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TECHNICAL ARTICLE—PEER-REVIEWED

Evaluation of Failure and Repair of the Jebba and the Shiroro Hydroelectric Power Stations

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Abstract Nigeria power generation hovers around 7000 MW as at January 2019; this is far less than the national required electricity per capita value. Jebba Hydroelectric Power Station (JHEPS) and Shiroro Hydroelectric Power Station (SHEPS) are two of the three major hydropower stations in the country in which their maximum average generation values are still less than the rated values of 578.4 MW and 600 MW, respectively. This paper presented some basic concepts of analysis of failure and repair. An algorithm was set up to extract the contiguous set of uptimes and downtimes to determine time-between-failures (TBF) and time-between-repairs (TBR) events; these events were analyzed for the stochastic study. It was observed that the longest uptime was 262 days and seen in turbo-alternator unit five, while the shortest was zero day and seen in the entire units except that of unit two. For JHEPS, the longest downtime was 133 days and seen in the turbo-alternator of unit one, and the least time-between-repairs is a day and common to all the units. The frequency distributions for both TBF and TBR showed that 79% of TBF events and 57% of TBR events are distributed in the first two classes. For SHEPS, 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.

Keywords Uptime · Hydroelectric · Turbo-alternator · Time between failures · Time between repairs · Contiguous state · Useful life

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Introduction

The economy of a society is greatly influenced by adequate provision and efficient distribution of electricity [1, 2]. It is in this light that this paper presents the study of one of the two major hydropower stations in Nigeria—the Jebba and the Shiroro Hydroelectric Power Stations.

Nigeria is a country with a population of about 190,000,000 and the most populous in Africa. As at December 2018, the population of Nigeria was estimated around 190,000,000 and the peak generation attained by the generating companies was around 7000 MW. Compared to South Africa, a nation well on its way to being in the class of top 20 economies, with a population of 50,000,000 people, has a grid-based generating capacity of

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40,000 MW [3]. Nigeria's population has rapidly increased to 180 million, and it is expected to reach 230 million by the year 2030; its electricity generation was less than 4000 MW [4] as at 2015, although a peak generation of 5074.7 MW was recorded as at October 2016 but only lasted for a few days [4].

JHEPS is located on the river Niger, about 64 miles due south of a much larger dam—the Kainji and approximately 350 km away from Lagos, Nigeria. It was built between 1981 and 1983, operation commenced in 1984, although official commissioning took place on April 13, 1985. It has six Kaplan reaction-type turbines, each using a five-bladed runner directly coupled to compatible alternators to give turbo-alternators [5, 6] rated at 96.4 MW and operating at a synchronous speed of 93.75 rpm [5] with a head of 27.6 m and a fast flow rate of 380 m^3/s. The dam with a live storage capacity of about 1,000,000,000.0 m^3 is constructed from zoned earth and rockfill materials and has a crest elevation of 108.0 m, when operating normally; the water level is about 99.0 m [5]. It has a spillway capable of discharging up to 13,600 m^3/s under normal operating conditions and 16,400 m^3/s at both 106.0 m elevation and emergency spillway levels. Each unit has an alternator that is linked to the turbine via a vertical shaft and generates at 16 kV, 50 Hz with a nominal power factor of 0.85. The electrical output from each unit is directly coupled to a compatible step-up transformer designed to produce 330 kV from the generated 16 kV [5].

SHEPS is situated in the Shiroro Gorge on the Kaduna River, approximately 60 km from Minna, capital of Niger State; the station was commissioned in June 1990 [7, 8]. The plant has an installed capacity of 600 MW from four generating units rated at 150 MW each at a net head of 97 m; each unit comprises a vertical Francis-type hydraulic turbine because of its robust and sustainability against high mechanical stress resulting from high heads [7].

Failure and Repair Concepts of a Turbo-Alternator

Failure of a turbo-alternator is an event after which the system is incapacitated to perform its purpose, i.e., the machine is in down state. Products like bulbs once failed cannot be repaired; therefore, repair is only applicable to a system which does not fail ones, and an example of such is a turbo-alternator which can undergo several repairs. 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) or 'down' (breakdown) states as shown in Fig. 1.

The state diagram is as shown in Fig. 2; since there are two states, there are 2^2 (four) possible transitions between the two states, 0 to 0, 0 to 1, 1 to 0 and 1 to 1; this is also illustrated in Fig. 2. λ is the hazard or failure rate, while μ is the repair rate.

In Fig. 3, the period of time from a repair time to a breakdown (a functional period without a breakdown, a single uptime) is known as time between failures (TBF) [9]. In contrast, the period of a single downtime is known as time between repairs (TBR) [10].

Computation of Time Between Failures and Time Between Repairs

To study the stochastic process representing the time between failures of a unit, assume that $Q_{\mathrm{up1},k}$ is the time at the start of an 'up' period, k, and $Q_{\mathrm{up2},k}$ is the time when the unit fails.

Then, the duration of the kth running period designated as $q^{w}_{\mathrm{up},k}$ for the w-th unit satisfies the expression:

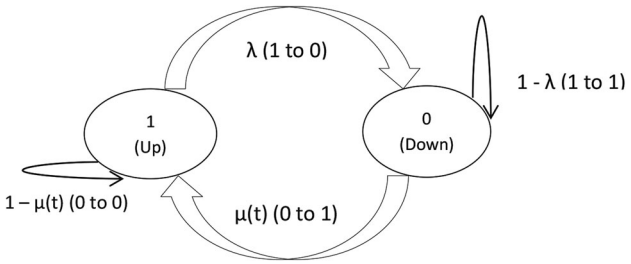


Fig. 2 State diagram of a two-state system

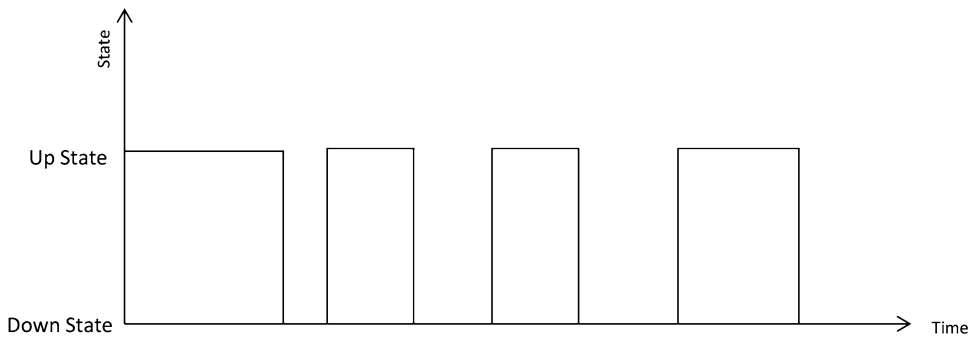


Fig. 1 Time diagram of a two-state system

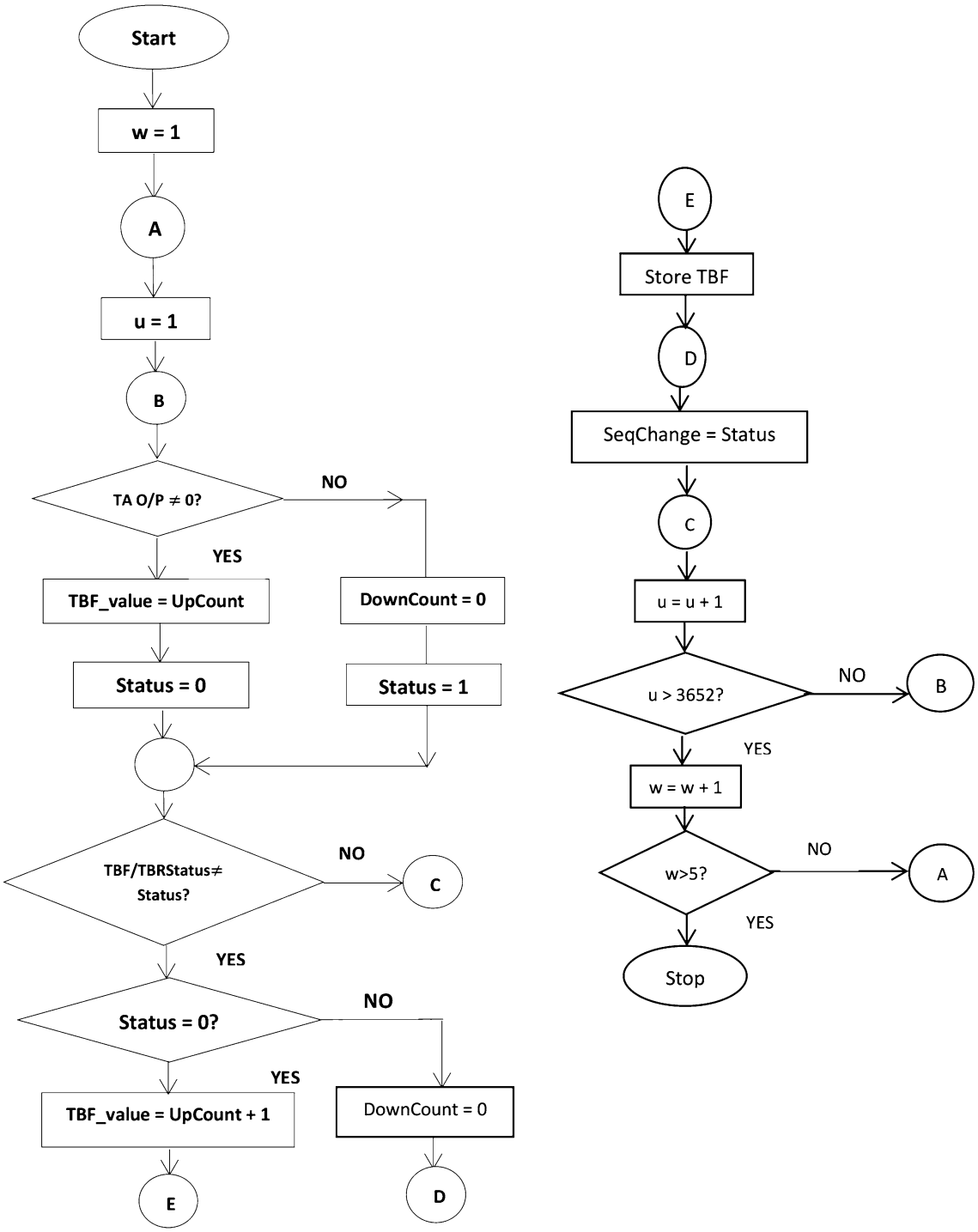


Fig. 3 Flowchart for extraction of time between failures for turbo-alternator units 1 to 5. O/P—output, *w*—number of available turbo-alternators, *u*—numbers of days in view, *k*—event counter

$$q^{w}_{\mathrm{up},k} = Q^{w}_{\mathrm{up2},k} - Q^{w}_{\mathrm{up1},k} \quad \text{(Eq 1)}$$

In order to generate the sequence of time between failures, an algorithm shown below was realized. It involves generating a variable that is zero 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 E_{wu} be the output energy for TA_w on day u in the database; then, the auxiliary sequence for daily condition of the TA_j satisfies:

$$H_{wu} = 0, \text{ if } E_{wu} = 0, \\ = 1, \text{ if } E_{wu} > 0, \quad \text{for } u = 1, 2, \ldots, 3652 \text{ [i.e. 10 years period]} \quad \text{(Eq 2)}$$

The set $\{H_{wu}\}$ 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 Fig. 3.

The study of failures of unit w is the study of the distribution of the spell of uptimes or time-to-failures for the unit. The sequence of time between failures for each TA for a period of a single event is given as Y^w

$$Y^w = \{t^w_{\text{up},k} : k = 1, 2, \ldots, N^w_{\text{up}}\} \quad \text{(Eq 3)}$$

where N^w_{up} is the total number of 'uptimes' events for the w-th TA.

A stochastic approach was applied to study the distribution failure satisfied by the sample, Y^w. Sturges' rule was adopted to determine the intervals and exploit both basic and internal functions to extract the frequencies of occurrence of each interval [11].

$$y = 1 + 3.3 \log N \quad \text{(Eq 4)}$$

$$c = \frac{max[A] - min[A]}{y} \quad \text{(Eq 5)}$$

where y—is the number of class intervals; N—number of samples available; A—the set in view, which may be either the sequence of time between failures or time between repairs; c—the class width.

The frequency function of EXCEL-VBA was used for grouping the failure and repair events.

Results and Discussion

For JHEPS, unit 1 recorded the least events for both failures and repairs, it has 88 breakdowns and 87 repairs within a period of 10 years (2005 to 2014), and this is closely followed by unit 2. TA2 recorded the highest number of events; it has 151 failures and 150 repairs events. It was observed that all the TAs except that of unit 4 had their numbers of TBF a unity higher than that of TBR, this implies that such TAs are working as at the end of data computation.

For SHEPS, the number of events seems often than that of JHEPS as there are 592, 543, 482, and 583 in units 1, 2, 3, and 4, respectively. The longest event for units 1, 2, 3, and 4 is 17, 38, 46, and 31, respectively, as seen in Fig. 4.

Time-Between-Failures Events for JHEPS

The frequency distribution of TBF of each unit is shown in Table 1. TBF values are in days, while the 'frequency' is the number of events within a range of TBF in a particular class.

The width of the class for each TA unit differs because the number of events is not uniform for all the units. In Table 1, it can be seen that the first class possesses the highest number of data in all the units.

In all the cases, the histograms seem to portray a process that is maximum at the start and tapers off with time. Nonetheless, caution must be taken because some of the histograms manifest behavior indicative of possibly more than one process.

Time Between Failures for SHEPS

The sequence of the TBF was computed; these are shown in Fig. 5a to d; as seen in the plots, unit 3 exhibits the

Table 1 Grouped data of histogram of time between failures

	TA unit 1		TA unit 2		TA unit 3		TA unit 4		TA unit 5	
Class	TBF	Frequency	TBF	Frequency	TBF	Frequency	TBF	Frequency	TBF	Frequency
1	1–22	38	1–22	128	1–25	52	1–14	87	1–30	96
2	23–44	35	22–46	14	26–50	23	15–28	26	31–60	25
3	45–66	6	47–69	1	51–75	5	27–42	10	61–90	1
4	67–88	0	70–92	4	76–100	3	43–56	4	91–120	0
5	89–110	4	93–115	2	101–125	1	57–70	1	121–150	1
6	111–132	2	116–138	1	126–150	5	71–84	0	151–180	0
7	133–154	2	139–161	0	151–175	1	85–98	0	181–210	0
8	155–176	0	162–184	0	176–200	0	1	1	211–240	0
9	177	1	185–207	0	201	1	113	1	241	2
10	…	…	298	1	…	…	…	…	…	…

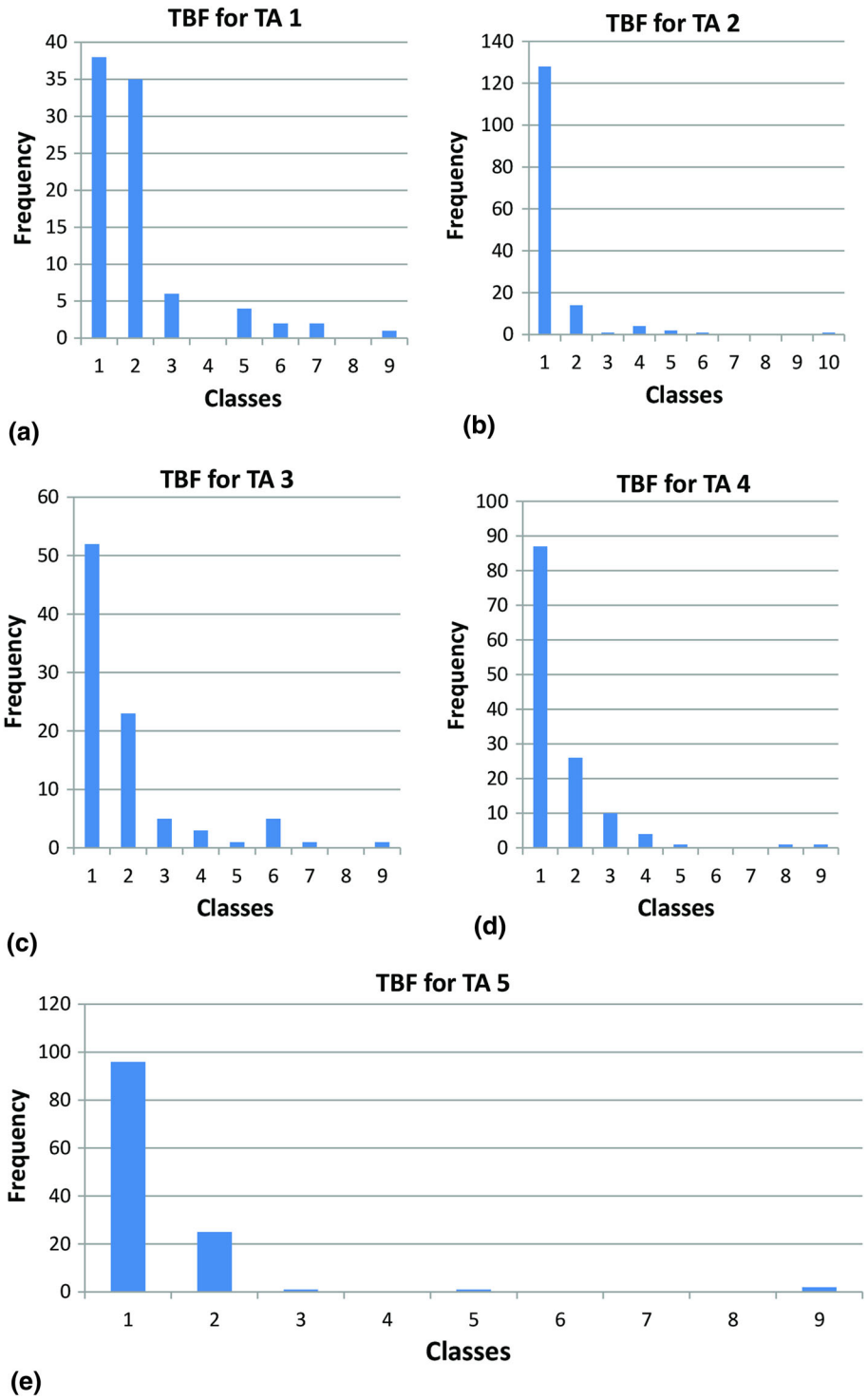


Fig. 4 Distribution of TBF events for JHEPS: (**a**) unit 1, (**b**) unit 2, (**c**) unit 3, (**d**) unit 4, (**e**) unit 5

longest range of TBF, while the shortest maximum value of TBF was seen in unit 1.

In all cases, the histogram seems to portray a process that is maximum at the start and tapers off with time.

Time-Between-Repairs Events

The frequency distribution of TBR of each unit is shown in Table 2; all the TA has the longest TBR in the first group which is an indicative of good repair culture as short times are spent in repairing the TAs. A good repair characteristic

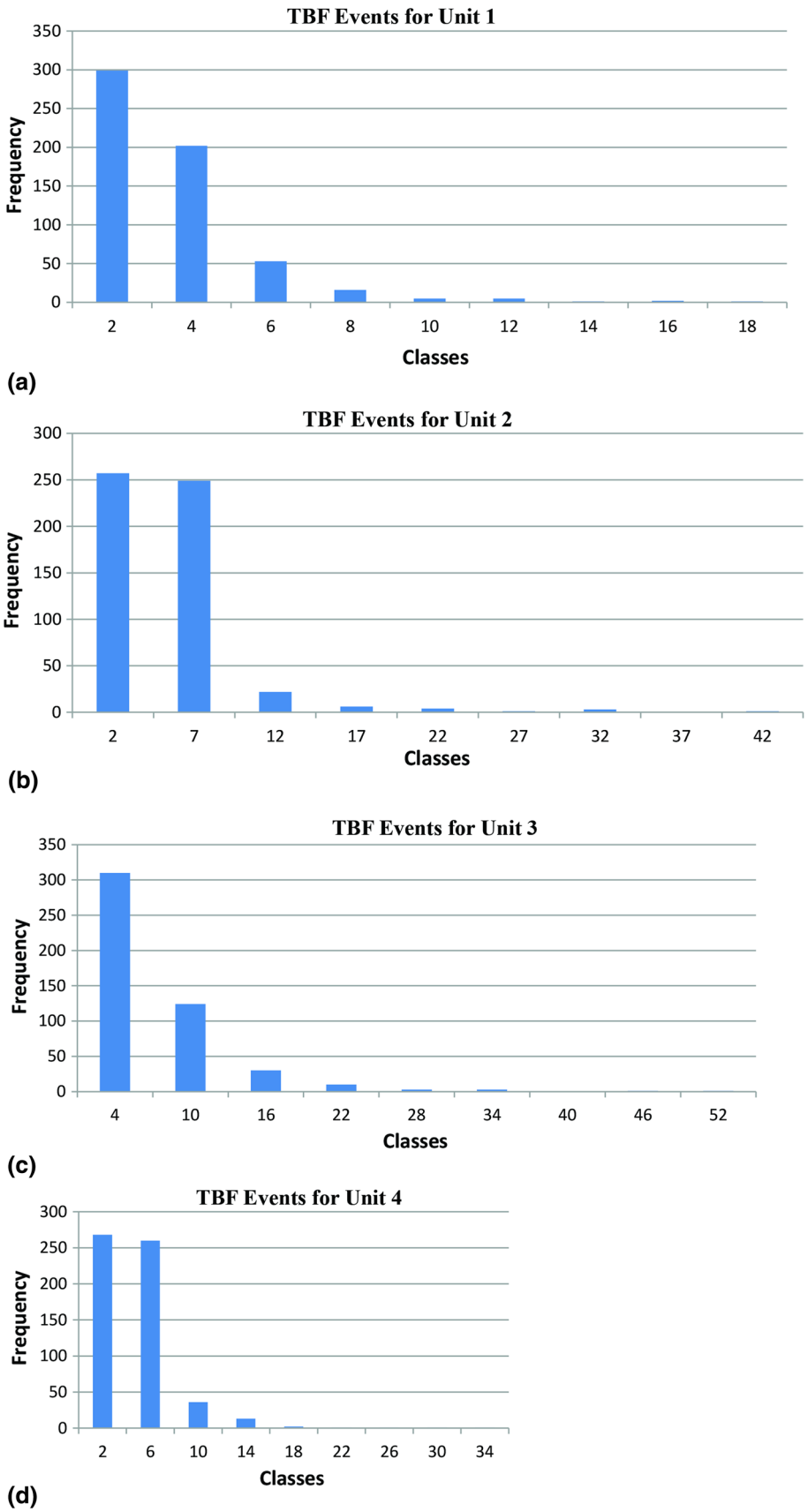


Fig. 5 Distribution of TBF events for SHEPS: (**a**) unit 1, (**b**) unit 2, (**c**) unit 3, (**d**) unit 4

Table 2 Grouped data of histogram distribution of time between repairs

	TA unit 1		TA unit 2		TA unit 3		TA unit 4		TA unit 5	
Class	TBR	Frequency	TBR	Frequency	TBR	Frequency	TBR	Frequency	TBR	Frequency
1	1–16	70	1–3	67	1–5	63	1–14	87	1–5	71
2	17–32	13	4–6	19	6–10	9	15–28	17	6–10	25
3	33–48	1	7–9	8	11–15	2	29–42	15	11–15	13
4	49–64	1	10–12	5	16–20	2	43–56	4	16–20	5
5	55–80	1	13–15	14	21–25	3	57–70	6	21–25	5
6	81–96	0	16–18	11	26–30	6	71–84	0	24–30	1
7	97–112	0	19–21	12	31–35	2	85–98	0	31–35	2
8	113–128	0	22–24	4	36–40	2	99–112	0	36–40	1
9	129	1	23–27	4	41	1	113	1	41	1
10	…	…	…	6	…	…	…	…	…	…

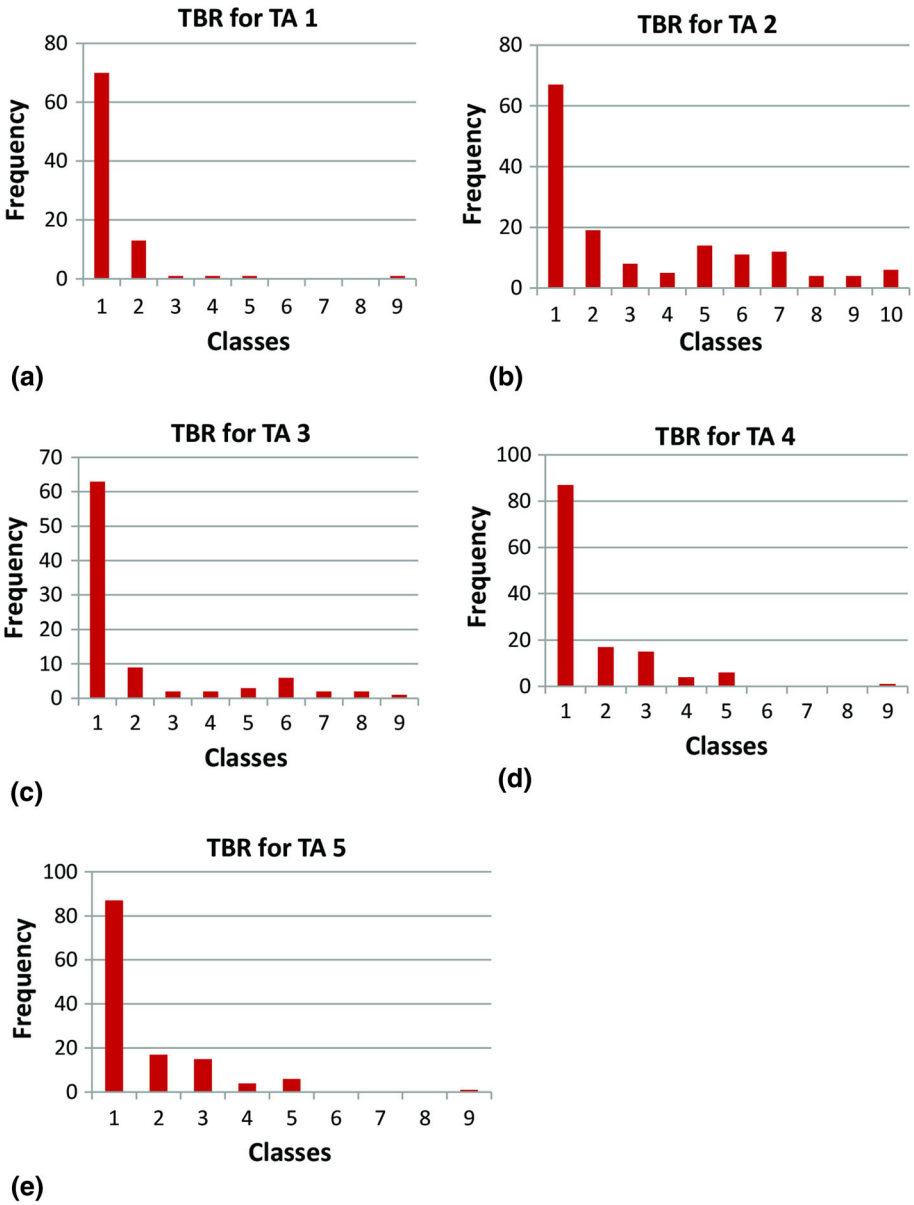


Fig. 6 Time-between-repairs distribution for JHEPS (2005–2014): (**a**) unit 1, (**b**) unit 2, (**c**) unit 3, (**d**) unit 3, (**e**) unit 5

is said to be that that has most of its TBR in the earlier groups.

Table 2 shows the repair distribution of the JHEPS; most of the repair events are distributed to the least classes of the group. Histograms are shown in Fig. 6.

Conclusion

TBF distributions of the TA at JHEPS are in the earlier frequency group; this shows that there are more short times to breakdown than long times which is a bad behavior. The maximum uptime recorded during this period is 262 days (approximately 9 months) as seen in TA5; however, this unit did not show a good failure behavior when observed over the entire period in consideration, and unit 4 has the least maximum uptime of a value of 123 days.

Unit 2 showed the least maximum breakdown duration of 39 days, while the longest TBR was seen in unit 1, a value of 133 days. Below are some recommendations for better performance of the station.

SHEPS was observed to have the maximum number of breakdowns in each of its turbo-alternators compared to that of the JHEPS.

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