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Risk Rating for Risk-Based Maintenance: A Case Study of Small Hydropower Plant in Nepal

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Abstract:
Fourth generation maintenance philosophy and Quality management system 9001:2015, emphasis on the concept of risk based thinking. And it is one of the challenging part of maintenance department to adopt these philosophy by quantifying all the activities of the department. Risk rating based on reliability is one of the techniques to quantify the maintenance activities for those organizations, whose reliability of goods and services matter in the market. Hydropower sector is also among them whose reliability matters highly in consumer life standard. So this paper approaches to rate the risk of hydropower based on the reliability of components for the implementation of Risk-based maintenance. From the study of data recorded in log book of a small hydropower plant located in western part of Nepal, it was found that the overall reliability score of the plant was 0.9819, which was low as compared to other hydropower of Nepal, where turbine section of both the units of the plant found a higher risk score than other systems. Study adopted two tools i.e. Analytical Hierarchical based Fault Tree Analysis and Critical Analysis Technique to find the critical assets and Failure Mode and Effect Analysis for the rest of all to quantifying the risk in component level. The analysis shows that the cooling system as the critical asset for both the units and it contributes 72% and 64% in the reliability of the turbine section. The critical assets thus obtained was validated through the critical analysis technique. From which the risk score of cooling system found 90% in both the units. To analyze the risk in component level, Failure Mode and Effect Analysis of different sub component of critical assets was done. Among the sub-components of the cooling system, radial tube filter gets the highest risk score. Its components; cartridge, tube, and joints have the risk score of 450, 192, and 96 respectively. And from the critical analysis of the rest of the subsystems of uint-I and unit-II, components such as bearings, breaker of the transmission system, transmission equipment, excitation system and transformer of unit-I and breaker of the transmission system, transmission equipment and excitation system of unit-II are found to have higher critical score, hence, it is recommended to apply preventive activities on these components as per the manufacturer to reduce the risk that could be caused by their failure.

Keywords: Critical analysis, Critical Assets, Hydropower, Maintenance, Risk, Reliability

1. Introduction

Maintenance is a common word which is used frequently in operation management of capital goods and service industries. There is no exact evidence of the evolution of the word “maintenance” but it is generally believed that it starts from the first industrial revolution, where, firstly the handily work was mechanized in the United Kingdom [1]. At that time the word maintenance referred to “fix it when it gets broken” and the machine which could not be fixed were replaced. At the mid-19th century, when the second industrial revolution started in America, with discoveries and innovations, factories started to replace people with machines. With the increase in density of machinery, failure frequency also increased which forced the maintenance team to create a new technique to reduce their workload. So they introduced a proactive technique called time-based maintenance, which involves the replacement of every part at specific time intervals when needed [1]. This technique decreased somehow a load of maintenance team but increase the cost of maintenance. After the world war II, when the economy of big nations got collapse due to the expense of weapons in war, then they start to rethink about the cost reduction technique in their manufacturing system. With the end of war, most of the factories that were converted to produce military product return back to produce the domestic product. Hence to reduce the production cost, many changes were made in the production line as well as the philosophy of maintenance. Then the maintenance word refers to activities that protect the equipment or component from breakdown. So different kinds of maintenance strategies were developed. Some of them are planned/ preventive maintenance strategy, the system for planning and controlling work strategy, etc [2]. These strategies have the same motto to stop the possible future breakdown in any machinery parts. This period is called the second generation of maintenance. In the war,Japan was one of the most victim nation. This aftermathgave birth to the new concept of maintenance, where the responsibility to take care about the machine was given to the limited person only. The responsibility was given to the respective machine operator to keep the machine or equipment in top operating order to reduce the extra manpower cost which was spent for maintenance staff. This concept is now popular as total productive maintenance [1]. After 1975, due to rapid technological advancement and increase in awareness in the consumers, the producer needs to provide their goods and services with additional features called reliability. As reliablity is the probability that something will work efficiently once when user want to do it. [3] Thus to survive in this competitive global market, the producer has to ensure their goods and services are reliable. For this, they search for a suitable maintenance strategy which is economical and ensures the system is reliable. In this period, maintenance has been defined as the activities which help to ensure the assets will provide the desired function in a specified time. So in this period, different kinds of maintenance strategies were developed such as condition-based maintenance, Reliability centred maintenance, proactive and strategies thinking strategies, etc. These maintenance are categoried as the third generation of maintenance [2]. Furthermore, after 2000 AD, the philosophy of quantifying risk comes into action, as per this philosophy different kind of maintenance such as Risk-based maintenance, Risk-based life assessment, Reliability-based maintenance, Reliability centred risk-based maintenance was developed and are considered as the fourth generation of maintenance [2]. The main theme of these maintenance strategies is to quantify the risk and measure the activities that are intended to preserve the function of an asset.

Furthermore, after the enrollment of ISO 9001:2015, it made a compulsion to implement risk-based thinking to all of the activities of the department of the organization to measure the ultimate performance of that department [4]. Due to this, the engineering and maintenance department of any organization has to quantify all of its maintenance activities. Form this no one can use the word preventive or corrective or other maintenance strategy name without quantifying that activity with a numerical value. The main objective of that action is to avoid the non-value added activities which are continually performed from a long period and also to prioritize the maintenance resources towards the assets which carry the most risk in the system [4]. As it focuses on continual improvement, which also helps to measure the performance of the activities assigned in a fixed time interval. So Risk-based maintenance is one of the technique which can fulfill the above requirements and also helps to determine the most economical use of maintenance judiciously to optimize the performance by minimizing the risk of failure.

Moreover, every organization wants to enhance its customer satisfaction by providing reliable product and services. And consumer also prefers more reliable product and services from the market [5].

Energy is one of the integral element of life which is greatly affected by reliability. Energy consumption rate determines the condition of living standard of people of any country. As research shows that the consumer is always willing to transition to a reliable energy source and can pay 19-25% more for reliability [6]. As per the report of National Planning Commission, per energy consumption is limited to 245 kWh [7] . The traditional type of fuel has a great share for the national energy consumption [8]. The energy consumption pattern will not improve until the consumer transit the source of fuel to electricity, which has a great extent of use. Nepal Electricity Authority is only the official distributor of electricity in Nepal and announced the end of load shedding and offering different offers to increase the consumption of electricity [9], but these cannot be materialized in the real field. The data shows

LPG import from India which is mostly used in the kitchen for cooking purpose and easily replaced by electricity, has not been significantly decreased before and after different offers of NEA [10]. The main reason behind is the frequent power outage and uncertainty of electricity supply besides the major cities of the country. So to make the reliable supply it needs to make a reliable transmission and distribution system along with the reliable source. As hydropower is the main source of energy in the context of Nepal, this paper approaches to rate the risk of hydropower by concerning the reliability of service to implement the risk-based maintenance in hydropower.

2. Methods and material

Aiming to achieve the objectives of the study, the research framework was prepared as shown in the figure 1. And to run the applicability of this methodology, a small run- of – river type hydropower of capacity 4.5MW was selected, and with rated design head 65.4 m and discharge 8.3 m3/s. It has two units of horizontal shaft Francis turbines to generate electricity.

2.1 Risk score through AHP based FTA

Initially the fault tree was constructed as per the failure event recorded in the different log sheet maintained at a different section of hydropower in the period of seven years of operation.To analyze the risk of hydropower from the point of view of reliability, fault tree was computed based on Analytical Hieratical Process (AHP) based fault tree analysis (FTA) technique. AHP based FTA technique was employed because it proscribed to the initial initiating event and can overlook subsystem dependency. This technique employs three theories i.e. setting a hierarchical structure, setting the relative importance and maintaining logical consistency [11]. As per these theories, firstly Fault tree model of hydropower was prepared. The hierarchical structure of fault tree was set as per the events that leads to failure to generate electricity in hydropower. As per the markov three state model, hydropower are guided by two undesirable event i.e Scheduled outage and Forced outage. Scheduled outage covers all the planned events due to which hydropower unable to deliver electricity and Forced outage covers the events that are due to the failure in the components of hydropower [12] . The data such as failure rate and the mean downtime of past seven years of operation, were taken from the maintenance log sheet of the hydropower as provided by the management. The failure rate and Mean down time of each stages was calculated by the following relations.

OR gate:

$$\lambda = \lambda 1 + \lambda 2 + \dots\dots\dots$$

$$MDT = \frac{\lambda 1 \times MDT1 + \lambda 2 \times MDT2 + \dots}{\lambda 1 + \lambda 2 + \dots} \quad (1)$$

Source: [13]

AND gate:

$$\lambda = \lambda 1 \times \lambda 2 \times (MDT1 + MDT2)$$

$$\frac{1}{MDT} = \frac{1}{MDT1} + \frac{1}{MDT2} + \dots\dots\dots \quad (2)$$

Source: [13]

To maintain logical consistency while drawing the decision about most contributing event reliability and availability were calculated from the following relation in each stage of Fault tree.

$$\text{Reliability}, R(t) = 1 - \int_0^t f(t)dt = e^{-\lambda t} \quad (3)$$

Source: [14]

$$\text{Avialability}, A = 1 - \text{Unavailability}$$

$$\text{Unavailability}, U = \lambda \times MDT \quad (4)$$

Source: [14]

2.2 Risk Score through Critical Analysis

After computing the data the most contributing event was identified and the risk was rated in terms of reliability and its contribution in overall reliability of the plant. To validate this result, the risk was calculated through critical analysis was done, concerning the contribution in reliability, availability, production and cost of maintenance. The formula used for calculating Equipment Criticality (EC) was:

$$EC = (30P + 30R + 25A + 15C)/3 \quad (5)$$

Source: [15]

Where, EC: is the equipment criticality (percentage), P: is the contribution in production, R: is the Contribution in Reliability, A: is the equipment availability, C: is the maintenance cost [15]. After identifying the critical assets, the study proceed to find the risk score in component level and this was done through Failure Mode and Effect analysis (FMEA).

With reference to the criticality and risk score, different maintenance strategies were also selected to decrease the risk of the particular component in hydropower. As Risk-based maintenance is the continuous process and after implementing these strategies based on the risk quantified as criticality and score in FMEA, the performance of the system is measured continuously and if the criticality increased, the maintenance strategy will be changed and if the criticality decrease then the other simpler maintenance strategies will be selected.

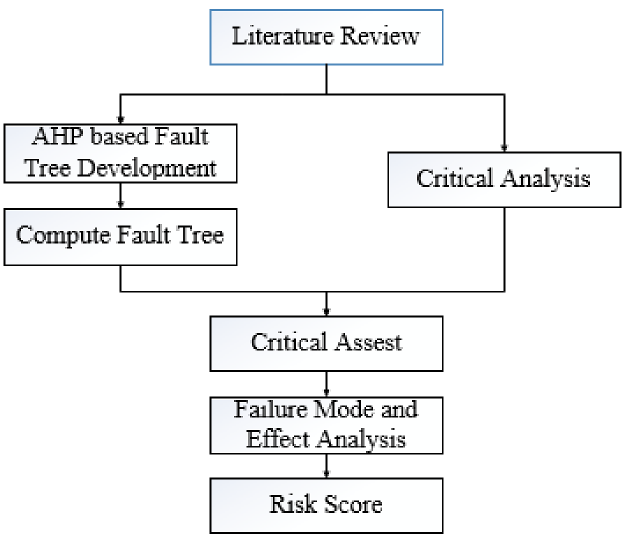

Figure 1: Framework for Risk Rating

3. Results and Discussion

From the analysis of failure event of hydropower under study, the fault tree of the plant were prepared and computed by using the data such as failure rate and mean downtime recorded at the log-sheet of hydropower plant, from fiscal year 2069/70 to 2075/76. The result shows the reliability of unit-I is 0.9268 and unit-II is 0.933. And the overall reliability was found as 0.9813, which was low as compared to Sunkoshi Small Hydropower Plant. As the reliability of Sunkoshi hydropower plant was 0.999 [16]. The study was concerned to the Electromechanical (EM) system, to implement the risk-based maintenance concerning the reliability of the component, so by analyzing the sub-system of the EM system of hydropower, the reliability and availability of unit-I and unit-II are shown in the figure 2. By computing the fault tree and analyzing the result, the reliability and availability of the Turbine section of both the unitsfound less than other sub-systems. It was found that Turbine section of unit-I contributes 54% in the reliability and 83% in availability of EM section of unit-I, similarly, transmission system contributes 33% and 12% in reliability and availability, whereas the contribution of generator section is only 13% and 6% in reliability and availability of EM section of Unit-I.

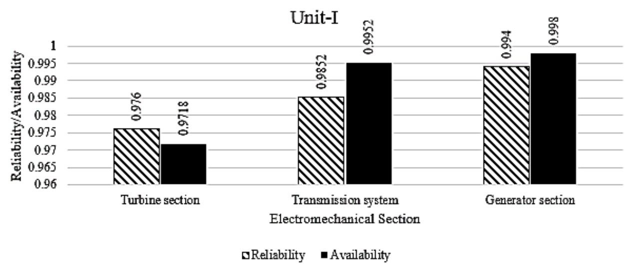

Figure 2: Reliability & Availability of sub-component of Electromechanical section of Unit-I

Likewise, analyzing the data of unit-II, it is found that the Turbine section contributes almost 48% and 64% in reliability and availability. Transmission section contributes 36% in reliability and 31% in availability of electromechanical Section of Unit-II. As in Unit-I, in Unit-II also the generator section has found little contribution in both reliability and availability of EM section of unit-II. It is observed that the generator section contributes only 17% and 6% in reliability and availability of EM section of Unit-II.

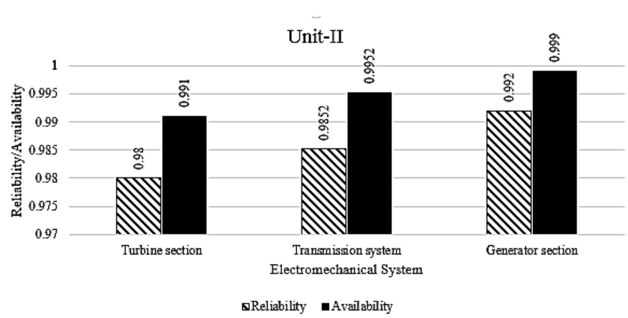

Figure 3: Reliability & Availability of sub-component of electromechanical(EM) system of Unit-II

From both the analysis it was found that the contribution of the turbine section was more in the reliability and availability of the EM section of hydropower under study. From the fault tree analysis, the major failure in turbine section were caused due to failure of cooling system, due to faulty guide-vane, and excessive shaft vibration and problem in gate system. From the analysis, it was found that the contribution of the cooling system in reliability is 72 percent in unit I which is more than other subsystems which are shown in figure 4. In the cooling system, total 40 failures were observed with total breakdown hours of 501 hours in the past seven years of study. Whereas there was only 9 failure in intake gate system, eight failure in guide-vane and 4 failure due to excessive shaft-vibration. However, the breakdown time records higher due to excessive shaft vibration which affects plant for 1116.36 hours where faulty guide-vane and intake system fails for 39.4 hours and 68 hours respectively. In the fault tree faulty guide-vane and excessive shaft vibration are the intermediate events whereas cooling system and intake system are the basic events and the contribution of the cooling system seems more than other events so the cooling system is the critical assets of the unit-I.

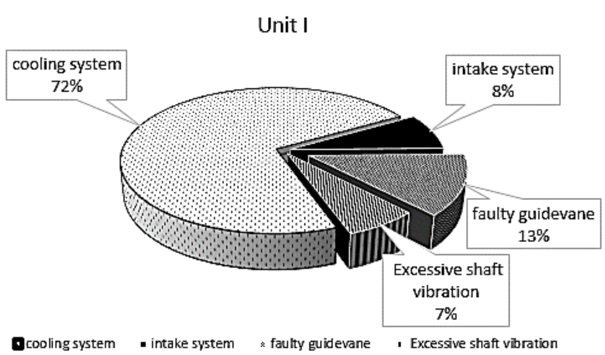

Figure 4: Reliability contribution of the different subsystem in Unit-I

Similarly, from the analysis of failure data of Unit-II, the contribution of the turbine section found more in reliability than other components. In Unit-II also, the contribution of the cooling system in reliability founds more than other subsystems. The contribution of the cooling system was 64 percentage which is more than other subsystems of the problem in the turbine system in the fault tree. From the analysis of data, 33 failure with 295 hours of the outage found recorded in cooling system in the past seven years , and contributes 64% in reliability. Faulty guide-vane is also another sub-system which contributes 27 percentage in the reliability of the plant where it fails for 14 times and disturbs 118.18 hours. Excessive shaft vibration and problem in intake gate fails only for one and three times in seven years period of analysis. The contribution of the different subsystem is shown in figure 5. As cooling system was the basic event of fault tree so critical assets for unit-II was Cooling System. From analysis of bothy the units it was found that system suffers majorly from the failure in the cooling system.

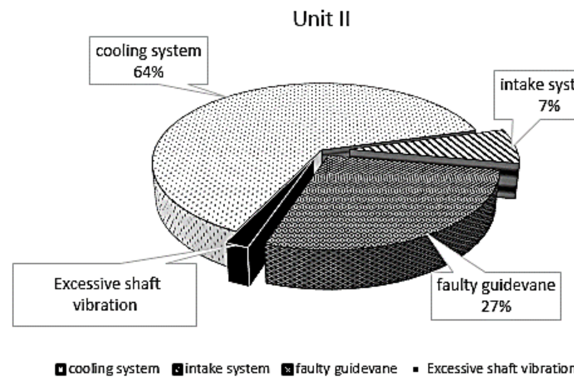

Figure 5: Reliability contribution of the different subsystem of the turbine section of Unit-I

3.1 Rating through Critical Analysis

On the other hand, to rate the risk and validate the result of analysis through AHP based FTA technique, critical analysis of the major component of hydropower were done, where different components were selected from the log sheet as per their contribution to reliability and availability of plant. Concerning the contribution in reliability, availability, impact in production and the cost of maintenance the criticality of the component were calculated. The criticality analysis of Unit-I is shown in the figure 6.

The maintenance strategies were selected based on the criticality of the component. As if criticality is below 50% it was recommended to run to failure maintenance, and if the criticality was above 65% these components were recommended for preventive maintenance. And rest of the components scored between 50% to 65% were recommended to adopt condition-based maintenance i.e proactive maintenance strategy [15]. Those components, which were not included in this analysis, were already filtered from the fault tree as they have less contribution in reliability which ultimately gets the less risk score.

From the critical analysis of unit-I, it was found that, bearing of turbine section, breaker of the transmission

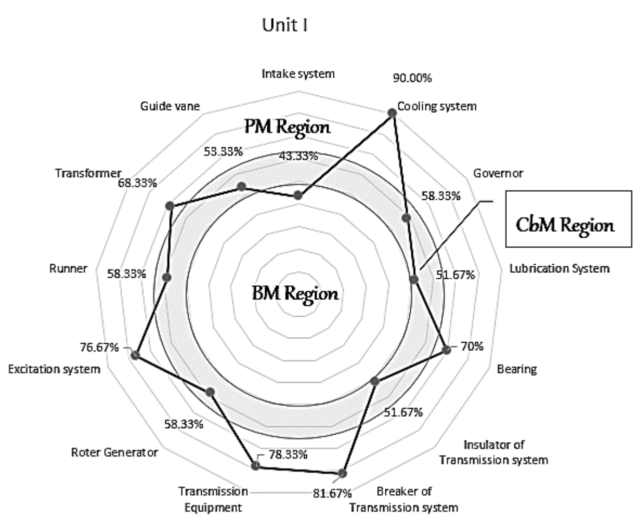

Figure 6: Risk Score through Critical analysis in Unit-I

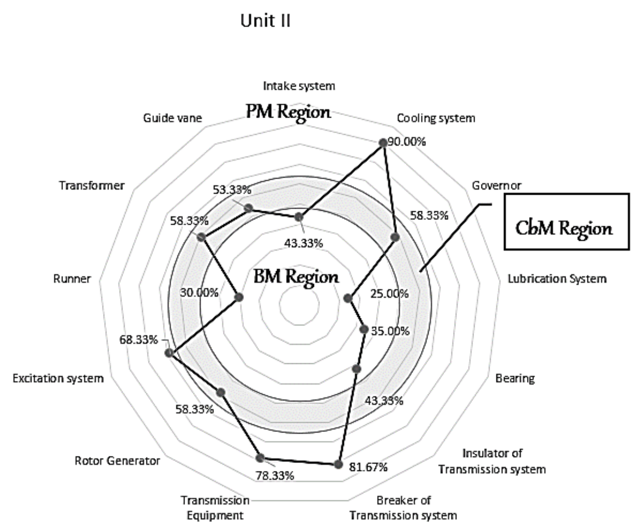

Figure 7: Risk Score through Critical Analysis in Unit-II

system, transmission equipment such as transmission line and transmission tower, excitation system of generator section, and the transformer found higher criticality score which was greater than 65%. So by taking this as a risk score, these are suitable to adopt preventive actions that were recommended by the manufacturer. And other components such as the Governor, Lubrication system, Insulator, Rotor of generator section, Runner, and guide-vane of the turbine section have the intermediate criticality score so these should be condition monitor in the regular basis to reduce the risk criticality level. And other components along with intake system seems less critical as they obtain less than 50% risk score so it is assumed that these will not significantly affects the reliability of unit-I. This will help to reduce non-value-added activities that are spent in the component which have the low-risk level.

Furthermore, from the critical analysis of unit-II, excitation system, breaker of the transmission system and transmission equipment found more critical as their criticality score ranges above 65%, were rated as a highly risky component. So these components were recommended to operate with special care. Components such as runner, insulator of transmission system, bearing, and lubrication system obtain critical score with criticality less than 50% showing the less risk level. So for these components we can adopt breakdown maintenance which is less resource intensive. From above analysis, it is found that, cooling system is the critical assets for both the unit, as it gets highest critical risk score in both the analysis of unit-I and unit-II. And it needs the component level study to improve the reliability of the system, so to generate component level risk score generation, the component of cooling system was proceed to FMEA.

3.2 Rating through FMEA

After finding the cooling system as the critical assets for both the unit, the failure mode and effect analysis was done and the risk score was rated as per the different failure mode they possess and their effect in the performance of hydropower. In FMEA different kinds of potential failure mode were studied and their effect was analyzed with their probable cause. The FMEA risk score of different sub-component was determined based on the difficulty of detection of particular failure mode, the severity of the failure effect and chances of occurrence of that cause. The FMEA risk score for different sub-component of the cooling system is shown in the figure 8.

As per the philosophy of risk based maintenance, every maintenance strategy should be focused on to decrease the risk score as generated from the FMEA. Furthermore, by analyzing the score thus generated, it can clearly say that the main cause of failure in the cooling system was due to the failure in the Radial Tube (RT) filter. Where the failure in cartridge and tube was observed higher than other components of the cooling system. The failure mode was chocking, and deposition in the tube, as the water used in the cooling system was directly taken from the penstock pipe which contains a large amount of limestone that cannot be

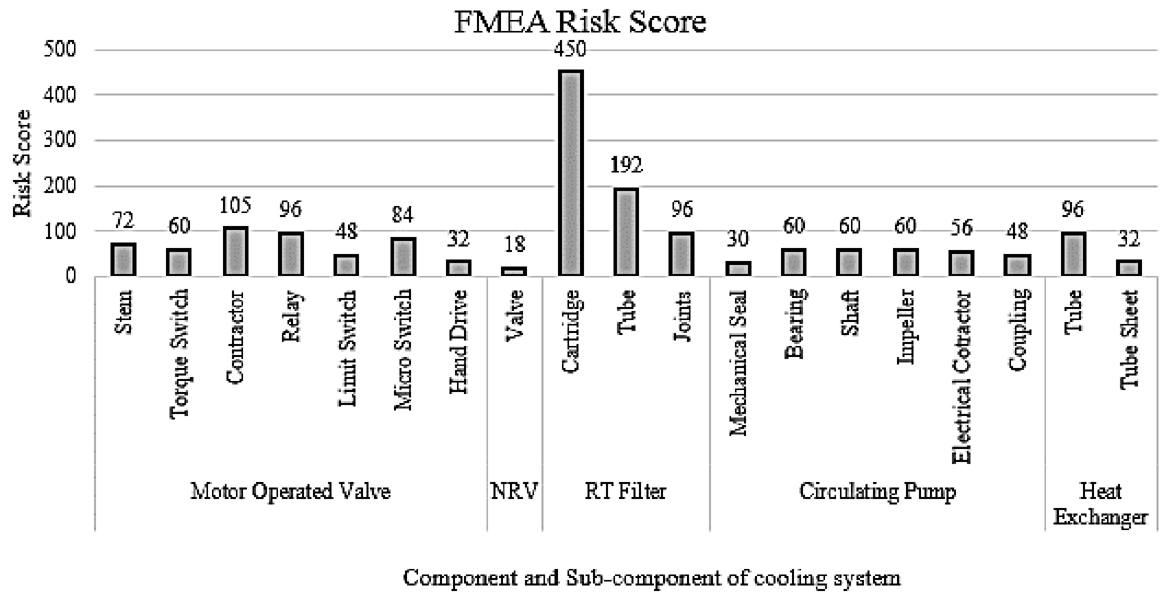

Figure 8: FMEA Risk Score of cooling system

settled in descending basin. So preventive action such as increase the frequency of flushing in RT filter, timely Ultraviolet (UV) thickness detection technique and frequently measure the flow are some of the technique were recommended to decrease the risk score thus generated. And similar kinds of preventive strategies can be used to decrease the rated score as recommended by the manufacturer for the rest of the components of the cooling system. As the risk score of RT filter and its subcomponents was found too high so only preventive strategy may not be sufficient, So with the help of different literature [17] [18] [19], and analyzing the problem of RT filter, following strategies can be implemented after detail cost-benefit analysis if the above mentioned risk-based strategies do not work.

- To use cyclone separator instead of the RT filter
- Making redundant of the RT filter system by adding another parallel RT filter
- By converting the open-loop to close loop water cooling system

These are the risk-based system upgrading strategies that can be used to decrease the current risk level of the cooling system.

4. Conclusion

In this paper, an approach of rating risk of the different component to determine the specific maintenance strategy to implement the fourth generation maintenance has been carried out. And from the results and their analysis, the following conclusions are drawn:

- Overall Reliability Score of unit-I and unit-II of hydropower found as 0.92 and 0.93 which is low as compared to Sunkoshi small hydropower plant, Nepal.
- Reliability Risk score of turbine section found more than other subsystem of both the units, as it contributes 54% and 48% respectively in reliability.
- Contribution of cooling system found more in turbine section of both the units, as it obtain the reliability risk score of 72% and 64% in unit-I and unit-II respectively, which is much more than other components of turbine section
- Chocking in the cartridge of RT filter, layering in tube and leakage from the joints,are the failure mode in RT filter which has higher FMEA score than other components of the cooling system showing the higher criticality of the component.
- Bearings, Breaker of the Transmission system, Transmission equipment, Excitation system and

Transformer of Unit-I and Breaker of the Transmission system, Transmission Equipment and Excitation system of Unit-II are found higher critical score so are recommended to adopt preventive activities as per the manufacturer to reduce the risk in terms equipment criticality score obtained from the critical analysis.

- Lubrication system, Guide-vane, Governor, Insulator of Transmission system, Rotor of Generator, and Runner of the turbine of Unit-I and Guide-Vane, Governor, Rotor Generator and Transformer of Unit-II have the intermediate criticality score so recommended adopting frequent monitoring and recovering technique to minimize the risk of failure.

References

[1] "How Maintenance Practices Have Changed — History of Maintenance," https://ftmaintenance.com/ maintenance-management/ how-maintenance-practices-have-changed-history-of-maintenance/, (Accessed: 2019/11/11).

[2] A.N.S. and M. J., "Risk based maintenance technique and application," *Journal of Hazardous material*, pp. 653–661, 2007.

[3] D. Kiran, "Realibility Engineering," in *Total Quality Management*, pp. 391–404. Butterworth-Heinemann, 2017.

[4] ISO, "Quality Management System-Requirements," International Organization for Standardization, Geneva, Switzerland, 2015.

[5] C. Okeefe, "www.sooperarticles.com," *Sooper Articles*, 2012, https://www.sooperarticles.com/technology-articles/importance-reliability-business-how-provide-1105525.html, (Accessed: 2020/08/08).

[6] T. Hadush, "Need for improved reliability of electricity supply in Ethiopia", (Interview: 2017/03/10).

[7] "Concept paper of 15th five-year plan," National Planning Commission, Government of Nepal, Kathmandu, Nepal, 2019.

[8] "Energy data sheet," Nepal Water and Energy Commission Secretariat, Kathmandu, Nepal, 2014.

[9] "NEA annual report - 2076," Nepal Electricity Authority, Kathmandu, 2076.

[10] "Foreign Trade Statistics of Nepal - Annual Trade Data for Fiscal Year 2075/76 (2018/19)," Trade and Export Promotion Centre, Ministry of Industry, Commerce and Supplies, Government of Nepal, Kathmandu, 2019.

[11] O. S. and K. S. Vaidya, "Analytic hierarchy process: An overview of applications," *European Journal of operational research*, vol. 169 , no. 1, pp. 1–29, 2006.

[12] A. R Majeed and N. M. Sadiq, "Availability and Reliability Evaluation of Dokan Hydro Power Station," in *2006 IEEE/PES Transimission and Distribution Conference and Exposition: Latin America*, 2006.

[13] D. J. Smith, *Reliablity, Maintainability and Risk*, Sixth edition, pp. 104–105. Butterworth-Heinemann, London, England, 2001.

[14] S. Chaturvedi, "Reliability model and failure parameter grouping for maintenance analysis of hydro power plants: a review," *International Journal of Advance Research in Science and Engineering*, pp. 957-965, 2018.

[15] A. Gomaa, "Maintenance Planning and Management, A Literature Study," American University in Cairo, Cairo, 2003.

[16] D. Sapkota, T. R. Bajracharya and M. C. Luitel, "Reliability and Availability Evaluation of Sunkoshi Hydro Power Station," in *Proceedings of IOE Graduate Conference*, Kathmandu, Nepal, 2014.

[17] B. J. Flehinger, "Reliability Improvement through Redundancy at Various System Levels," *IBM Journal of Research and Development*, vol. 22, doi:10.1147/rd.22.0148 , pp. 148–158, 1958.

[18] S. Kaushish and B. Naidu, "Silting Problems in Hydropower Plants," in *Proceedings of the 2nd International Conference on Silting Problems in Hydropower Plants*, 2002, AA Balkema Publishers Bangkok, Thailand.

[19] S. K. Shah and D. R. Shrestha, "Design Modification of Cooling Water System for Hydropower Plants [A Case Study of Middle Marsyangdi Hydropower Plant in Nepal]," *Global Journal of Researches in Engineering*, vol. XV, no. VI, pp. 9–16, 2015.