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Failure Behaviour of the Shiroro Hydroelectric Power Station Turbo-Alternators: A Performance Evaluation

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Abstract: *A reliable electrical power supply is non-negotiable for national growth and development, as electricity is needed in virtually every sector of production and commercial activities. The Shiroro hydroelectric power station (SHEPS) commissioned in 1990 comprises four units of turbo-alternators made of Francis turbine rated at 150 MW each. In this paper, an EXCEL-VBA script was used to extract a contiguous set of up and down times which were used to compute 'time-between-failures' (TBF). The failure events and failure rate of each unit were estimated using the power generation data of the station from the year 2008 to 2015. A structured database was organized for accurate analysis. Unit 3 was found to have the longest TBF with a value of 46 days, while the least was found in unit 1 with a value of 17 days. The Reliability value of each unit was also computed and unit 3 was found to be the only unit having a value up to 70%. SHEPS was found to still be in its productive age and possesses a tendency of still generating close to the rated value if properly refurbished.*

Keywords: *Turbo-alternators, Failure events, Failure rate, Time-between-failures, Nigerian Shiroro Hydro-Station.*

1. INTRODUCTION

As at January 2019, Nigeria power generation still lies below 10,000 MW (Transmission Company of Nigeria [TCN], 2019), which is still far below the expected value that can supply the ever-increasing energy demand. The per capita consumption of electricity in Nigeria is 12 W as compared to that of South Africa which is 496 W and that of the USA is 1,363 W (Onakoya, Onakoya, Jimi-Salami, & Odedairo, 2013). This is a great set back to the development of the nation and calls for a way out of the unsustainable power supply.

Hydropower constitutes about 29% of the Nigerian power generation system (Thomas, Akorede, Ogunbiyi, Olufeagba, & Samuel, 2017) of which Shiroro Hydroelectric Power Station (SHEPS) is one of the three major stations. It is situated in the Shiroro Gorge on the Kaduna River, approximately 60km from Minna, capital of Niger State (Gbadamosi & Ojo, 2015). The station was commissioned in June 1990 (Gbadamosi & Ojo, 2015; Zarma, 2006). This made the Shiroro project the 3rd hydroelectric power station and the 6th generation station in Nigeria (Zarma, 2006).

The plant has an installed capacity of 600 MW from four generating units rated at 150 MW each at a net head of 97m (Zarma, 2006). Each unit comprises a vertical Francis type hydraulic turbine because of its robustness and sustainability against high mechanical stress resulting from high heads. The Francis turbine is controlled by an electro-hydraulic governor system. The turbine drives a synchronous generator of salient pole construction having a net output of 150 MW.

The Shiroro dam is made of concrete face rock fill (CFRD) dam with a crest length of 700 m rising 125 m above the original river bed, the width of the dam at its toe is over 300 m, whilst its crest accommodates a 7.5 m wide service road (Gbadamosi & Ojo, 2015). The failure condition of the plants required examination as the station generation capacity is below 65% of the rated capacity (Gbadamosi & Ojo, 2015), and a critical study of the plant's conditions could provide the management with ample information for proper decision making in terms of maintenance and upgrade.

The Failure of a system is better prevented than 'removed' after occurrence, it is natural for any system under operation to experience failure due to some reasons. The failure of an engineering system is better prevented than allowed to occur for repairs to be carried out, at a cost (e.g. cost of spare-parts, skilled labour, logistics, etc.). So, the analysis of failure behaviour of engineering systems is important, especially those that are of germane function(s).

The failure of a turbo-alternator is an event after which the machine becomes unable to perform its function. Some breakdown systems or objects could be repaired as and when they experience failure. Therefore, repairs are applicable to systems or equipment that can afford to fail more than once, such as a turbo-alternator which can undergo several repairs (Thomas, Akorede, Ogunbiyi, &Olufeagba, 2018). Turbo-alternator as a single system has no redundancy built in it and hence has its operational status as either functioning or not, that is, it has ‘up’ (functioning) and ‘down’ (breakdown) states. There are four possible transitions between the two states, 0 to 0, 0 to 1, 1 to 0 and 1 to 1. This is illustrated in Figure 1 (Thomas, Akorede, Ogunbiyi, &Olufeagba, 2018), where λ is the failure rate, while μ is the repair rate. It is to be noted that the failure rate is measured in terms of “failure per day”.

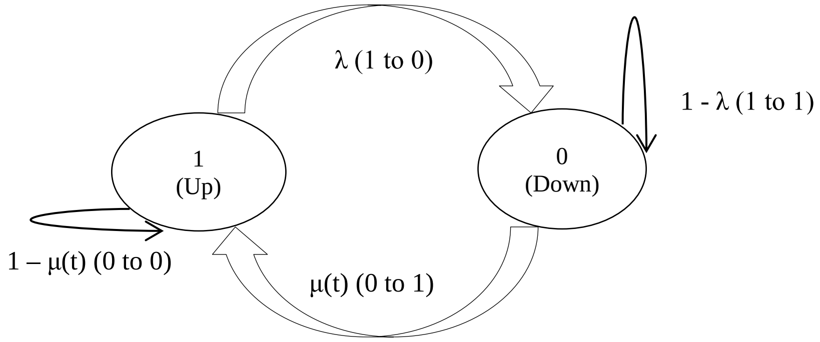

Figure 1: State Diagram of a two-state system

A ‘failure event’ or just an ‘event’ is defined as a single occurrence of contiguous up-state that is a period without an interruption in the functionality of the machine.

2. MATERIALS AND METHODS

The generation record of the 4 turbo-alternators at the SHEPS for the period of 2008 to 2015 was collected and organized into an EXCEL VBA® database, which is necessary for proper and accurate reference and calling-up of a particular range of values.

The way the failures occur may be random but the duration when the unit is functioning will also be essentially random and will tend to satisfy the exponential distribution, a condition that is true during the useful life of the unit (O’Conor, 1981).

The period of time from a repair time to a breakdown (a functional period without a breakdown, a single up-time) is known as time-between-fail (TBF) (PALL corporation, 2006).

Mean-Time-Between-Failures (*m*) of a particular turbo-alternator is the average time that is equivalent to the individual TBFs of the alternator under the period considered, and it is measured in ‘*days*’.

Given f(t) as the probability density function (PDF) of TBF of a turbo-alternator unit, f(t) can be expressed as given in Equation (1) (Adediran, 2014).

$$f(t) = \lambda \ell^{-\lambda t} = \frac{1}{m}\ell^{-1/_m t}, t \geq 0, \lambda > 0, m > 0 \quad (1)$$

where: $\lambda = \frac{1}{m}$ (2)

t = Operating time

Mean time to failure (MTBF) viewed from time of observation, γ can be expressed as:

$$m = \int_{\gamma}^{\infty} tf(t)dt = \int_{\gamma}^{\infty} t\lambda e^{-\lambda t}dt = \gamma + \frac{1}{\lambda} \quad (3)$$

$$m = \gamma + \frac{1}{\lambda} = \frac{1}{\lambda}, \quad for\ \gamma = 0 \quad (4)$$

It can be seen from Equation (4) that MTBF is the inverse of the exponential distribution's constant failure rate, and this is only true for the exponential distribution.

The work here studied the distribution of failures in the third decade of operations and drew conclusions about the process best approximating the stochastic process.

In order to study stochastic process representing the time -to -fail of a unit, assume that $T_{up1,k}$ is the time at the start of an 'up' period, k, and $T_{up2,k}$ is the time when the unit fails.

The boundary of the kth running period designated as $t^j_{up,k}$ for the j-th unit satisfies the expression:

$$t^{j}{}_{up,k} = T^{j}_{up2,k} - T^{j}_{up1,k} \quad (5)$$

In order to generate the sequence of time-to-fail, an algorithm shown below was realized. It involves generating a variable that is "0" if a unit is non-functional due to breakdown or servicing and "1" when operational. This definition may experience problems in instances where units work for part of a day. In this work, units that are not available for the full day were assumed to have failed.

Let P_{ji} be the output energy for TA_j on day i in the database, then the auxiliary sequence for daily condition of the TA_j satisfies Equation (6).

$$W_{ji} = \begin{cases} 0, if\ P_{ji} < 0 \\ 1,\ if\ P_{ji} > 0 \end{cases} for\ i = 1,2, \ldots ,2923 \quad (6)$$

The set $\{W_{ji}\}$ contains all the information about the condition of the units over the given period. An algorithm was designed to determine the number of working days for each set of contiguous 'ones'. It employs a number of variables internally for enabling the count and was realized as shown in the flowchart in Figure 2.

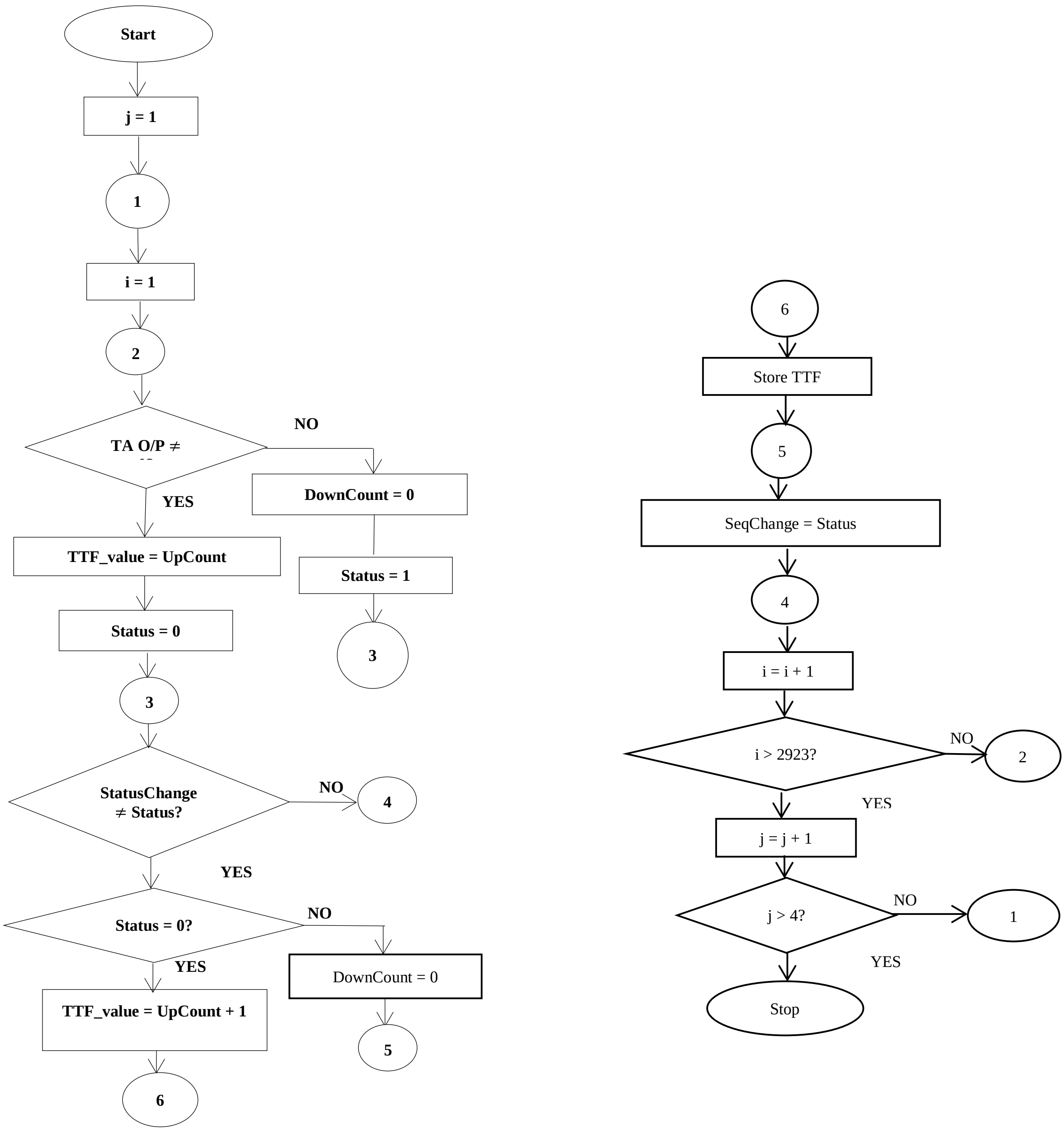

Figure 2: Flowchart for Extraction of TTF for TA Units 1 to 4.

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3. RESULTS AND DISCUSSION

Table i shows the distribution of failures event, the algorithm set up in Figure 2 was developed with EXCEL VBA scripts and applied to the database of the 8 years generation record of the SHEPS. It can be seen from Table 1 also that unit 3 has the minimum number of events, while unit 1 has the maximum number of events.

Table i: Summary of TBF variables

TA Unit	Min Event	Max Event	No. of Events
1	1	17	592
2	1	38	543
3	1	46	482
4	1	31	583

The sequence of the TBFs was computed, and these are shown in Figures 3 to 6, as seen in the plots unit 3 exhibits the longest range of TBF, while the shortest maximum value of TBF was seen in unit 1.

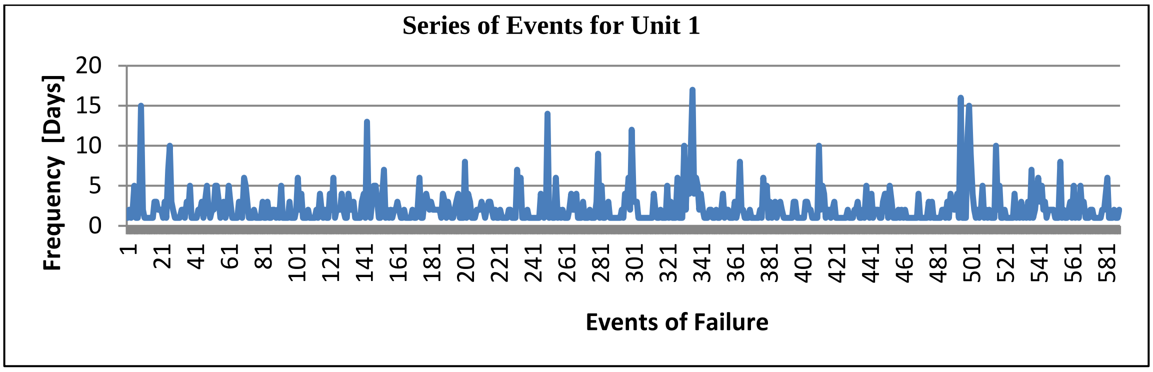

Figure 3: Sequence of Time-between-failure of Unit 1

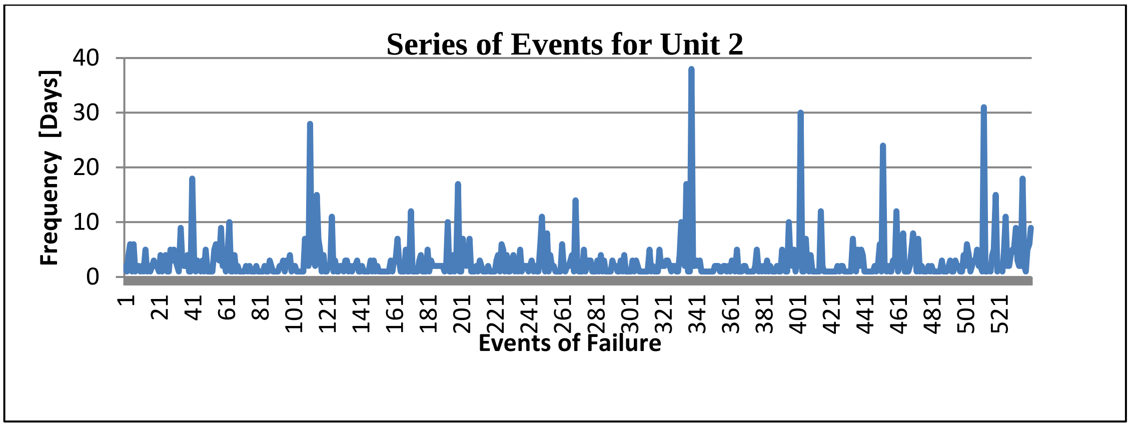

Figure 4: Sequence of Time-between-failure of Unit 2

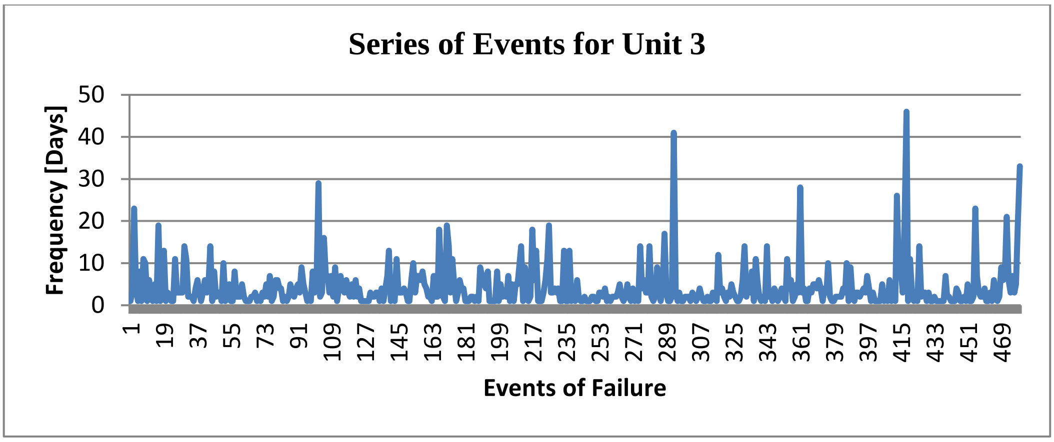

Figure 5: Sequence of Time-between-failure of Unit 3

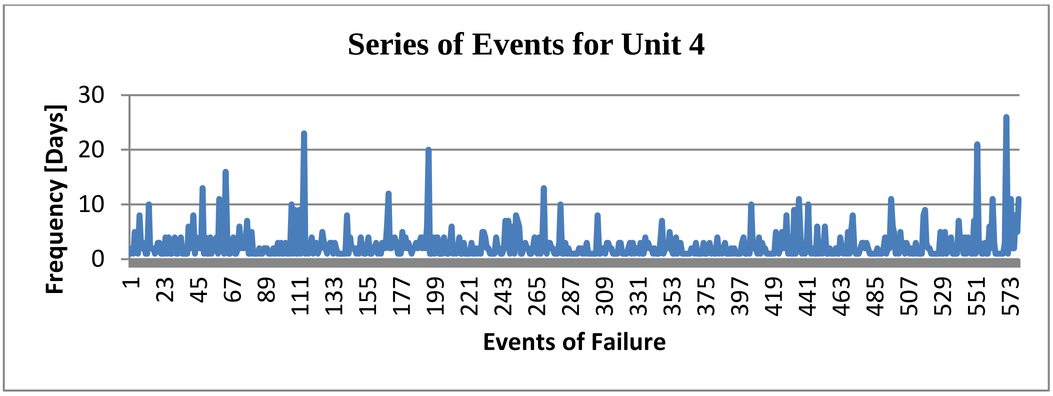

Figure 6: Sequence of Time-between-failure of Unit 4

In order to study the nature of the failure process, an approximate distribution was determined by constructing the histogram of the process. A 'class' is a set of data that closely fit into a single event, and the class width is selected such as would best fit the number of events available for each unit.

The histogram distribution for each turbo-alternator are shown in Figures 7 to 10, and the study of these distributions reveals the shape of an exponential distribution, which shows that the trend pattern of the station failure and that of TA's are in their useful age. In all cases, the histogram seems to portray a process that is maximum at the start and tapers off with time.

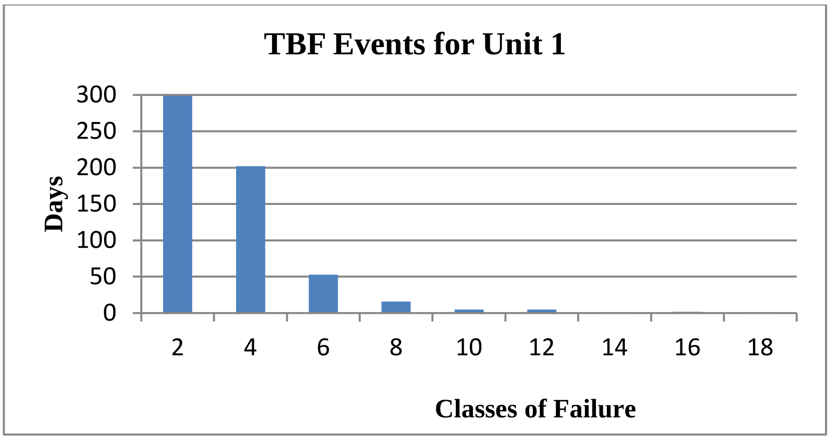

Figure 7: Event Distribution for Unit 1

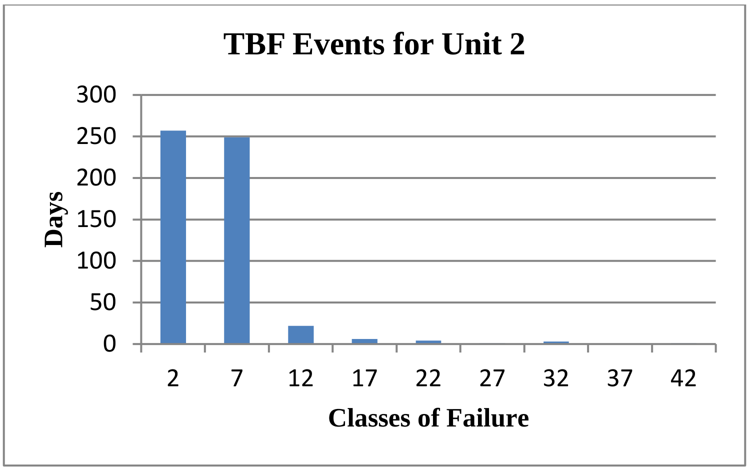

Figure 8: Event Distribution for Unit 2

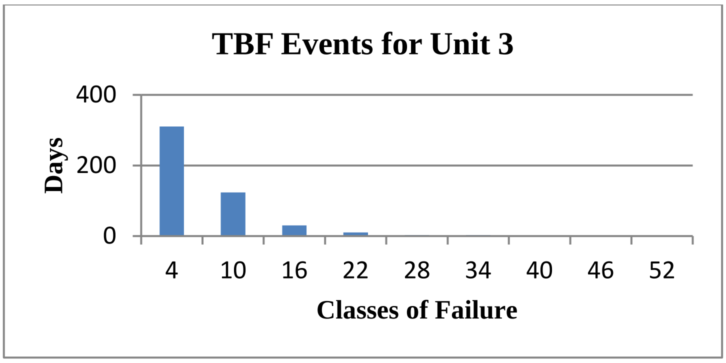

Figure 9: Event Distribution for Unit 3

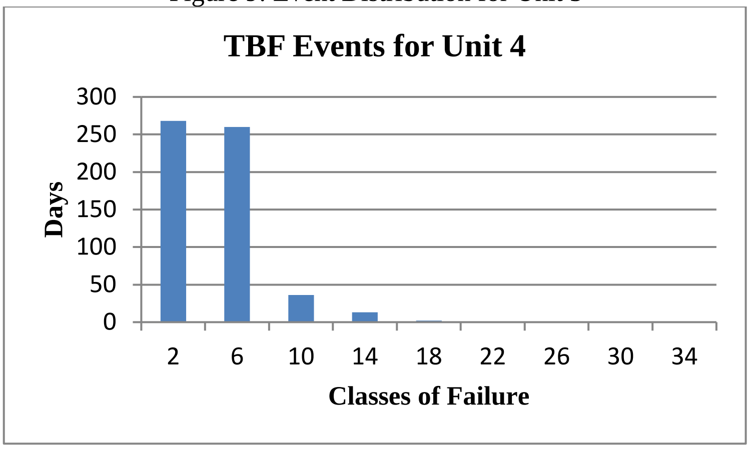

Figure 10: Event Distribution for Unit 4

4. CONCLUSIONS AND RECOMMENDATIONS

The power generation situation at the Shiroro hydropower station has been considerably analysed, and the performance of each of the units in the station was also recorded and the data base of 8years (2008-2015) was prepared for the station, Microsoft EXCEL was used in the preliminary analysis of the performance of the station.

In this study, performance evaluation has been carried out on Shiroro hydropower plant with emphasis on the operational parameters such as availability factor and overall reliability of the plant.

The preliminary study of the distribution shows that only turbo-alternator 3 has the reliability to be more than 70%, the remaining units are found to have Reliability values less than 70%.

Conclusively, the system is not adequate to meet the load demand due to low reliability of the constituent units. Further works on this station could include detailed Reliability study, Efficiency evaluation etc.

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