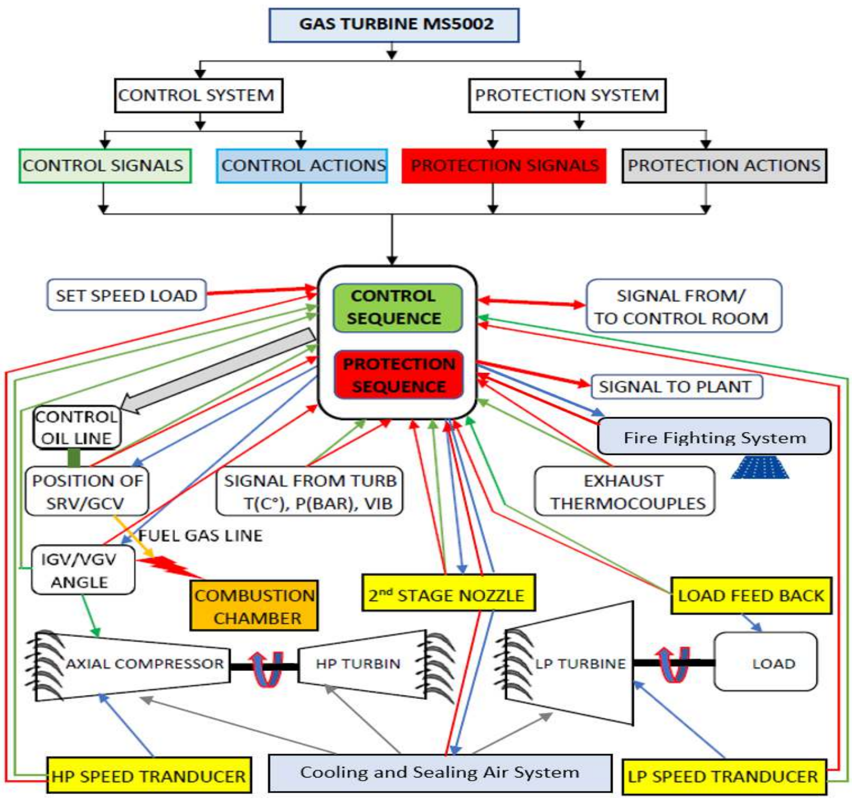

Fig.1. Control and Protection System of Gas Turbine

To illustrate how this method can be applied in practice, showed in the following graph of FTA (see Fig. 2), a gas turbine power station has a control and protection system that includes various systems such as lubricating oil (LOS), hydraulic oil (HOS), control oil system (COS), etc. Where these events represent the high level in terms of the amount of failure because their failure leads to the failure of the control system, and there are different sensors, and the motors shown in the figure with codes (F1, F2...., F541 see table 2) They are linked to each other, which represents the first causes of system failure.

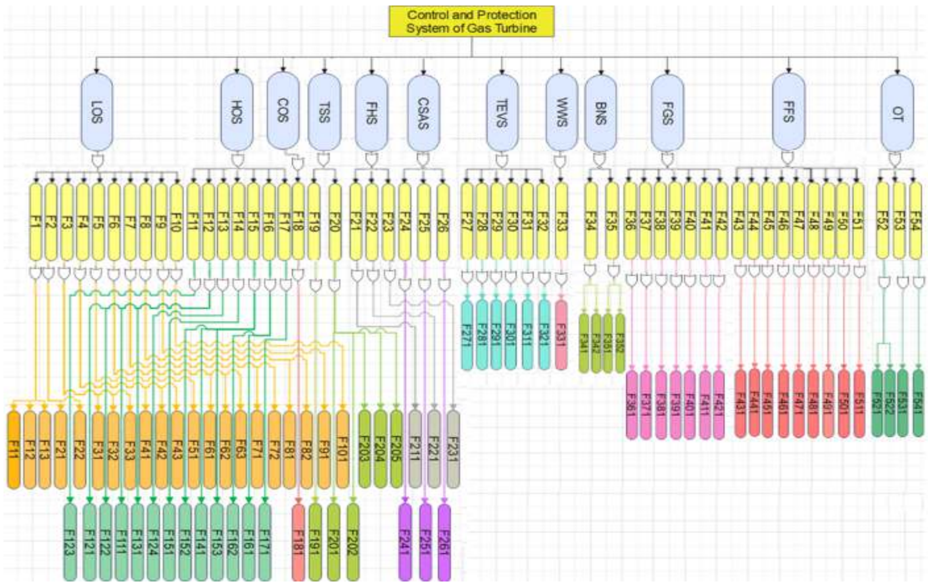

Fig.2. Fault tree diagram of control and protection system of gas turbine

To complete the transfer of the FT to the probability space through the stored data and using the conditional probabilities parameters shown below.

Table-1: Conditional probability table for all events

A		True		False	
B		True	False	True	False
Event (E)	True	1	1	1	0
	Fals	0	0	0	1

- If the cause E has no direct cause, E(P) will be defined. When the cause E can take two probabilities true or false, it is necessary to define the two numbers P(A=True) and P(A=False).
- Then , If the effect G has a single direct cause E1, it is necessary to define P(G/E), which consists four numbers P(G=V/E1=V), P(G=V/E1=F), P(G=F/E1=V), and P(G=F/E1=F).
- Also, we can calculating the remaining causes (E2, E3, ..., En) using the same method, but the calculation becomes increasingly difficult as the number of causes and probabilities increase.

Table-2: Basic faults and events of control and protection system of gas turbine

Mark VIe	G.T SYSTEMS	FAULTS / CODE		CAUSES /ACTION	
Control and Protection System of Gas Turbine (Mark VIe)	***Lube Oil System LOS***	Lube oil tank	F1	Oil pressure (control / trip)	F11
				Oil level	F12
				Electric heater / temperature	F13
		Main lube oil pump	F2	Mineral oil vapor separator fan motor	F21
				Vaporextractor	F22
		Auxiliary lube oil pump/motor	F3	Start-up / Shutdown / Cool-down	F31
				Low pressure	F32
				Oil vapor separator / extractor fans	F33
		Emergency lube oil pump/motor	F4	Pressure	F41
				Under voltage	F42
				Overload	F43
		Lube oil duplex filters	F5	Pressure difference	F51
		Lube oil heaters	F6	Lube oil tank level low	F61
				Over temperature (a-b-c)	F62
				pressure – control / trip (a-b-c)	F63

		Thrust bearing #1 and 4	F7	Drain oil temperature	F71
				Low pressure	F72
		Journal bearing # 1,2,3 and 4	F8	drain oil temperature	F81
				Low pressure	F82
		Mineral oil cooler fan motors	F9	Temperature C°	F91
		Air cooler motors fan	F10	Vibration transmitter (A-B-C)	F101
	Hydraulic Oil System HOS	Main & auxiliary hydr-oil pumps	F11	Trip - Loss of flame / Oil pressure	F111
		Ratchetpump /motor	F12	Valve position – closed	F121
				Under voltage	F122
				Overload	F123
				Starting clutch position – engaged	F124
		Hydraulic oil duplex filters / header	F13	Low pressure	F131
		Hydraulic oil filters	F14	High difference pressure.	F141
		Inlet guide vane operation (IGV)	F15	Servovalve (LVDT Position)	F151
				Start-Up (low opening position)	F152
				After loading (high opening position)	F153
		Turbine air bleed valves (antisurge)	F16	Turbine speed < 92.5% (BV Opened)	F161
				Turbine speed > 92.5% (BV Closed)	F162
		Nozzle Guide Vanes (NGV)	F17	Close / Open	F171
	Control Oil System COS	Control oil trip	F18	Overspeed protection (GT trip: oil drain valves open → gas servo valves closing)	F181
	Turbine Starter System TSS	Hydraulic ratchet	F19	Start-Up / Cool-Down	F191
		Starting motor	F20	Start-Up	F201
				Clutch disengaged / Stop	F202
				Hydraulic torque converter open/close	F203
				Purge/Ignition/Warmup (periods)	F204
				Acceleration phase	F205
	Filter House System (FHS)	Inlet air filter	F21	Pressure control	F211
		Inlet filter inspection door	F22	Close / Open	F221
		Dust extractor fan motor	F23	Alarm/Trip	F231
	Cooling and Sealing Air System CSAS	GT ready to CRANK / START-UP	F24	Close / Open	F241
		Emergency shutdown	F25	Trip	F251
		Journal bearing # 1,3 and 4	F26	Air pressure > Oil pressure	F261
	Turbine Enclosure Ventilation System TEVS	Main & stand-by ventilation air fan motors	F27	Ventilation cutout (fire detected, CO2, Gas detected at inlet filter)	F271
		Fire dampers / inlet damper	F28	Close / Open	F281
		GT compartment internal temp C°	F29	Control – Trip	F291
		GT compartment ventilation outlet	F30	Close / Open	F301
		Coupling compartment ventilation	F31	Outlet Close / Open	F311
		Coupling compartment internal	F32	Control temperature – Trip	F321
	Water-wash System WWS	Axial compressor fouling	F33	Mode (Online / Offline)	F331
	Bently Nevada System (BNS)	HP Shaft	F34	Radial and seismic vibration (alarm/trip)	F341
				Axial displacement (Alarm/Trip)	F342
		LP Shaft	F35	Radial and seismic vibration (alarm/trip)	F351
				Axial displacement (Alarm/Trip)	F352
	Fuel Gas System FGS	Solenoid and servo valves	F36	On/Off	F361
		LVDT sensors	F37	Position	F371
		Stop / Speed Ratio Valve (SRV)	F38	Gas pressure (Close /Open)	F381
		Gas Control Valve (GCV)	F39	Regulate the fuel supply quantity	F391
		Fuel gas supply temperature	F40	ALARM/TRIP	F401
		FG control valve actuation/Position	F41	Close / Open	F411
		Warm-up line vent valve status	F42	Close / Open	F421
	Fire Fighting System FFS	Fuel gas shutoff valve actuation	F43	Close / Open	F431
		FGvent valve actuation	F44	Close / Open	F441
		Safety depressurized	F45	Trip	F451
		Control oilsolenoid valve	F46	Close / Open	F461
		Interstage fuel gas vent valve	F47	Close / Open	F471
		Firefightingdampers actuation	F48	Close / Open	F481
		Battery of CO2 initial discharge	F49	Off	F491
		Turbine enclosure vent	F50	Fan #1 cut out	F501
		Enclosure firedetected	F51	Trip (firefightingstarting)	F511
	Over Temperature OT	Wheel spaces temperature	F52	Thermocouple 1st stage temperature FWD/AFT inner #1 (Alarm/Trip)	F521
				Thermocouple 2nd stage temperature FWD/AFT inner #1 (Alarm/Trip)	F522
		Exhaust temperature monitoring	F53	Thermocouple (1÷13) (Alarm/Trip)	F531
		Combustion chambers	F54	Flame detectors: Loss of flame	F541

Table-3: A priori and a posteriori probability of control and protection system of gas turbine

Events	Faults Code		A priori Probability	A posteriori Probability Of each events		
LOS	F1	F11	0.0001	0.0008	0.0054	TOP EVENT 0.026
		F12	0.0003			
		F13	0.0004			
	F2	F21	0.0002	0.0002		
		F22	0.00005			
	F3	F31	0.0003	0.0007		
		F32	0.00024			
		F33	0.00015			
	F4	F41	0.00001	0.0009		
		F42	0.0002			
		F43	0.0006			
	F5	F51	0.000013	0.00001		
	F6	F61	0.0004	0.00075		
		F62	0.0001			
		F63	0.00025			
	F7	F71	0.00029	0.0006		
		F72	0.0003			
	F8	F81	0.0007	0.0008		
		F82	0.00008			
	F9	F91	0.00045	0.00045		
	F10	F101	0.00018	0.0002		
HOS	F11	F111	0.000027	0.00003	0.0047	
	F12	F121	0.00001	0.00114		
		F122	0.0003			
		F123	0.00023			
		F124	0.0006			
	F13	F131	0.0009	0.0009		
	F14	F141	0.002	0.002		
	F15	F151	0.0001	0.0005		
		F152	0.0003			
		F153	0.00008			
	F16	F161	0.0001	0.00015		
		F162	0.00005			
	F17	F171	0.00003	0.00003		
COS	F18	F181	0.0002	0.0002	0.0002	
TSS	F19	F191	0.0001	0.0001	0.002	
	F20	F201	0.0004	0.0018		
		F202	0.0006			
		F203	0.00004			
		F204	0.0007			
		F205	0.00008			
FHS	F21	F211	0.0001	0.0001	0.0006	
	F22	F221	0.0004	0.0004		
	F23	F231	0.00009	0.00009		
CSAS	F24	F241	0.0002	0.0002	0.0009	
	F25	F251	0.00025	0.00025		
	F26	F261	0.00045	0.00045		
TEVS	F27	F271	0.00042	0.00042	0.0013	
	F28	F281	0.0001	0.0001		
	F29	F291	0.0003	0.0003		
	F30	F301	0.0002	0.0002		
	F31	F311	0.00008	0.00008		
	F32	F321	0.0002	0.0002		
WWS	F33	F331	0.0006	0.0006	0.0006	
BNS	F34	F341	0.00027	0.00082	0.002	
		F342	0.00055			
	F35	F351	0.0005	0.0012		
		F352	0.0007			
FGS	F36	F361	0.002	0.002	0.004	
	F37	F371	0.0001	0.0001		
	F38	F381	0.0003	0.0003		
	F39	F391	0.0004	0.0004		
	F40	F401	0.0003	0.0003		
	F41	F411	0.0005	0.0005		
	F42	F421	0.0004	0.0004		

FFS	F43	F431	0.00025	0.00025	**0.0025**	
	F44	F441	0.00015	0.00015		
	F45	F451	0.0004	0.0004		
	F46	F461	0.0003	0.0003		
	F47	F471	0.0002	0.0002		
	F48	F481	0.0001	0.0001		
	F49	F491	0.00035	0.00035		
	F50	F501	0.0005	0.0005		
	F51	F511	0.0003	0.0003		
OT	F52	F521	0.0001	0.0003	**0.002**	
		F522	0.0002			
	F53	F531	0.00065	0.00065		
	F54	F541	0.001	0.001		

By using the fault tree, we can find out the causes for the greatest impact on the gas turbine control and protection system, by representing all the main and secondary events in Table 2, then by calculating the probability of each event (a quantitative description) based on the raw data stored by the experts (as shown above in Table 3), through this table we can draw a Bayes diagram represented in the fig 4, as it consists of three basic levels of events starting from the base up to the top of the pyramid (control and protection system failure), where the first level represents the various systems such as LOS, HOS, COS, etc. which are an integral part of the main protection system, as its failure leads to the failure of the gas turbines. The second level represents all the main events leading to the failure of the first level systems, the last level, which represents the secondary events that cause the failure of the second level. In this study, according to The values obtained by calculating a posteriori probability of failure for each component of the first level (monitoring systems) show us that the impact of these systems on the highest event is divided into three sections according to the severity of their impact, where the lube oil system represents the highest percentage with 21%, followed by the hydraulic oil system and The fuel gas system accounts for 18% and 15%, respectively, while the second section is represented by the firefighting system by 9%, while the other three systems (turbine starter, Bentley Nevada and Over Temperature system) are equal in terms of impact by 8%. As for the turbine enclosure ventilation system It is affected to a lesser extent than the previous systems by 5%, while the last section is due to the remaining systems (cooling and sealing air system, filter house system, control oil system and water-wash system) with small percentages in terms of impact limited between 1% and 3% (see fig 3).

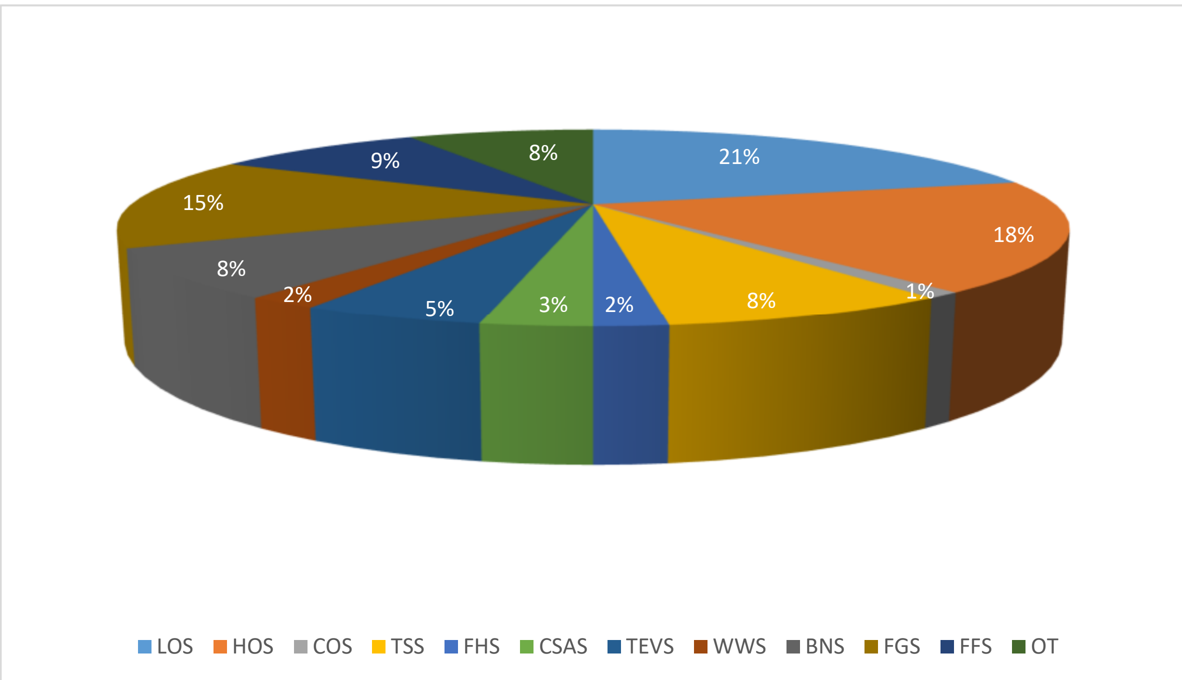

Fig.3. The impact percentage of each subsystem on the control and protection system of gas turbine

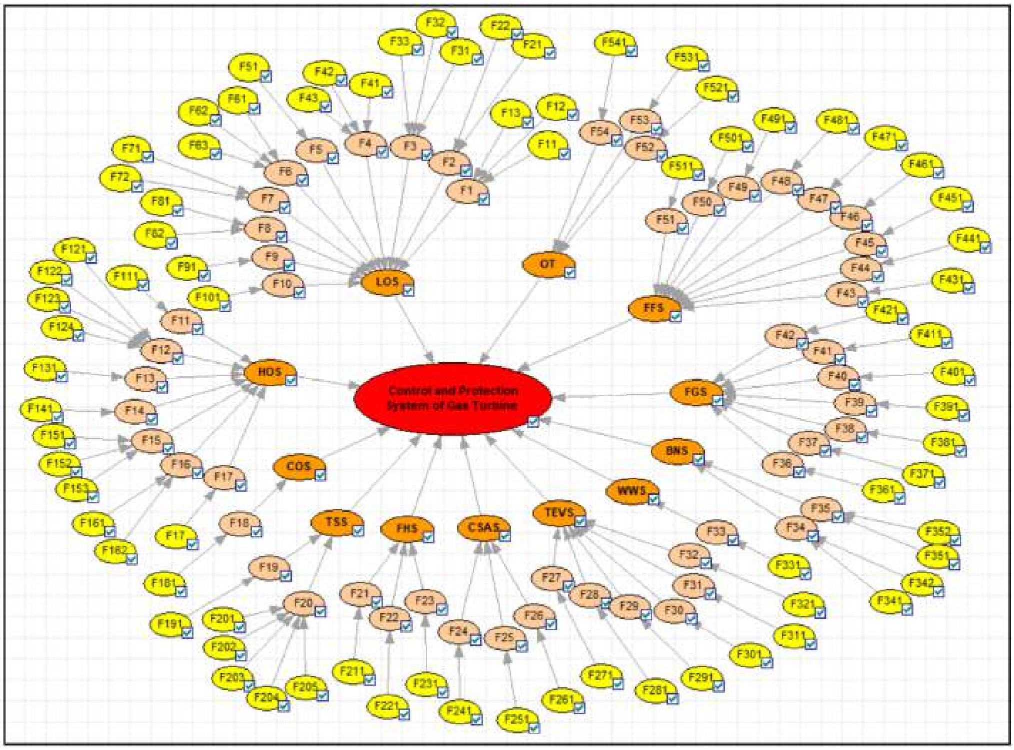

Fig.4. Bayesian network of control and protection system of gas turbine fault

V. Conclusion

In this study, a probabilistic analysis of a gas turbine protection system was performed, using an approach integrating two well-known methods, namely Fault Tree Analysis FTA and Bayesian Network BN, so that the FTA depends initially on the knowledge of all the undesirable causes that can lead to the system failure, through evaluating the probability of each cause and event using the available data and expert knowledge that would help us to build a Bayes diagram to estimate a posteriori probabilities, The results obtained show that it is possible to predict the occurrence of undesirable events that cause the failure of control and protection system of gas turbine. Through the results obtained we found the lubrication system has the highest impact on the control and protection system with 21%, followed by the hydraulic oil system and the fuel gas system with 18% and 15%, respectively, while the other subsystems contribute the lowest impact rates, which leads us to focus on the need to take preventive measures to reduce the severity of these events.

With this approach, we can gain as much information as we did not have before, such as predictions, learn which failure patterns are most significant based on the severity of their impact on the system (qualitative and quantitative knowledge), and help us define prioritization strategies to mitigate risks.

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