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Failure Modes and Effect Analysis of Turbine Units of Pumped Hydro Energy Storage Systems

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Abstract: In the present paper subject of the investigations is the reliability assessment of the single-stage reversible Hydropower Unit No. 3 (HU3) in the Bulgarian Pumped Hydro-Electric Storage (PHES) plant "Chaira", which processes the waters of the "Belmeken" dam and "Chaira" dam. Preceding destruction of HU4 and its virtual simulation, analysis and the conclusions for the rehabilitation and safety provided the information for the possible processes in HU3. Detailed analysis of the consequences of prolonged use of HU3 was carried out. The Supervisory Control and Data Acquisition (SCADA) system records were studied. Fault Tree Analysis (FTA) is applied to determine the component relationships and subsystem failures that can lead to an undesired primary event. The functional structure of the system was depicted as a causal chain of failure effects. The probability of system failure was estimated based on the failure probabilities of the primary events. The effects of static loads, dynamic loads and low-cycle loads were investigated. Based on the experience and the investigations of the HU4 and its damages, as well as of the failures in the stay vanes of HU3 it is recommended to organize monitoring for water ingress into the drainage holes, which will allow detecting failures in a timely manner.

Keywords: FMEA; accident analysis; hydro energy; pumped hydro energy storage; fault tree analysis; failure prediction

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1. Introduction

This article is related to the contract of the "National Electric Company" EAD (NEK AD) of Bulgaria [1] for investigation and analysis of the possibility of safe operation of HU3 at the "Chaira" PHES Plant. A brief history of the construction and operation of the Chaira HPES coul be found in [2].

The object of the contract was investigation of the single-stage reversible HU3 reliability at the "Chaira" PHES plant, which processes the waters of the "Belmeken" Dam and the "Chaira" Dam (Figure 1). The "Belmeken" Dam is located at an altitude of about 2000 meters. The upper water level of the dam is at an altitude of 1920 m. The lowest level is at 1865 m. The Figure 1 also shows the altitude of the dam walls. The dam contains 144 million cubic meters of water. The "Chaira" Dam is located at an altitude of about 1200 meters. It contains about 5 million cubic meters of water. The upper water level of the dam is 1260 meters, and the lower 1231 meters. The plant consists of four Hydro Units that are located at an altitude of 1169 meters. The power generated of the "Chaira" PHES is 864 megawatts, and in pumping mode it consumes 788 megawatts. The water pipes are divided into two levels, each with 2 pipes with diameters of 4.4 - 4.2 meters. The level of the upper section is at about 1900 meters altitude. The total length of the pipelines is 2510 meters for the upper level and 1816 meters for the lower level, respectively. The flow rate of each pipe is about 7.2 cubic meters per second.

The scheme of each powerhouse is presented on Figure 2. The rehabilitation of HU3 unit began on 20.02.2021, with the completion of repair and installation activities and the adjustment of the unit's systems. As a result of the damages that occurred in HU4, on 02.06.2022 and before the start of the trial testing stages of HU3, the activities were terminated by the contractor in order to prevent similar damage as of HU4 [3].

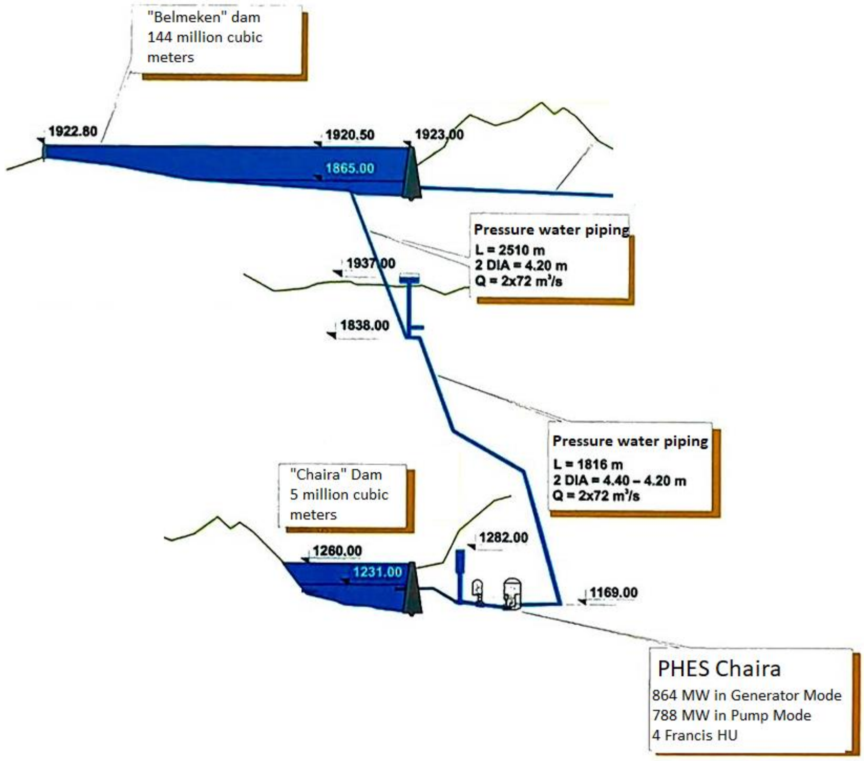

Figure 1. Principal scheme of the PHES "Chaira" plant.

Cases of failures in hydroelectric power plants and, respectively, in the HPES are not unusual worldwide. Such cases have been described in the literature since the beginning of the 20th century. In [4] many incidents are listed although it is not the complete one. Predominantly Francis turbine are applied eider as turbines or as pumps, since this type of structures are especially effective for both cases. Many cases of Francis turbines failures for the period since 1990 till 2010 are analyzed in the paper of Yasuda and Watanabe [5]. Incidents were reported for power plants in Canada, China, Australia, Iran, Nepal, USA. One of the most dramatic cases was reported for the Sayano-Shushenskaya power station [6]. In the scientific literature mainly the destructions and failures of the turbine blade are discussed. In [5] there are no cases analyzed regarding the damages of the stay vanes. Severe vibrations were the reasons for the cracks found in two runners of a Francis turbine of 330 MW in China 2000 [7]. Damages as a result of erosion of the turbine blades and guide vanes are reported in Nepal 2003 [8]. Cracks were found at the trailing edges of the turbine blades of Francis turbines in Iran 2006 [9] and Canada 2008.

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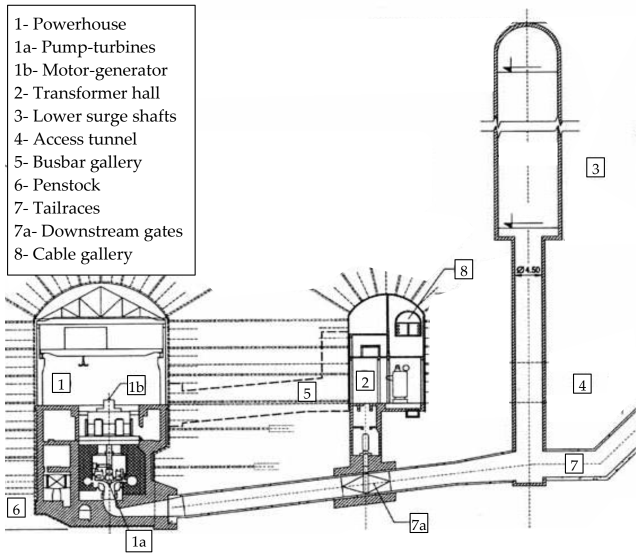

Figure 2. Structure of a unit of PHES "Chaira"plant.

Other nature of destructions of a Francis turbine of 88MW was reported in USA in 2008. The runner blades had severe damage by hard-hitting with a freed guide vane. Similar case was reported in on the Tocantins River in central Brazil [10]. The cause was the dropping of a link pin of the guide vane operating mechanism. In 2010 in Canada [11] many cracks were found at the flange fillet of main shaft at runner side.

Some cases of the spiral casing destructions of the Francis turbines are also discussed. In Australia in 1990 a Francis turbine of 150 MW the spiral case failed by the excessive pressure rise due to the instant shut-down of all guide vanes [12]. Spiral case embedment and destruction was discussed in several articles of Chinese scientist [13,14].

It should be noticed that the investigations of possible destructions of the Francis turbines stay vanes could not be met in the scientific literature. Todorov at al. [15–17] analyzed the destruction of the Francis turbine stay vanes of the PHES "Chaira" HU4 and the possible reasons for the occurrence of cracks. They conducted detailed investigations and the influence of the concrete erosion [15] of the spiral casing destruction and the stay vanes [16]. The fatigue of the material was also discussed [16,17].

The unprecedented accident at HU4 of the Chaira HPP [17] necessitated the termination of the rehabilitation of HU3. The main cause of the accident at HU4 was the complete destruction of all blades, an event that has not been described in scientific publications. In Figure 3 a stay vane No. 1 of HU4 and the cracks are shown. It was proven that the reason for the stay vanes destruction was the low cycle fatigue of the material.

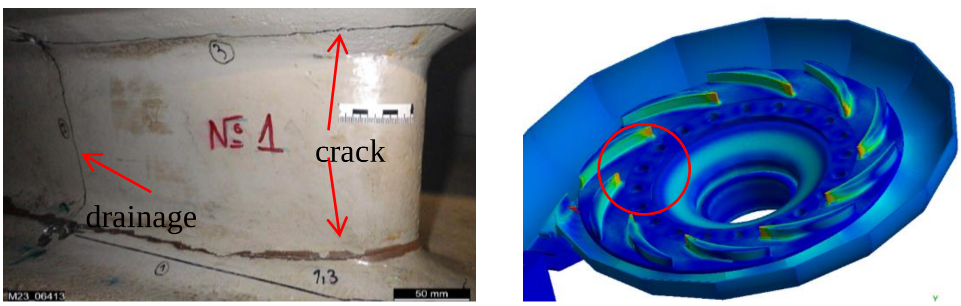

Figure 3. The cracks of the stay vane No. 1 of HU4 [17].

The survey of the scientific literature sowed that the problems of fatigue life and service live of Francis turbines was the scope of many publications. In [18], it is recommended for the fatigue safety factors to be more than 1.5 and the guidelines are proposed for the determination of fatigue cycles and crack propagation calculations. In [19] fatigue reliability of welded steel structures is analyzed. Liu et al. [20] reviewed the publications on the fatigue damage mechanisms in hydro turbines. Lyutov et al. [21] used the stress pulsations amplitude to estimate the number of cycles until the moment of fatigue failure. The numbers of loading cycles and oscillation frequency are also used to calculate the runner service time. Paresas et al. [22] estimated the fatigue life of Francis turbines based on experimental strain measurements. Biner et al. [23] performed a numerical fatigue damage analysis of a variable-speed Francis pump turbine in start-up and generating modes. In case of variable loading conditions the use of the correct factor of safety in structural strength calculations is of particular importance

Zhang et al. [24] studied the major factors affecting fatigue life prediction of steel spiral cases in pumped-storage power plants. They expect that the factors identified in the paper would assist in understanding the role of adequate fatigue design and analysis of PHES plants.

A key element in the analysis of failures and, most importantly, the probability of their occurrence, is the risk assessment methodology. A type of methodology that is increasingly being used in modern products is the Failure Modes, Effects and Analysis (FMEA). Its premise is the availability of quantitative estimates of the probability of a given type of failure occurring and examines in greater detail the types of failure of the facility.

A suitable for conducting reliability and safety analyses is the method of Fault Tree Analysis (FTA). This method uses systems analysis to determine the component relationships and subsystem failures that can lead to an undesired event, known as a primary event. The automotive industry mainly uses FMEA, the aerospace industry uses FTA. In many cases, the best results are obtained by combining several analysis methods.

Souza and Álvares [25] applied FMEA and FTA method for assessment of the reliability of hydraulic Kaplan turbine used in the hydroelectric plant of Balbina – Amazonas — Brazil. They showed the contribution of each one for the predictive maintenance. Peeters et al. [26] assessed the FMEA model in order to select the critical system level failure modes. For each of them a function level FTA is performed, followed by an FMEA. Infraspeak Team [27] published a paper about the difference between the FTA and FMEA models. It is shown that each analysis has its own approach to failures, which could lead to different results.

Another type of analysis, included in some international standards does not require a quantitative assessment of the probability of a particular type of failure, but only a description of the possible failures, their effects and the risk of failure (criticality). This type of analysis is known as Risk Hazard Analysis (RHA). This type of analysis is described in detail by the standards DIN EN ISO 12100 [28].

Flynn [29] discussed the methods used to identify hazards and the causes and consequences of accidents. It is emphasized that many accidents occurred because of a lack of knowledge of the system, process, or substance being dealt with. The company TheSafeyMaster published a study report [30] for consultancy and training services about Hazard Identification and Risk Assessment. It is clearly stated that the hazard identification and risk assessment are critical processes that the organizations need to undertake to ensure the safety of their employees.

This article examines the possibility for the accidents at XA3 of the PHES “Chaira” plant. The causes of the XA4 accident were analyzed and the design documentation, the installation process, the SCADA system records, the protocols of the current repairs performed and the results of the virtual modeling of the hydro units were studied. The results of the XA4 investigations were compared with the data from the investigations of XA3, which did not suffer an accident, but it is identical to XA4, both in terms of construction and installation performance. The results of the SCADA system records and information, as well as the operation data of XA3, were compared with those of the damaged XA4.

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The probability for the system failure was estimated based on the failure probabilities of the primary events. Creation of the so-called fault tree is based on: system and functional analysis; definition of the unwanted event (failure at the basic level); determination of the types and categories of the failures; depiction of the effectiveness of failures in the fault tree to the main events; assessment of the main events from the input data (failure frequency, duration of the events); probabilistic assessment of the fault tree. The effects of static loads, dynamic loads and low-cycle loads were investigated. A systematic risk analysis has been carried out. The results of the application of FMEA and FTA are supplemented with the results of the hazard and operability study RHA, with the best solutions being achieved through a combination of the analysis methods.

Based on the experience and the investigations of the HU4 and its damages, as well as of some failures in the stay vanes of HU3 it is recommended to organize monitoring for water ingress into the drainage holes, which will allow detecting failures in a timely manner.

2. Materials and Methods

2.1. Risk Analysis. Essence

Risk hazard analysis (RHA), set out in some international standards and safety requirements for a number of devices, does not require a quantitative assessment of the probability of given types of failures. Only a description of the possible failures, their effects and the risk of failure occurring (criticality) is needed. It is used to identify and assess potential risks in the use of the device. The measures taken to ensure operational safety are to be documented, and it is not required to include all measures taken with regard to the safety of the device. It should be noted that technical and formal errors are possible when preparing the documentation.

The presented description of RHA is based on and described in details by the German standard DIN EN ISO 12100 Part1 [28]. It applies to lifting facilities but also is used for other equipment. The specific possible risks and their causes are the main objects of consideration. The analysis report should also contain prescriptions for operational control, based on knowledge of the nature of the occurrence of failures and their specificities. The identification of the risk level is obtained through assessment of the risk and the corresponding types of dangerous failures. The frequencies and the possibility of failures occurrences are determined according to a scale defined in the standard and shown in Figure 4.

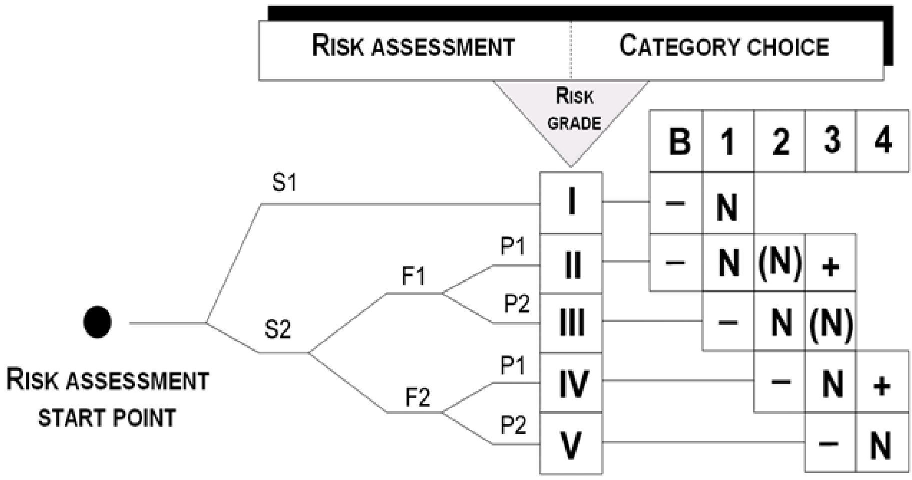

Figure 4. Risk assessment system for performing RHA according to DIN EN ISO 12100 Part1.

The notations presented on the Figure 4 are as follows:

B: 1-4: Categories for security related parts of controls;

N: Normal category for the risk level

(N): Additional directions for standard solutions of protection devices and electronical devices (Category can generally be accomplished by using electronics);

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+: Deviation to an upper category;
-: Deviation to a lower category;

Hazard Analysis documentation is prepared in order to be more clear and understandable and thus, the hazardous location, the hazard cause and the operating method are also listed enciphered. The so defined type of hazard is evaluated as follows:

(S): Grade of the possible injury
S1: Light Injury
S2: Severe permanent injury
(F): Frequency of the incidence
F1: Rarely to often
F2: Frequent to always
(P): Possibility of risk prevention
P1: possible risk prevention under certain circumstances
P2: almost impossible

The DIN EN ISO 14121-1 [31] standard defines the risk as a combination of the probability of damage occurring and its degree of criticality. There are a large number of procedures to analyze these factors. In general two main types of risk analysis are applied – deductive and inductive. The deductive procedure starts with an event and analyzes its causes. The inductive procedure assumes the existence of possible deviations in a process or a system and analyzes their effects.

The technical context of the present study requires that the concept of safety analysis to be considered, although the term risk analysis is often used in connection with economic analyses.

2.2. Methodology Used for Analysis of Failures and Their Effects

The main method for reliability analysis and definition of the probability of damages and destructions is based on the investigation of the Failure Modes, Effects and Criticality Analysis (FMECA) [32]). This method is increasingly being used in modern products. The premise is the availability of quantitative estimates of the probability of a given type of failure and its detailed examination. The FMECA is performed prior to any failure actually occurring. FMECA analyzes risk, which is measured by criticality (the combination of severity and probability), to take action and thus provide an opportunity to reduce the possibility of failure.

FMECA and Failure Mode and Effects Analysis (FMEA) [25–27} are closely related tools. There are two activities to perform FMECA: create the FMEA; perform the criticality analysis. Each tool resolves to identify failure modes which may potentially cause product or process failure. FMEA is qualitative, exploring "what-if scenarios", where FMECA includes a degree of quantitative input taken from a source of known failure rates. A source for such data is Military Handbook 217 [33] or equivalent.

As already mentioned, there are a large number of methods for performing analysis and evaluation. The automotive industry mainly uses FMEA, while the aerospace industry uses Fault Tree Analysis (FTA), although very often these two methods are applied sequentially [27]. The chemical industry often uses the Hazard and Operability (HAZOP) study [34]. In many cases the best results are obtained by combining several methods for risk and safety analysis.

The FMEA methodology was developed in the NASA space program in 1959/60. FMEA is applied to the study of potential weaknesses in the planning and design phase. This analysis methodology is of a preventive nature.

The analysis of certain risk involves consideration of each system unit and its association with the probability of hazard. An important element of FMEA is the determination of a quantitative expression of the risk - Risk Priority Number (RPN), which assesses the criticality of the specific failure. The RPN is determined as follows:

$$S \times O \times D = RPN, \quad (1)$$

where

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- S (severity, criticality) assesses the degree of significance of the failure;
- O (occurance, failure intensity) assesses the likely occurrence of such a failure;
- D (detection, detectability) represents the probability of detecting the cause of the failure.

The RPN value is used for decisions regarding the need for intervention and changes. The values indicate the following:

- RPN values up to 40 indicate low risk (no need for corrective actions);
- RPN values in the range 40 ÷ 100 indicate moderate risk (certain actions are needed to improve the study object);
- RPN values above 100 are classified as unacceptable risk (urgent actions are needed).

The generally accepted values and descriptions of these parameters are given in Tables 1–3.

Table 1. Criticality levels and their assessment (S).

Level	Description	Rating (S)
None	No effect on components	1
Minor	Minor effect on the system	2
Very low	Slightly pronounced impact on the system	3
Low	Low level of criticality regarding the functioning of the system	4
Average	The system is functioning, with broken parameters	5
High	Reduced system functionality	6
Very high	Loss of important system functions	7
Dangerous	Functions are lost, leading to potential danger to users	8
Very dangerous	Potentially dangerous system condition, with indications allowing preventive action	9
Extremely dangerous	System condition with possible critical impacts on personnel, without possibility of detection and prevention	10

Table 2. Failure intensity assessment (O).

Intensity	Probability	Rating (O)
Extremely low	$\leq 1 \cdot 10^{-5}$	1
Low	$1 \cdot 10^{-4}$	2
Average grade	$5 \cdot 10^{-4}$	3
	$1 \cdot 10^{-3}$	4
	$2 \cdot 10^{-3}$	5
High degree (repeatability)	$5 \cdot 10^{-3}$	6
	$1 \cdot 10^{-2}$	7
	$2 \cdot 10^{-2}$	8
	$5 \cdot 10^{-2}$	9
Very high degree	$\geq 1 \cdot 10^{-1}$	10

Table 3. Detection rate and rating (D).

Grade	Description	Rating (D)
Very high	Very high probability of failure detection	1
High	High probability of failure detection	2

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Relatively high	Relatively high probability of failure detection	3
Medium	Average probability of detecting failure	4
Relatively low	Relatively low probability of detecting the potential cause/mechanism of failure	5
Low	Low probability of detecting the potential cause/mechanism of failure	6
Very low	Very low probability of detecting the potential cause/mechanism of failure	7
Weak	Weak probability of detecting the potential cause/mechanism of failure	8
Very weak	Very weak probability of detecting the more potential cause/mechanism of failure	9
Impossible	Inability to establish the refusal	10

3. Results

3.1. Fault Tree Analysis of the HU3 of PHES "Chaira"

FTA is suitable for conducting reliability and safety analyses. The methodology uses system analysis to determine the relationships and subsystem failures that could lead to an undesired event, known as a primary event. The FTA enables the representation of the functional structure of the system as a causal chain of failures and their effects. The main aim is the probability of total system failure to be estimated based on the probabilities of the main failure events. The FTA shows which failures cause emergency events and the aim is evaluating and predicting possible preventive measures. Further, a quantitative analysis is also performed to calculate the probability of occurrence an undesirable event. In general, the following components and fault categories are used:

- Primary failure (failure of a component under normal operating conditions);
- Secondary failure (failure of a component as a result of secondary failure from a primary failure or as a result of extreme operating conditions);
- Errors as a result of incorrect operation or misuse.

An important factor is the nature of the fault linkage. While an "OR" combination of two inputs is sufficient to trigger a fault, an "AND" connection requires both inputs for it to occur.

The creation of the so-called fault tree occurs when performing: system and functional analysis; defining the unwanted event (failure at the basic level); determining the types and categories of failures; depicting the effectiveness of failures in the fault tree to the main events; evaluating the main events from input data (failure frequency, times); probabilistic assessment of the fault tree (calculation of the above event).

A section of the Francis turbine and its simplified mayor units and parts are shown in Figure 5. The following parts are denoted by numbers: 1- the concrete surrounding structure; 2 – the spiral casing; 3 – the stay vanes; 4 – the guide vanes; 5 – the bolts of the upper 6 and the lower 7 covers; 8 - the bearing; 9 – the runner.

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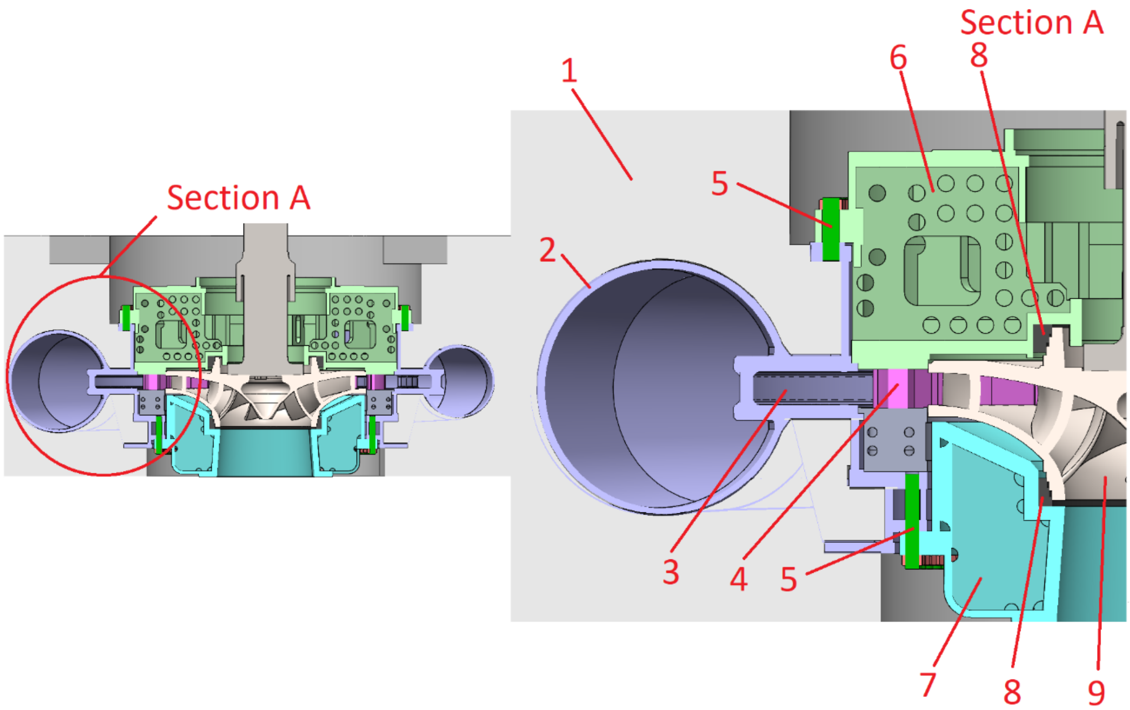

Figure 5. A section of the Francis turbine and its main units and details.

Based on the results, it is possible to determine the most effective measures to eliminate weak points and optimize reliability and safety. This analysis is related to the possible failures of the stay vanes of the spiral casing (stator columns) and the effects caused by them. The following possible failures of the stay vanes are described further down.

- Primary failures/shutting out (PF):
  - PF1: Crack formation on the faces of up to three stay vanes due to low-cycle material fatigue;
  - PF2: Crack formation on the faces of more than three stay vanes due to low-cycle material fatigue;
  - PF3: Violation of the bond between concrete and spiral casing leading to a backlash.
- Secondary failures/shutting out (SF):
  - SF1: Failure of up to three stay vanes;
  - SF2: Failure of all stay vanes;
  - SF3: Significant deformations in the spiral casing;
  - SF4: Increased load on the lower and upper covers;
  - SF5: Increased load on the bolted connections of the covers, due to their overloading by bending moment.
- Effects because of failures (EFF):
  - EFF1: Deteriorated guide vanes bearing – violation of clearance and coaxiality between the guide vanes and the bearings, leading to difficult closing (switching off) of the vanes control;
  - EFF2: Deteriorated runner to spiral casing clearance – violation of clearance between the runner and the spiral casing and possible mutual contact;
  - EFF3: Damaged bolted connections of covers – destruction of bolted connections of the covers, due to their overloading by bending moment;
  - EFF4: Cracks in the concrete – cracking of the concrete, due to overloading of the spiral casing and total failure of the stay vanes.

These failures and their effects are used to construct the fault tree, which is drawn as a pictogram that highlights the system relations. It is shown in Figure 6.

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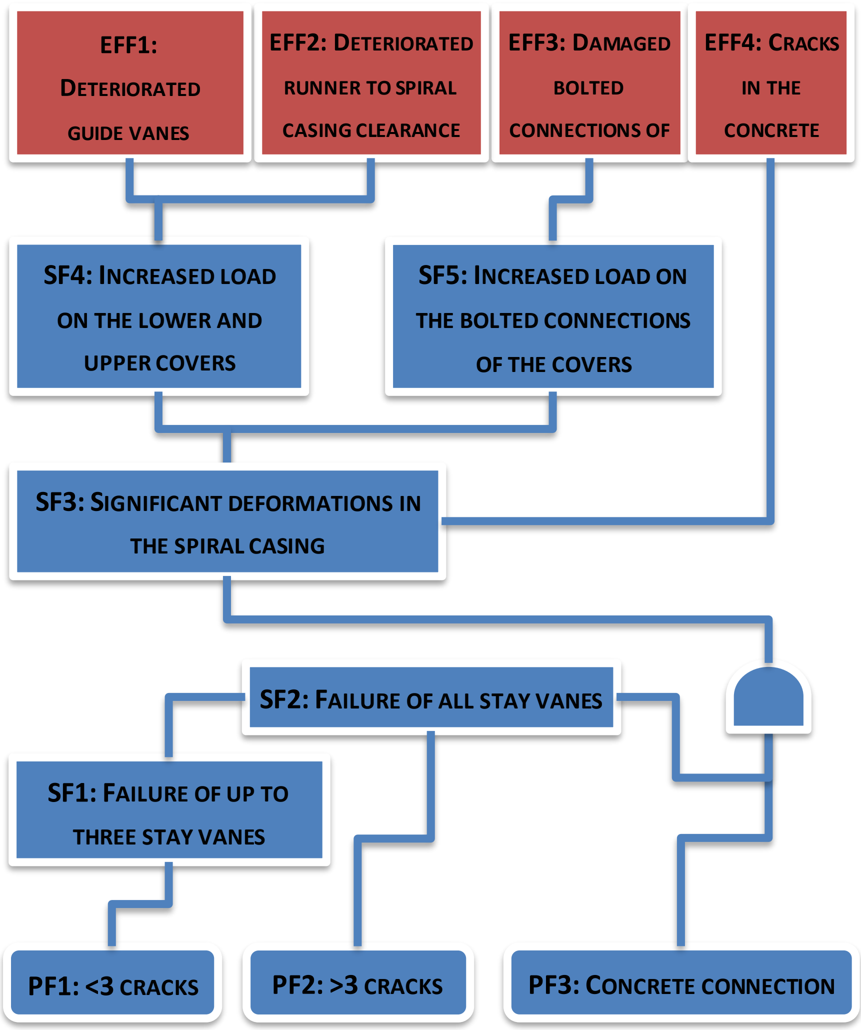

Figure 6. Fault tree related to stay vanes.

3.2. Analysis of Failures in the Stay Vanes of HU3 and Their Effects

The present project focuses on the stay vanes and assessment of their reliability. The analysis and risk assessment are mainly related to the occurrences of failures and the possible consequences. The following possible turbine operating modes are defined:

- G1: Nominal generator mode – mode of the system operation as a generator in a steady state;
- G2: Peak loads in the generator mode – process of switching to a nominal generator mode for which the loads on the runner and the entire structure increase;
- P1: Nominal Pump mode, - mode of operation of the system as a pump in a steady state;
- P2: Peak loads in the pump mode – process of switching to a nominal pump mode for which the loads on the runner and the entire structure increase;
- P3: Pump mode when runner spins – mode in which the runner spins infor a closed system until the required speed and pressure are reached;
- A1: Drop of the load mode – sudden loss of load on the runner leading to an increase of the rotation speed;

The possible failures modes are systematized using the compiled failure tree described in sections 3.1 and 3.2 and are also presented in Table 4.

Table 4. Possible failure modes and their effects.

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Effect of refusal	Mode	Effect	Mark
EO1: Violation of the clearance and alignment between the guide vanes and bearings leading to difficult or no control	P1/P2/	Strong vibrations in the structure; Water appearing in the service area through drainage holes in the stay vanes.	EO1.1
	G1/G2	Strong vibrations in the structure; Water appearance in the service area through drainage holes in the stay vanes; Difficulty for closing the water flow and switching off the machine	EO1.2
	A1	Strong vibrations in the structure; Water appearing in the service area through drainage holes in the stay vanes; Rapid increase of the machine rotation frequency and danger of exceeding critical ones, leading to destruction; Serious damage to the electrical part of the system	EO1.3
EO2: Violation of the clearance between the runner and the spiral casing and contact	G1/G2/ P1/P2/A 1	Strong impacts to the structure; Water in the service area; Risk of destruction of the runner bearing; Possible mechanical damage to the spiral casing and the runner	EO2
EO3: Destruction of bolted connections of the covers due to overloading by bending moment	G1/G2/ P1/P2/A 1	Strong impacts to the structure; Massive water ingress into the engine room; Difficult or impossible closing of the guide vanes	EO3
EO4: Cracking of the concrete due to overloading of the spiral casing and broken integrity of the stay vanes	G1/G2/ P1/P2/A 1	Severe deformations in the structure; Difficult or impossible closing of the guide vanes Danger of destruction of the runner bearing; Serious damages to the electrical part of the system	EO4

The failure modes and their effects so identified are quantitatively assessed as criticality level, intensity of occurrence and degree of detectability in Table 5.

Table 5. Evaluation of failure modes.

Failure effect	Criticality (S)	Intensity (O)	Detectability rate (D)	RPN
EO1.1	2	2	6	24
EO1.2	3	2	6	36
EO1.3	8	2	2	32
EO2	6	2	1	12
EO3	10	1	2	20
EO4	9	2	1	18

The results are also visualized as a criticality matrix, shown in Figure 7.

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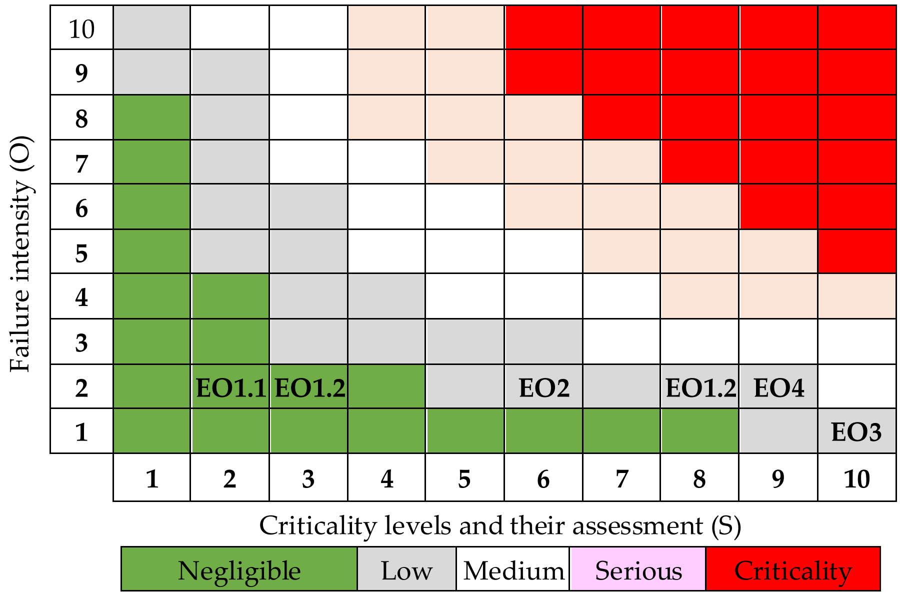

Figure 7. Failure criticality matrix.

4. Discussion

The processes of analysis related to the rehabilitation, incidents and repairs of the units of the HPES "Chaira" was imposed after the shutdown for rehabilitation of hydro unit 3. Damages to the stator columns was found, which was not critical at this stage. Soon after that a very serious damage occurred in hydro unit 4, which necessitated a thorough analysis of both hydro unit 4 and hydro unit 3 in order to prevent critical accidents and to plan the appropriate repairs. After the detailed analysis of the failed PHES HU4 [16,17] and the analysis of the records of current repairs and emergency situations in HU3 and HU4, a number of recommendations can be made regarding the maintenance and control of the units in PHES "Chaira".

Main attention should be paid to regular inspection and planned repairs. Events that depend on the degree of detectability should be taken into account. These are the units and places classified with 10 points for detectability D (Inability to establish the refusal, Table 3). Places and units that cannot be identified visually must be equipped with sensors and control devices. These are the guide vanes, the water ingress in the bearings, the gap between the concrete and the spiral casing. Special attention should be paid on the deflections of the bolts of the upper and the lower covers, the stresses in the spiral casing.

Regular inspections of the stay vanes and the cavities on their surfaces because of the cavitation effects are needed. The welded parts of the stay vanes shout be regularly monitored. The regimes of welding of cavities and cracks should be not extreme and must not be the reason for changing the characteristics of the metal.

5. Conclusions

The main task of this study is to propose measures and activities regarding the rehabilitation of HU3, PHES "Chaira", by analyzing the causes of the damage to its stator columns.

The analysis of the accident that occurred on the identical structure of HU4, PHES "Chaira" and its full analysis, concrete, spiral chamber, stator columns, loads, strength and deformation characteristics of the materials of the critical elements are the basis of the comparative analysis of HU3, PHES "Chaira". The destruction of HU4 and its virtual simulation, analysis and the conclusions for the rehabilitation processes and safety programs provided the information for the possible failure processes in HU3.

Detailed analysis of the consequences of prolonged use of HU3 was carried out. The records of the accidents and the rehabilitation processes were studied and used as the major information for the conclusions and proposal of the safety measures.

Fault Tree Analysis (FTA) is applied to determine the component relationships and subsystem failures that can lead to an undesired primary event.

The probability of system failure was estimated based on the failure probabilities of the primary events. The effects of static loads, dynamic loads and low-cycle loads were investigated.

Based on the experience and the investigations of the HU4 and its damages, as well as of the failures in the stay vanes of HU3 it is recommended:

- regular inspection and planned repairs be to provided;
- units that cannot be surveyed visually must be equipped with sensors and control devices, these are
  - the guide vanes and their welding places;
  - the water ingress in the bearings;
  - the gap between the concrete and the spiral casing;
  - the deflections of the bolts of the upper and the lower covers;
  - the stresses in the spiral casing;
- monitoring for water ingress into the drainage holes should be organized.

These measures and additional equipment will allow for the timely detection and prediction of failures.

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