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Evaluation of the Main Causes of Diesel Engine Injector Failure using Fault Tree Analysis

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Abstract

The maintenance of the diesel engine parts in any electric power station contains many problems that lead to stopping. Several reasons lead to such problems; these reasons should be analyzed and evaluated in order to eliminate their effects. This paper is based on evaluation of the main causes that lead to diesel engine injector failure as a main part of electric power stations, using fault tree analysis (FTA). The FTA is the most broadly utilized strategies in the industrial area to perform reliability analysis of complex designing frameworks. A fault tree is a logical representation of the relationship of basic events that lead to a given unwanted event (i.e., top event).

Starting with introducing the FTA and how it could be utilized in analyzing the reasons of main issues that lead to that the injector stops working, in which the probability of occurrence of each issue is calculated. The application of the root cause analysis principle of diesel engine injector failure in diesels Haditha station is chosen as a case under study. According to the probabilities' evaluation by using the FTA based on of the causes under the top event its value was (0.80). It is concluded from the analysis that the three largest values of the occurrence of a problem with the diesel engine injector are 0.50 for fuel problems, 0.20 for overloads, and 0.18 for nozzle head corrosion. Plant management can define a specific plan with taking into consideration the calculated value of each cause in order to reduce their impacts and to avoid long downtime hours compared to operating hours. Finally, recommandations are suggested to overcome these causes.

Keywords: *Fault tree analysis (FTA), Fault tree symbols, injector, qualitative assessment.*

1. Introduction

Given the importance of maintenance of all kinds, it is recommended implementing it and adhering to the time and operating hours specified for its work. Providing all maintenance requirements and tolerance for one minute under any circumstances, especially during peak work times, is essential in order to avoid a damage that may be caused to parts of the generating units and expose them to a stoppage. This state leads to energy loss, stopped production, and losses in lives and money.

Most engineering systems are maintained the mainteance work when they fail, and the maintenance work is performed on them to keep their operation. [1]

Fault tree analysis (FTA) is one of the analytical methods for tracking events, which can be contributed to identify the most important parts that cause the malfunction or stoping the work. Accordingly, the sub-causes of the problem is displayed and the probability of an undesirable fault event is calculated.

In this paper adopting the FTA is considered in the proposed methodology to determine the main and sub causes, and their probabilities of the parts of power plants' stoppage.

The focus on the most influential causes probabilities in order is essential to find the solutions to these causes which significantly reduce the rate of breakdowns.

2. Fault Tree Analysis (FTA)

An FTA begins with a top fault event and continues deductively by inquiring, "How could this event have occurred?". Immediate contributing causes to this top fault event are distinguished and afterward recorded as a component of the following lower level of analysis (sub-faults). These sub-fault events are then associated as affecting contributions to the upper-level event by the same token either "AND" gates or "OR" gates. A definitive outcome is a qualitative fault tree ending in a bunch of basic faults and undeveloped events. [2]

The FTA is a technique for planning a fault tree that intelligently examines the causal relationship of a framework disappointment, and discovers the likelihood of a framework disappointment. [3]

The FTA is deductive in nature implying that the analysis begins with a top event (system failure) and works in reverse from the highest point of the tree towards the leaves of the tree to decide the root causes of the top event. [4]

Failure itself can be characterized as the interruption of an item's capacity, from a component to a complex system, to carry out its function. The failure of a part can be classified into three groups [5]: 1) Primary failure, 2) A component is in a damaged state (non-working state), and 3) Command faults.

3. The Symbols used in the FTA

The essential symbols utilized in the FTA are assembled as events, gates, and transfer symbols. Fig.1 shows them with their definitions [6] [7] [8]:

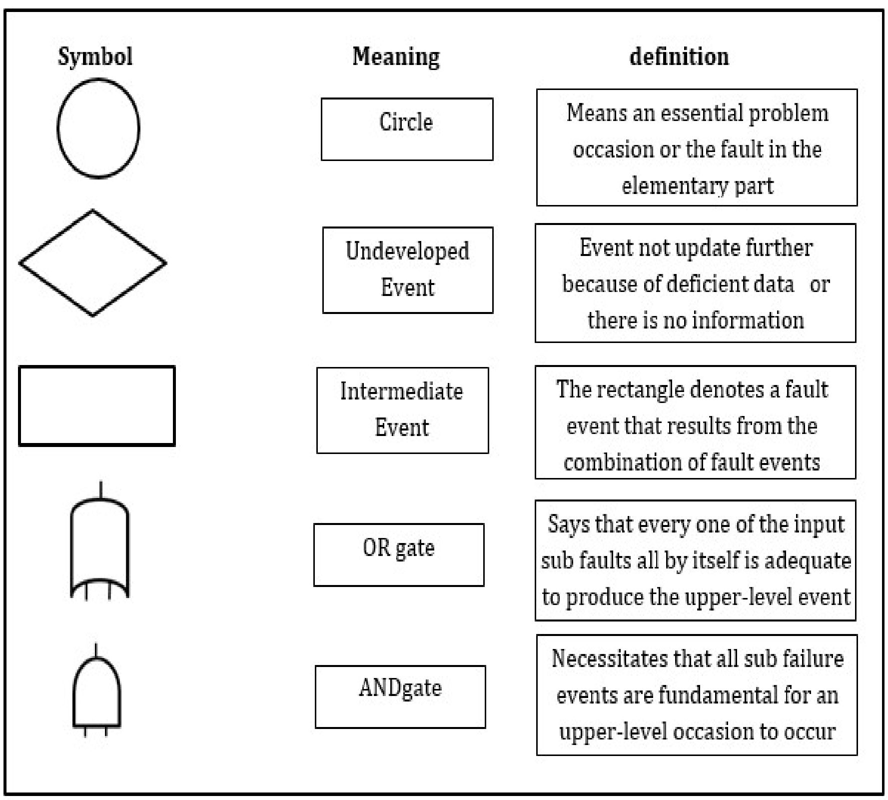

Fig.1. The fault tree symbols.

4. Research Methodology

The research methodology is based on applying the FTA to evaluate and calculate the failure rate of the part under study. To arrange the work steps, a flowchart is used to define processes in sequence. The utilization of standardized symbols for represent the steps of methodology makes the flow chart simpler to decipher. [9]

4.1. Proposed Flow Chart Methodology

The main steps in the proposed methodology are as follows:

1. Describing of the whole system, and studying its work, to select the part with frequent failure with the ability to be maintained.
2. Collecting all the data on faults and dividing them into main faults, in which the root causes of the main problems branch off, as to be illustrated in details in the **qualitative assessment** method followed.
3. After clarifying all the reasons that led to the failure of the part under study, the FTA is drawn to analyze the problems more accurately and clearly.
4. Applying steps (6) (to be illustrated in the following section), according to the type of gate (OR or AND) in order to get the top event and draw the fault tree with related values (**quantitative assessment**).
5. A bar chart is drawn to illustrate the most influential causes and to choose an appropriate maintenance plan that reduces breakdowns and costs.
6. Suggesting solutions to reduce the influence of the occurrence are given.
7. If the suggestions improve the faults rates, then the aim is reached. But if not, new suggestions are given.

Fig.2. represents the steps of the proposed methodology processes.

4.2 The Assessment of Problem:

A fault tree is evaluated as Qualitative Assessment or Quantitative Assessment.

Qualitative Assessment is the kind of evaluation of an issue that has effectively occurred in a venture, to analyze the causes behind this issue. [10]

In **Quantitative Analysis**, the probability of the top event and other quantitative dependability files, for example, significant measures are numerically determined, given the failure rate or probability of individual system component. [4]

Two equations are used according to the type of gate (AND or OR) for quantitative analysis[11]:

For **AND gate** out fault event E_o is given by:

$$P(E_o) = \prod_{i=0}^{n} P(E_i) \qquad \dots (1)$$

and for **OR gate** out fault event Xo is given by:

$$P(X_o) = 1 - \prod_{i=1}^{k} \{1 - P(X_i)\} \qquad \dots (2)$$

Concerning analysis procedures, recognizing qualitative the FTA is performed, which thinks about the construction of the FTA; and quantitative FTA, which estimate the numbers, for example, disappointment probabilities for fault trees. [12]

Both qualitative and quantitative analyses bring a bunch of basic ways, often named "cut sets" or "min sets." These are group of parts that, when they happen, will cause a top fault event. [2]

In the case study of this research, both qualitative and quantitative assessment are shown.

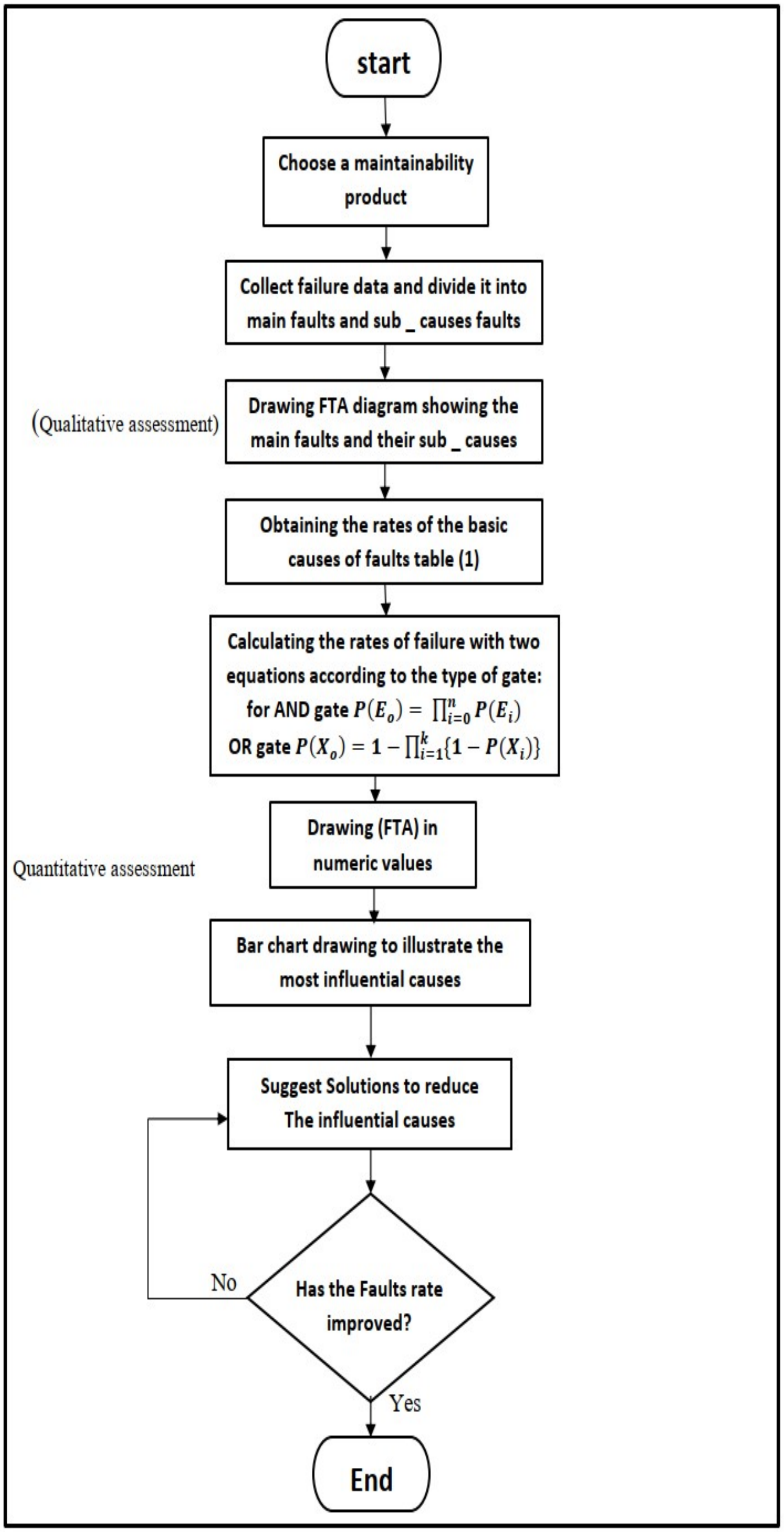

Fig. 2. The flowchart of steps of the processes flow.

5. Adopted Case Study

The case study adopted in this paper is the diesel engine injector in Haditha diesels station. The engine is a type of four-stroke internal combustion engine. Under such circumstances, the focus will be on the injector as a highly effective part of the diesel engine. It is one of the parts of the fuel system whose function is to inject fuel in the form of a mist with a force (3000bar) that reaches the combustion chamber. The presence of the injector results in more efficiency and lower cost in terms of fuel exchange. The injector is shown in Fig.3.

Fig. 3. The Injector.

6. Drawing the Fault Tree and Calculations

The fault tree is drawn from the data that the researcher collects (values and events) and were recorded through his attendance at the station and with the help of the engineer who is supervising the work and the workers. According to the data recorded in the power station foles, main and sub-causes are named. Table (1) lists the main problems and sub-causes events that cause the injector to stop working in order to draw a fault tree which represente the **qualitative assessment** as shown in Fig.4.

Table1,
The nomenclature of the main problems of the occurrence of malfunctions and their sub-causes.

Symbol of Event	Name of Event
E1	No maintenance order
E2	High fuel temperature
E3	Work for long periods
E4	Fuel laden with water
E5	Water leakage from the heat sink
E6	Fuel laden with impurities
E7	Fuel filter has stopped working
E8	Accumulation of previous fuel impurities
E9	Neglect of maintenance manger
E10	Urgent need for
E11	Increased pressure
E12	High temperature
E13	Other reasons
E14	Excessive pressure at the attached nozzle
E15	Over load
E16	Poor Maintenance
E17	Water in fuel
E18	Viscosity of the fuel
E19	Impurities in the fuel
E20	Injector vibration
E21	Other reasons
E22	Water pressure
E23	Defect in the washer
E24	Fuel heat
E25	Overloads
E26	Delay maintenance time
E27	Nozzle head corrosion
E28	Nozzle head does not pump fuel
E29	Fracture of the injector hull
E30	Fuel problems
E31	O-ring I
E32	O-ring II
E33	Diesel engine injector mal functioning

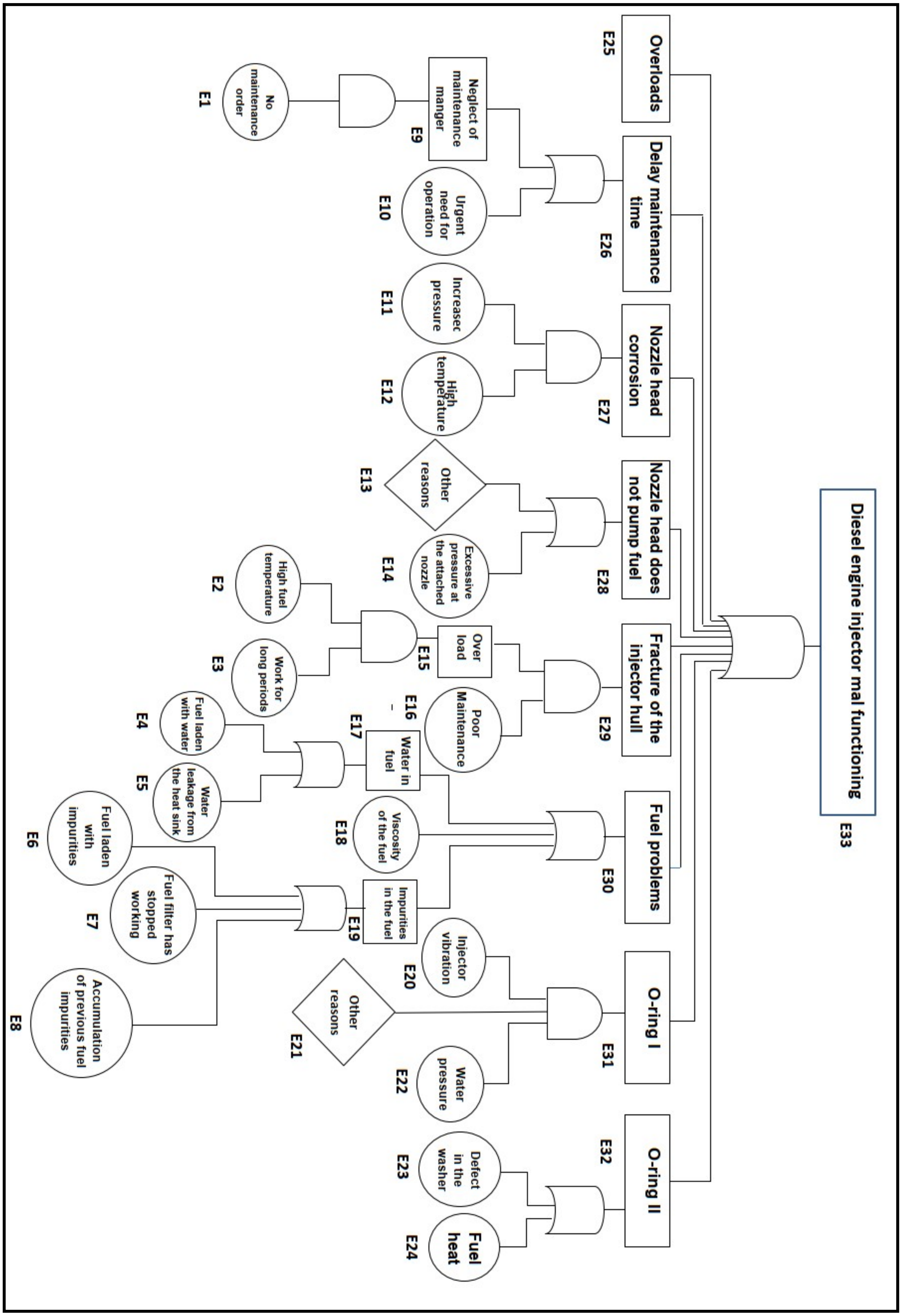

Fig.4. Fault tree analysis of diesel engine injector.

The presence in the station and data collection were done based on the realized events (previous faults) and calculating the probabilities of the basic events is shown in Table (2).

Table 2,
The probability of occurrence of basic events.

Events	Number
E1	0 .1
E 2	0.55
E 3	0.89
E4	0.0 5
E5	0.05
E6	0.04
E7	0.10
E8	0.06
E10	0 .05
E11	0.30
E12	0.60
E 13	0 .05
E14	0. 05
E16	0.20
E18	0 .30
E20	0. 20
E21	0.50
E22	0.50
E23	0.01
E24	0.05
E25	0.20

Using the data provided by Haditha diesel station company, according to their records as shown in Table (2) and the FTA the following calculators are performed, by apply 'OR' or 'AND' equation, as given:

1.The probability of event occurring E32 is (O-ring II = 0.06), which means that the injector has stopped working due to a malfunction or breakage in the O-rings of the refrigeration system, as given

$$P\,(E_{32}) = 1 - \{1 - P(E_{23})\}\{1 - P(E_{24})\}$$
$$- 1 - \{(1 - 0.01)(1 - 0.05)\}$$
$$= 1 - \{(0.99)(0.95)\}$$
$$1 - 0.99 = 0.06$$ (A very small percentage)

2.The probability of event occurring E31 is (O-ring I = 0.05), meaning that the injector stops are due to a malfunction or breakage in the fuel system's O-ring.

$$P(E_{31}) = P(E_{20})\,P(E_{21})\,P(E_{22})$$
$$= (0.20)(0.50)(0.50)$$
$$= 0.05$$ (A very small percentage)

3. The probability of event occurring E19 is (Impurities in the fuel = 0.20) caused by (E6 =Fuel laden with impurities, E7 =Fuel filter has stopped working, and E8 =Accumulation of previous fuel impurities) as given:

$$P(E_{19}) - 1 - \{1 - P(E_6)\}\{1 - P(E_7)\}\{1 - P(E_8)\}$$
$$= 1 - \{(1 - 0.04)(1 - 0.10)(1 - 0.07)\}$$
$$= 1 - \{(0.96)(0.90)(0.93)\}$$
$$= 1 - 0.80 = 0.20$$

In addition, the probability of an event occurring E17 is (Water in fuel = 0.10) caused by (E4 =Fuel laden with water, and E5 =Water leakage from the heat sink) as:

$$P(E_{17}) = 1 - \{1 - P(E_4)\}\{1 - P(E_5)\}$$
$$= 1 - \{(1 - 0.05)(1 - 0.05)\}$$
$$= 1 - \{(0.95)(0.95)\}$$
$$= 1 \quad 0.90 = 0.10$$

With the probability of an event occurring E18 is (Viscosity of the fuel = 0.30), giving the probability of an event occurring E30 as:

$$P(E_{30}) = 1 - \{1 - P(E_{17})\}\{1 - P(E_{18})\}\{1 - P(E_{19})\}$$
$$= 1 - \{(1 - 0.10)(1 - 0.30)(1 - 0.20)\}$$
$$= 1 - \{(0.90)(0.70)(0.80)\}$$
$$= 1 - 0.50 = 0.50$$ (Half the amount of failure)

4. The probability of an event occurring E15 is (Over load = 0.50) caused by (E2 =High fuel temperature, E3 =Work for long periods) as follows:

$$P(E_{15}) = P(E_2)\,P(E_3)$$
$$= (0.55)\,(0.89)$$
$$= 0.48 \cong 0.50$$

The probability of an event occurring E15 (Over load) with probability of an event occurring E16 (Poor maintenance) give the probability of an event occurring E29 as follows:

$$P(E_{29}) = P(E_{15})\,P(E_{16})$$
$$= (0.50)(0.20) = 0.10$$ (Small percentage)

5. The probability of an event occurring E28 is (Nozzle head does not pump fuel =0.10) as:

$$P(E_{28}) = 1 - \{1 - P(E_{13})\}\{1 - P(E_{14})\}$$
$$= 1 - \{(1 - 0.05)(1 - 0.05)\}$$
$$= 1 - \{(0.95)(0.95)\}$$
$$= 1 - 0.90 = 0.10$$ (Small percentage)

6. The probability of an event occurring E27 is (Nozzle head wear =0.18) as:

$$P(E_{27}) = P(E_{11})\,P(E_{12})$$
$$= (0.30)(0.60)$$
$$= 0.18$$ (Medium rate of faults)

7. The probability of an event occurring E9 is (Neglect of maintenance manager =0.10) caused by one event (E1 =No maintenance order) as:

$$P(E_9) = P(E_1) = 0.10$$

With the probability of an event, occurring E10 is (Urgent need for operation =0.05), giving the probability of an event occurring E26 as follows:

$$P(E_{26}) = 1 - \{1 - P(E_9)\}\{1 - P(E_{10})\}$$
$$= 1 - \{(1 - 0.10)(1 - 0.05)\}$$
$$= 1 - \{(0.90)(0.95)\}$$
$$= 1 - 0.855 = 0.145 \cong 0.15$$ (Medium rate of faults)

8. The probability of an event occurring E25 is (Over Loads =0.20)

9. Calculation the probability of occurrence of the top event E33 is (Diesel engine injector mal functioning =0.80) as follows:

$$P(E_{33}) = 1 - \{1 - P(E_{32})\}\{1 - P(E_{31})\}\{1 - P(E_{30})\}\{1 - P(E_{29})\}\{1 - P(E_{28})\}\{1 - P(E_{27})\}\{1 - P(E_{26})\}\{1 - P(E_{25})\}$$
$$= 1 - \{1 - 0.06\}\{1 - 0.05\}\{1 - 0.50\}\{1 - 0.10\}\{1 - 0.10\}\{1 - 0.18\}\{1 - 0.15\}\{1 - 0.20\}$$

$$= 1 - (0.94)(0.95)(0.50)(0.90)(0.90)(0.82)(0.85)(0.80)$$
$$= 1 - (0.20) = 0.80$$ (Top event)

Fig.5. shows the FTA with the values of the probability indicating the given error event and their occurrence with the calculated probabilities. (**quantitative assessment**).

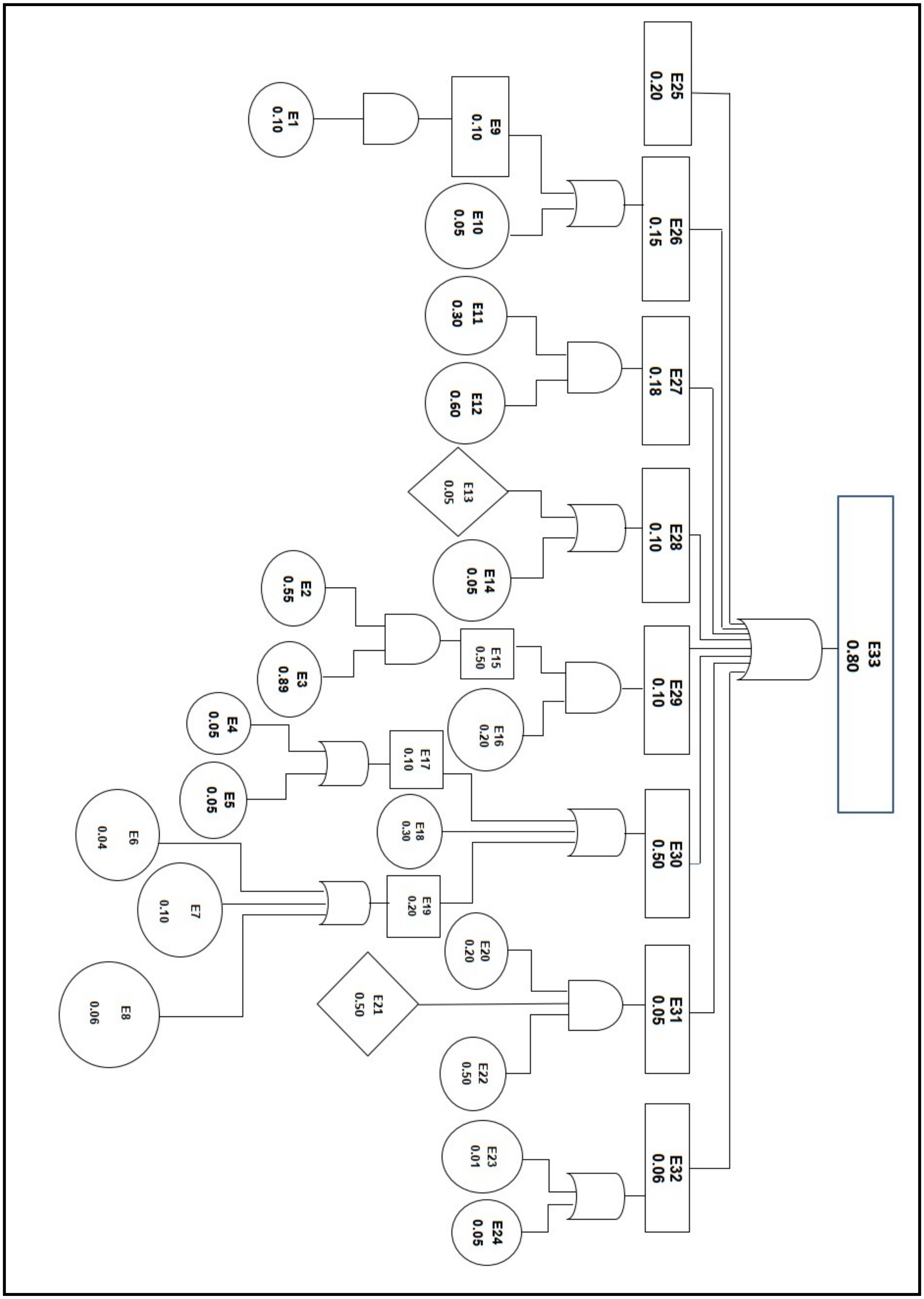

Fig. 5. Fault tree analysis with the values.

7. Results and Discussion

After calculating the failure rate of each cause that lead to injector failure and plotting the FTA with the values as shown in Fig.5., a bar chart is drawn to show the differences between the rates of faults causes and the most influential failures, which is shown in Fig.6.

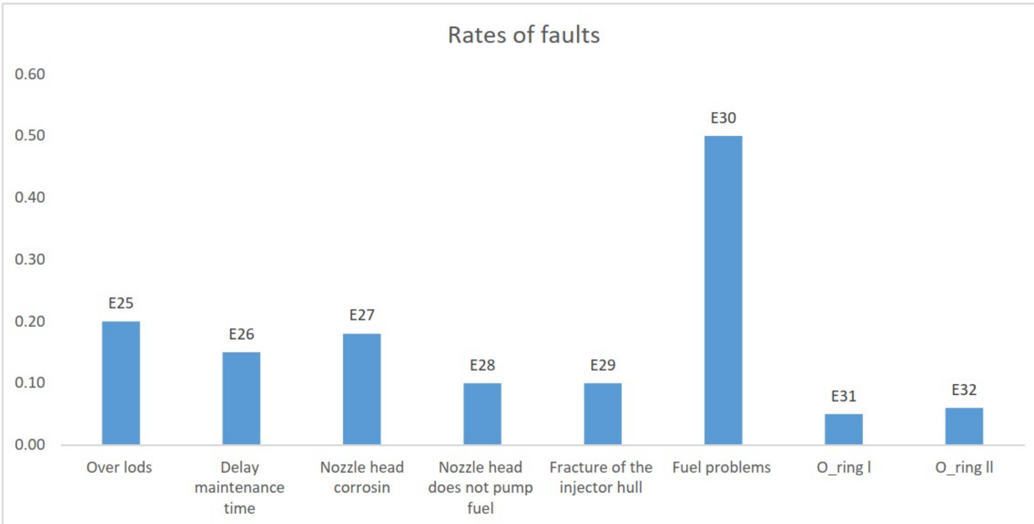

Fig. 6. The faults that occur to the diesel engine injector.

The bar chart is the best choice for comparing the calculated data to be represented in a way that shows the data which divided into nominal, numeric, and even symbolic categories. Here, the vertical bar chart is chosen, so that the longer bar is the greater size of the category. In Fig.6., the sum of rates gives a percentage of 98% and not 100%, this means that 2% is still not calculated and represents "other reasons" affecting the diesel engine injector malfunction, which is unknown factors.

Looking at the shape of the chart and based on the columns that represent the probability of faults occurrence, we find that the largest is fuel problems, followed by over loads, and then nozzle head corrosion. By analyzing the main reasons for the occurrence of these faults through the FTA several solutions are suggested to reduce these faults.

For discussing these results and according to the presentation and calculations, the followings points are highlighted:

1. In the FTA, the focus of the researcher is to identify the main causes firstly and then to identify their sub-causes, with assuming that no error occurs in identifying the causes.
2. For logical consideration, the two gates OR and AND are used for linking in the plotted fault tree.
3. To solve the root causes, it is possible to significantly reduce the percentage of errors that causes the injector to stop working.
4. The bar chart is used to compare the results of the data, showing the largest failure rates according to the length of the vertical bar.
5. It is concluded from the bar chart that the three largest values of the occurrence of a problem with the diesel engine injector are E30= 0.50 (fuel problems), E25= 0.20 (overloads), and E27= 0.18 (nozzle head corrosion).

8. Conclusions and Recommendations

Through the calculations, it is found that the main and sub-causes lead to the clarity of the probability of failure by 80%, which was a high percentage of failure. By studying the ratios of the main causes as shown in the bar chart in Fig.6., we have to focus on the most influential causes in order to find the solutions to these causes which significantly reduce the rate of breakdowns. Several plans and ideas have been proposed to solve and reduce these rates:

1. New maintenance plan is determined in which not only the rate of failures but also cost is reduced. The new maintenance plan depends on two types of maintenance according to the type of malfunction, these are:
a. Preventive maintenance (periodic) is done by supervising an engineer with (4-6) workers.
b. Corrective Maintenance (emergency) is done by workers with or without the supervising an engineer who performs quick and sudden. Maintenance such as a leak or breakage in a part of the injector that is replaced or repaired immediately to restart the engine; this type of maintenance does not depend on a specific time.
2. The cause E30 = 0.50 (fuel problems) can be reduced by:

a. Replacing the fuel filter every certain period of time to reduce the amount of impurities.

b. Checking the fuel before filling it into the engine to ensure its purity.

3. The cause E25 = 0.20 (overload), the rate of failures due to overloading increases with high temperatures, high pressures and electrical energy consumption, especially in summer. This rate can be reduced by:

a. Supplying water cooling systems to cool the injector.

b. Organizing a schedule for operating the motors to avoid power outages due to excessive loads.

4. The cause E27 = 0.18 (nozzle head corrosion) can be reduced by adjusting (O-ring) the nozzle of the cooling system, to prevent water leakage causing rust in the injector head.

Notation

P (Eo) = occurrence probability of the AND gate output fault event, Eo
n = total number of independent input fault events
P (Ei) = probability of occurrence of input fault event Ei, for i=1, 2, 3,… ,n.
P (Xo) = occurrence probability of the OR gate output fault event, Xo
k = total number of independent input fault events
P (Xi) = probability of occurrence of input fault event Xi, for i =1, 2, 3,… ,k .

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تقييم قابلية الصيانة لمكونات منتج للتخطيط الامثل للصيانة

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الخلاصة

تتضمن صيانة أجزاء محرك الديزل في أي محطة كهرباء العديد من المشاكل التي تؤدي إلى التوقف. عدة أسباب تؤدي إلى مثل هذه المشاكل ؛ يجب تحليل هذه الأسباب وتقييمها من أجل إزالة آثارها. تستند هذه الورقة إلى تقييم الأسباب الرئيسية التي تؤدي إلى فشل حاقن محرك الديزل كجزء رئيسي من محطات الطاقة الكهربائية ، باستخدام تحليل شجرة الأعطال. أن تحليل شجرة الأعطال (FTA) هو أكثر الاستراتيجيات استخدامًا على نطاق واسع في المجالات الصناعية لإجراء تحليل موثوقية من خلال أطر التصميم المعقدة. شجرة الأعطال هي تمثيل منطقي لعلاقة الأحداث الأساسية / الأولية التي تؤدي إلى حدث معين غير مرغوب فيه (على سبيل المثال ، الحدث الرئيسي).

تم البدء بتقديم تحليل شجرة الاعطال (FTA) وكيف يمكن استخدامه في تحليل أسباب المشكلات الرئيسية التي تؤدي إلى توقف الحاقن عن العمل من خلال حساب احتمال حدوث كل مشكلة. تم اختيار تطبيق مبدأ تحليل السبب الجذري لفشل حاقن محرك الديزل في محطة الديزل في حديثة كحالة دراسية تطبيقية. وفقًا لتقييم الاحتمالات باستخدام تحليل شجرة الاعطال للاسباب المؤدية للحدث الرئيسي، كانت قيمته (٠,٨٠). تم الاستنتاج من التحليل بان اكبر القيم المحتملة لاسباب العطل لحاقن محرك الديزل كانت ٠,٥ لمشاكل الوقود، ٠,٢ للحمل العالي و ٠,١٨ لتأكل راس النوزل يمكن لإدارة المصنع تحديد خطة محددة مع الأخذ في الاعتبار القيمة المحسوبة لكل سبب لتقليل آثارها من أجل تجنب ساعات التوقف الطويلة مقارنة بساعات التشغيل. تم اقتراح توصيات للتغلب على هذه المسببات.