Journal of Energy Technologies and Policy
ISSN 2224-3232 (Paper) ISSN 2225-0573 (Online)
Vol.2, No.2, 2012

Reliability Evaluation of Kainji Hydro-Electric Power Station in Nigeria

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Abstract

By virtue of the vital nature of electric power, both to our economic and personal well being, a power system is expected to supply electrical energy as economical as possible and with a high degree of quality and reliability. This research aimed at evaluating the reliability performance of Kainji hydro electric power station of Nigeria. The result of this study is intended to provide improved criteria for future proposals, and serves as a basis for generation expansion planning of hydro electric power stations and the entire power generation system in Nigeria. Herein reliability evaluation based on the Frequency and Duration (F & D) approach is adopted. A set of reliability parameters which quantify generating unit reliability, are computed for each unit using the annual outage durations. The overall stations reliability is evaluated by the convolution of the generation and load models, using the Frequency and Duration (F&D) approach. The study generally shows that the generating units at Kainji hydro power stations have not been adequately maintained leading to frequent and delayed forced outage indicating unreliable performance of the individual units and the entire station.

Keywords: Reliability, Availability, Reliability Indices, Convolution, Probability, Frequency and Duration, Hydro-electric Power Station

1. Introduction

The high rate of electricity demand requires stable and continuous supply of electrical power to consumers. Hence improvement of the operational performance of a nation's electric supply is vital for its economic and social developments. Because electricity is used for the twenty four (24) hours of the day, it has come to play an important role in all aspects of our life. It has been observed that the energy generated by the major hydro-electric power stations in Nigeria does not meet up with the demand. Consumers of electricity both domestic and industrial have been looking forward to improved performance from what is presently obtainable. For this reason, several efforts have been made over the years to improve the performance of the Power Holding Company of Nigeria (PHCN).

Over the years operation of the Kainji hydro-electric power station in Nigeria, different types of faults have occurred on the units in the station and also on its associated auxiliary equipment resulting in forced outages of the units which have contributed to the apparent unreliability of the station. Since Kainji inception in December, 1968, a lot of researchers have made contributions by evaluating the reliability of these power station using different approaches like the loss of load probability (LOLP) and loss of energy (LOE) (Hall et al., 1968) which does not utilize the system load curve as the load model. The Frequency and Duration (F&D) method which utilizes the chronological load curve making it capable of computing the state probabilities and state frequencies of the failure will be adopted in this research, which will then help in long-range system planning.

Generating stations form an important and integral part of the overall power system and their reliability is reflected in the reliability of the overall national supply. Reliability of a generating station is a function of the reliability of the constituent generating units. Accurate estimates of generating unit reliability are needed for generating capacity planning and to aid improved criteria for future designs and operations. Reliability assessment of a generating system is fundamentally concerned with predicting if the system can meet its load demand adequately for the period of time intended.

Improving the availability of existing units is as important as improving the reliability expectation of units during the planning phase. The two are mutually supportive; design reliability impacts major changes in existing units, and information about operating availability is important to the system designers in both developing and developed countries.

From the afore mentioned problems, there is need for a more accurate and precise approach; Frequency and Duration (F&D) in the evaluation of their reliability, which will then serve as a contribution to the efforts already embarked upon by the management of Power Holding Company of Nigeria (PHCN) as well as other researchers towards the enhancement of the performance of the nation's electricity network in general.

Several techniques have been used in the reliability evaluation of power system generation (Valma et al., 2007; Vermaa et al., 2004; Burgio, 2008; D'Annunzio & Santoso, 2005) which considers different approaches in their reliability evaluation of different plants and using different models. Recently, Nillai (2011) work on Loss of Load Probability of a power System, in his work, he made an effort to evaluate the reliability of Kerala power system in India using the LOLP method, while in (Luo, 2003; Burgio et al., 2007; Rai et al., 1986), effort was made in simulating power system reliability using learning vector quantization and Mont Carlo simulation. As it can be seen so far, none among the previous studies has attempted using the F&D method in their evaluation. To the best of our knowledge, not only using the Frequency and Duration method in the Evaluation of the major hydro electric power station in Nigeria, this happen to be the first of its kind in evaluating the reliability of the station while considering separate units, and for a long duration and most recent.

For clarity and neatness of presentation, the article is outline in to five (5) sections. The First Section gives a general introduction of reliability assessment and reviews some literature relevant to the research. A clear introduction of reliability concepts, Markov processes as well as the methods to be adopted to achieve the goal of the research is presented in Section Two. In Section Three, method of reliability evaluation of the different types of systems, the method used to build the generation capacity model and the method of generating system reliability evaluation are reviewed. Section Four presents the overall results. In Section Five, we conclude the work with some recommendations. Finally, the references are presented at the end of the paper.

2. Reliability Concepts

Modern reliability evaluation techniques are used in a wide range of applications. They can be applied to large scale systems or systems in which failure can result in severe social consequences or to other products which individually have little socio-economic effect when they fail. It is therefore evident that all reliability engineers should have some awareness of the basic concepts associated with a particular application and also to the mathematical modeling.

This section introduces two concepts that are of central importance in any reliability work. These are the modeling and probability concepts. It also gives a review of the methods of evaluating the reliability of the different types of systems. The different methods of electric power generating system reliability assessment are also presented in this section.

2.1 Modelling Concept

A system is frequently represented as a set of smaller subsystems; the behavior of each subsystem having its own effect on the larger system. A subsystem is often referred to as a component. A component on the other hand is mostly represented as having two or more discrete states. Alternatively, it can be considered as having normally distributed state.

In electric power generating system, the most widely used modeling concept considers the various generating units as the constituent subsystems. In a power station comprising many generating units, others prefer to combine identical units and treat them as a component. The unit model, however, is usually discrete modeling. It has been shown (Allan & Takieddine, 1977) that the normal distribution model, though it requires less computational effort gives misleading results.

Here we shall model our system in terms of the units and the two state unit models will be adopted as was applied in (Rai et al., 1986).

2.2 Reliability Concept

Reliability is the probability of a device or system performing its intended function adequately for the period of time intended, under the operating conditions required. It should be noted that reliability is not the only performance criterion by which a device or system can be characterized. If a device fails, it can be repaired (repairable systems) and since it is not possible for a device to be used while it is being repaired, one might also measure its performance in terms of availability, which is, the fraction of time it is available for use and functioning properly. The availability of a repairable device is the proportion of time, in the long run, that it is in, or ready for, service. Another measure closely related to Reliability and Availability is the Maintainability and is defined as the probability of converting an existing system to the state it was when new. A device or system may be adequate but not reliable if it has poor maintainability.

2.3 Power System Reliability

Electric power has become an inevitable asset to consumers that its adequate and reliable provision had become essential. Reliability is and always has been, one of the major factors in the planning, design, operation and maintenance of electric power systems. The reliability of an electric supply system has been defined as the probability of providing the users with continuous service of satisfactory quality. The quality constraint refers to the requirement that the frequency and the voltage of the power supply should remain within prescribed tolerances. The actual degree of reliability experienced by a consumer could depend on the location of the consumer and the aspect of the power network such as generation, transmission and distribution systems. Some methods have been used in the reliability evaluation of some systems (Ehnberg et al, 2004).

To achieve a standard degree of reliability at the customer level, each of these systems must provide an even higher degree of reliability. However as systems grew larger and more complex, the need for rigorous analysis in the form of formal concepts and methods of reliability theory have been applied to almost every aspect of power system reliability evaluations.

2.3.1 Methods of Power System Reliability Evaluation

Power system reliability studies can be conducted for two (2) purposes:

1. Long-term reliability evaluations may be performed to assist in long-range system planning;
2. Short-term reliability predictions may be sought to assist in day-to-day operating decisions. Included are assessments of system security where the effects of sudden disturbances are evaluated.

Both types of studies may require very different models and mathematical approaches. The methods generally used in evaluating power system reliability include the Reserve Margin (RM), Loss of Largest Generating Unit (LU), Expected Unserved Energy (EUE) and the Emergency Operating Procedure Expectation (EOPE).

I. Reserve Margin: This is a measure of the available generating capacity over and above the amount required to meet the system load requirements. It is the difference between the total available generating capacity and the annual peak system load, divided by the peak system load. That is, the excess of installed generating capacity over annual peak load expressed as a fraction of annual peak load.

II. Loss of Largest Generating Unit: This reliability measure provides a degree of sophistication over the standard per cent reserve method by reflecting the effect of unit size on the reserve requirements. The Loss of Largest Generating Unit (LU) method compares the total installed generating capacity less the annual peak system load (reserve) with the largest installed units on the system.

III. Expected Unserved Energy: This measures the expected amount of energy, which will not be supplied per year due to deficiencies and/or shortages in basic energy supplies of generating capacity.

IV. Emergency Operating Procedure Expectation: This measures the expected number of days per year on which various emergency operating procedures would be required due to insufficient generating capacity.

2.3.2 Generation Model

As a result of outages, an element may, at times, actually have a partial capacity less than the rated capacity or maximum generation capacity. The generation model involves the construction of a capacity outage probability table, which is a tabulation of cumulative probabilities and frequencies and sum up its reliability characteristics.

Suppose there are n identical units installed in a system and that all units are independent:

$$P(X_k) = \binom{n}{k} r^k (1-r)^{n-k} \tag{1}$$

$$P_C(X_k) = \sum_{k \geq i} P(X_k) \tag{2}$$

$$F_C(X_k) = P(X_k).\, {}^{k}\!/_{t_r} \tag{3}$$

where, X_k denotes the level of outage capacity due to k failed units, r is the forced outage rate, $P(X_k)$, the exact probability of k failed units, t_r, the repair time (MTTR) and $P_c(X_k)$, $F_c(X_k)$ are the cumulative probability and frequency, respectively.

In practice, all units may not be identical. The following expressions then hold for the frequency and cumulative frequency while those for probability and cumulative probability remains as eqns. (1) and (2).

$$F_j = P_j(\lambda_j^{+} - \lambda_j^{-}) \tag{4}$$

$$F_{Cj} = F_{Cj-1} + P_j(\lambda_j^{+} - \lambda_j^{-}) \tag{5}$$

where, j is an index for the combined capacity states of the identical units, F_j, the frequency of state j, F_{cj}, the cumulative frequency of state j, λ_j^{+}, the transition rate from state j to the states with lower j index (higher capacity states) and λ_j^{-}, the transition rate from state j to the states with higher j index (lower capacity states).

Also, $\lambda_j^+ = k\mu$ and $\lambda_j^- = (n-k)\lambda$ (6)

Where, λ and μ are the constant failure and repair rates, respectively.

2.3.3 Load Model

While the generation model provides information on the probabilities and frequencies (including cumulative states) of the available generation, the load model provides information about the load demand states. The load models used are the cumulative load curve (load-duration curve) and the chronological load curve.

2.3.4 Loss of Load Probability

This method uses the load-duration curve as the load model. It can be made up of hourly readings, although more often, it is assembled from the daily peaks with the abscissa indicating the percentage of days when the peak exceeds the amount of load shown by the ordinate. It is assumed that the peak load of the day would last all day.

For a system having available generating capacity, C_j, with t_j, representing the percentage of time during which the load demand exceeds C_j, the overall probability that the load demand will not be met is called the Loss of Load Probability (LOLP) and is given by:

$$LOLP = \sum_j P[C = C_j]P[L > C_j] = \sum_j \frac{p_j t_j}{100} \tag{7}$$

Where, $P[C=C_j]$ and $P[L>C_j]$ represent the probabilities that of attaining the available generating capacity C_j and probability that the load demand, L, exceeds C_j.

2.3.5 Loss of Energy Method

This is the ratio, E, of the expected amount of energy not supplied during some long period of observation to the total energy required during same period. Using the same notations in the Loss of Load Probability (LOLP) method, the loss of energy is given by:

$$E = \sum_j \frac{p_j \int_0^{t_j} (L - C_j)\,dt}{\int_0^{t} L\,dt} \tag{8}$$

Where, t is the 100% of time for which the load exceeds L.

2.3.6 Frequency and Duration Method

This method uses the chronological load curve. Ringlee and Wood (Ringlee & Wood, 1969) proposed the first approximation of a daily load curve, which is basically a two-level load model. While the low-load level L_0 is always the same, the peak loads, L_i, are different for every day and occur in random sequence. The mean duration, t_i, of the peaks is described by an exposure factor given by:

$$e = \frac{t_i}{d_0} \qquad (9)$$

Where, d_0 is the length of the load cycle and $0<e<1$ is considered the same for every day.

The state probabilities of the load model are given by:

$$p_{L0} = 1 - e \quad , \qquad \text{and } p_{Li} = \alpha_i e \text{ , } i \neq 0 \qquad (10)$$

and the transition rates, according to Markov model, are given by:

$$\lambda_{L0}^{+} = \frac{1}{(1-e)d_0} \text{ , } \lambda_{Li}^{-} = \frac{1}{ed_0} \text{ ; } \qquad (11)$$

α_i are the relative frequencies of corresponding peak loads L_i so that $\Sigma\alpha_i = 1$ (i=1, 2, ….).

Out of the three (3) distinctly recognized analytical approaches to the problem of generating capacity reliability evaluation described above, the frequency and duration (F&D) method is adopted in this research. The reasons are as follows:

1. The Loss of Load Probability (LOLP) method only computes the probability of not having enough generation to meet the load demand;
2. Because the Loss of Energy (LOE) index compares the amount of energy not supplied during the long period of observation to the total energy required during that period, it is considered to have more significance than the Loss of Load Probability (LOLP) index in that it is an in-depth measure of reliability that will assume higher values for more serious events than for marginal failures even if their probabilities and frequencies are the same;
3. Since the true loss of energy cannot be accurately computed on the basis of the cumulative curve of daily peaks, the Loss of Energy (LOE) index is seldom used;
4. The load variations in the cumulative curve of daily peaks are not recognizable in load variation, making the output of the LOLP utilizing this load model a rather crude approximation of the true system failure probability and prevents the calculation of the system failure frequency;
5. The Frequency and Duration (F&D) method utilizes the chronological (or at least approximately) load curve making it capable of computing the state probabilities and state frequencies (including cumulative states) of failure. In addition, merging the generation and load models produces the probabilities, frequencies (including cumulative states) and durations of the margin states. The Frequency and Duration (F&D) approach also provides the system failure probability and frequency.

2.4 Convolution

The convolution of the generation model and the load model is made on the basis that the events are independent. Suppose each state k is assigned an index M_k indicating the margin by which the generation exceeds the load demand, then:

$$M_k = C_j - L_i. \tag{12}$$

The transition rate from a given state k to any higher-margin state is:

$$\lambda_k^+ = \lambda_{Li}^- + \lambda_{Cj}^+ \tag{13}$$

And to any lower-margin state is:

$$\lambda_k^- = \lambda_{Li}^+ + \lambda_{Cj}^- \tag{14}$$

Where, $\lambda_{Li}^+ = 0$ if $i \neq 0$ and $\lambda_{L0}^- = 0$ for the given load model.

The solution of the combined model can be obtained as follows:

1. Combine the identical margin states in a similar way as combining identical capacity states. We can call the state index for the reduced model m;
2. Use equations (2) and (5) to construct a margin table containing the probabilities and frequencies, respectively, where $M \le M_m$;
3. Suppose m_{Nm1} is the index of the first negative margin state, the system failure probability (P_F) and frequency (F_F) are obtained from the margin state table, respectively as:

$$P_F = P_{CNm1} \; ; F_F = F_{CNm1} \tag{15}$$

And the mean duration of system failure, T_F, is given by the ratio:

$$T_F = P_F / F_F \tag{16}$$

The Mean Loss of Load (MLOL) is given by:

$$MLOL = \sum_{M_k < 0} |M_k| \cdot P_k \tag{17}$$

Where, M_k is the negative entry in the margin state table and P_k, the exact probability for this entry.

Also in comparison, if the two-level load model is used, and if the loss of load at the low-load level is negligible, the P_F and LOLP indices relate as

$$LOLP = P_F / e \tag{18}$$

Where e is the exposure factor in the two-level load model,

The conversion of P_F to LOLP through dividing by e is true only if L_O is chosen to be 0; that is, no deficient states exist at the Low-load level.

3. The Power Station and Reliability Indices

3.1 Kainji Hydro Electric Power Stations

The construction of Kainji dam began in March 1964 and was completed on schedule and put into use in December, 1968. The power house is situated immediately downstream of the concrete dam. The station was initially proposed to take twelve 80MW generating units with an installed capacity of 960MW. Each unit is supplied with water from the reservoir through an 8.55m penstock and each penstock is supplied with water through two intake gates each of which is protected by screens on the upstream face of the dam.

Each unit is identified by the position of the intake gates supplying it.

Initially, four Kaplan type turbine generating sets (1G7, 1G8, 1G9 and 1G10) of 80MW capacity each were installed. In February, 1976, two additional Kaplan type turbine units (1G11 and 1G12) of 100MW capacity each were put into use and in August, 1978, two 120MW fixed blade propeller type turbine sets (1G5 and 1G6) were also put into use, bringing the total number of units to eight and the installed capacity at Kainji to 760MW.

Over the years of operation of the station, different types of faults have occurred on the units and have contributed to the unavailability of the units in addition to outages for maintenance. Each outage, when it occurs, is recorded under the columns; Date, Unit, Time Off, Time On, Duration, Type, Load Loss and Remarks.

3.2 Computation of Reliability Indices

The reliability indices give an "at-a-glance" picture of the reliability characteristics of devices or systems in general. The relationship between unit outages and some reliability parameters are specified in a number of literatures (Anonymous, 1984; Papadapoulos, 1983; Wang, 1980). These indices along with their formulae are listed as follows:

Forced outage rate (FOR) $= FOH/(FOH+SH)$ (19)

Mean time to failure (mean up time, MTTF) $= SH/N$ (20)

Mean time to repair (mean down time, MTTR) $= FOH/N$ (21)

Mean time between failures (period, MTBF) $= MTTF+MTTR$ (22)

Frequency (f) $= 1/MTBF$ (23)

Failure rate (λ) $= 1/MTTF$ (24)

Repair rate (μ) $= 1/MTTR$ (25)

Availability (A) $= \mu/(\lambda+\mu)$ (26)

Unavailability (U) $= \lambda/(\lambda+\mu)$ (27)

Where the symbols are defined as follows:

N (number of failures) – number of times a unit experience forced outage

FOH (forced outage hours) – time in hours during which a unit or major equipment was unavailable due to a forced outage

SH (service hours) – total number of hours the unit was actually operated with breakers closed to the station.

4. Results and Discussion of Results

4.1 Results

4.1.1 Reliability Indices

The reliability indices of Kainji hydro station were computed for each of the eight (8) units between 2004 and 2007. The reliability indices of Kainji hydro units for the four (4)-year period was obtained. The average indices for all the units for the duration of study where all computed as shown below. Where (-)

stands for Not Applicable (NA)

Table 1. Average Reliability indices for Kainji units (2004-2007)

UNITS	**1G5**	**1G6**	**1G7**	**1G8**	**1G9**	**1G10**	**1G11**	**1G12**
SOH (h)	0	176.25	346.49	385.34	200.43	234.27	339.30	265.90
FOH (h)	35040	7964.87	336.05	10179.5	2292.48	99.90	904.79	4871.38
SH (h)	0	27075.13	34703.9	24860.5	32747.5	34940.1	34135.2	30168.62
NF	4	10	9	8	11	7	10	14
SOR (%)	-	0.64676	0.98855	1.52635	0.60832	0.66602	0.98421	0.87368
FOR (%)	100	22.73079	0.95904	29.0510	6.54246	0.28510	2.58216	13.90234
MTTR (h)	8760	901.8471	38.2587	1031.77	191.789	14.5679	199.785	345.825
MTBF (h)	8760	3630.823	3976.29	5061.06	3267.01	6160.64	4346.05	2609.415
λ (/h)	-	0.000372	0.00026	0.00046	0.00034	0.00020	0.00029	0.000478
μ (/h)	0.0001	0.001109	0.02613	0.00096	0.00521	0.06864	0.00500	0.002892
A (%)	-	77.1495	99.0295	70.6554	93.4047	99.7131	97.4047	85.9825
U (%)	-	22.8505	0.9705	29.3446	6.5953	0.2869	2.5953	14.0175

Table 2. Average Reliability indices for Kainji station (2004-2007)

UNITS	SOH (h)	FOH(h)	SH (h)	NF	SOR (%)	FOR (%)	MTTR (h)	MTBF (h)	λ (/h)	μ (/h)	A (%)	U (%)
INDEX	243.5	3331.12	27328.9	9	0.8831	10.8647	389.12	4150.188	0.00034	0.0157	89.048	10.9515

4.1.2 Generation Model

The generation model involves the construction of a capacity outage probability table, which is a tabulation of cumulative probabilities and frequencies and sum up its reliability characteristics. For this study, the model proposed by Hall et al. (1968) was adopted. For Kainji station, units with identical capacity states were combined (Jimoh and Adegboye, 1995) to take the form: (2x160MW); (1x200MW) and (1x240MW).

For the new capacity state z to be valid, the combination of two states x and y having identical capacity, the resultant capacity, availability and failure rate, respectively, will be such that (Hall et al., 1968):

$$C_z = C_x = C_y \tag{28}$$

$$P_z = P_x + P_y \tag{29}$$

$$\lambda_z = \frac{P_x \lambda_x + P_y \lambda_y}{P_x + P_y} \tag{30}$$

Using this approach, the generation model for Kainji station is constructed and shown in Table 3.

Table 3.0 Generation model for Kainji station

J	**C_j (MW)**	**P_j**	**P_{cj}**	**λ^+**	**λ^-**	**F_j**	**F_{cj}**
1	760	0.52206	1.00000	0.00000	5.51040	2.87677	0.00000
2	600	0.18424	0.47799	7.79300	4.13280	2.19758	2.86974
3	560	0.09212	0.29376	7.79520	4.13280	1.09879	2.19499
4	520	0.09212	0.20164	7.79520	4.13280	1.09879	1.83762
5	440	0.01626	0.10952	15.59040	2.75520	0.29823	1.52024
6	400	0.03231	0.09326	15.39040	2.75520	0.39645	1.31139
7	360	0.03251	0.06078	15.59040	2.75520	0.59646	0.89428
8	320	0.01626	0.02824	15.59040	2.75520	0.29823	0.47698
9	240	0.00287	0.01198	23.38560	1.37760	0.07104	0.26833
10	200	0.00287	0.00911	23.38560	1.37760	0.07104	0.20319
11	160	0.00574	0.00624	23.38560	1.37760	0.09255	0.14206
12	0	0.00031	0.00031	31.18080	0.00000	0.01378	0.01578

4.1.3 Load Model

The load model provides information about the load demand states. Using the method proposed by Ringlee and Wood (1969) for the first approximation of a daily load curve, which is basically a two-level load model, the low-load level L_0 is always the same while the peak loads, L_i, are different for every year and occur in random sequence. An exposure factor of 0.7 is assumed so as to fully describe the mean duration, t_i, of the peaks (d_o=1 year). The load model developed using (Anonymous Kainji, 2007) is shown in Table 4.

Table 4.0 Load model for Kainji station

I	**L_i (MW)**	**α_i (100%)**	**P_{Li}**	**λ_{L0}^{+} (/yr)**	**λ_{Li}^{-} (/yr)**
0	215	-	0.3000	3.33333333	0
1	395	18.7500	0.1313	0	1.42857
2	435	7.5000	0.0525	0	1.42857
3	475	16.2500	0.1138	0	1.42857
4	510	15.0000	0.1050	0	1.42857
5	515	13.7500	0.0963	0	1.42857
6	520	13.7500	0.0963	0	1.42857
7	535	15.0000	0.1050	0	1.42857

4.1.4 Convolution

The convolution of the generation model and the load model was made on the basis that each of the events are independent. This results to the margin Table 5, which gives the probability, frequency and the corresponding cumulative values of attaining a particular margin. This is similar to some recent work that uses modeling and simulation methods (Olssom, 2009; Salomonsson, 2009; Sendegeya, 2009).

Table 5.0 Margin Table for Kainji station

M_m	**λ_m^{+}**	**λ_m^{-}**	**P_m**	**F_m**	**P_{cm}**	**F_{cm}**
545	0.00000	8.84373	0.15662	-1.38509	1.000	-0.023
385	7.79300	7.46613	0.05527	0.01807	0.478	2.854
365	1.42857	5.51040	0.06852	-0.27969	0.843	1.362
345	7.79520	7.46613	0.02764	0.00909	0.293	2.180
325	1.42857	5.51040	0.02741	-0.11188	0.775	1.642
305	7.79520	7.46613	0.02764	0.00909	0.201	1.842
285	1.42857	5.51040	0.05938	-0.24240	0.747	1.754
250	1.42857	5.51040	0.05482	-0.22375	0.688	1.996
245	1.42857	5.51040	0.05025	-0.20511	0.633	2.220
240	1.42857	5.51040	0.05025	-0.20511	0.583	2.425
225	8.50949	5.79947	0.05969	-0.17741	0.642	4.135
205	9.22157	4.13280	0.02418	0.12305	0.422	2.836
185	15.39040	6.08853	0.00969	0.09017	0.093	1.296

165	9.22267	4.13280	0.02176	0.11077	0.664	4.884
145	15.59040	6.08853	0.00975	0.09268	0.061	0.888
125	9.22304	4.13280	0.03788	0.19282	0.816	6.606
125	9.22377	4.13280	0.00484	0.02462	0.254	2.109
125	9.22157	4.13280	0.02096	0.10665	0.388	2.664
105	15.59040	6.08853	0.00488	0.04634	0.028	0.471
90	9.22157	4.13280	0.01934	0.09844	0.368	2.557
85	9.22304	4.13280	0.03305	0.16821	0.758	6.315
80	9.22157	4.13280	0.01773	0.09024	0.330	2.368
65	9.22157	4.13280	0.01934	0.09844	0.313	2.278
50	9.22377	4.13280	0.00967	0.04924	0.238	2.031
45	11.82217	3.67360	0.02148	0.12892	0.490	5.188
40	9.22377	4.13280	0.00887	0.04514	0.220	1.937
25	16.30469	4.42187	0.01053	0.06531	0.223	2.154
10	9.22377	4.13280	0.00967	0.04924	0.146	1.694
5	14.35390	3.21440	0.01396	0.11696	0.322	4.279
0	9.22377	4.13280	0.00887	0.04514	0.128	1.599
-15	16.30469	4.42187	0.01053	0.06531	0.128	1.753
-35	16.95230	2.75520	0.00781	0.11110	0.231	3.358
-55	23.38560	4.71093	0.00172	0.03214	0.006	0.136
-70	17.01897	2.75520	0.00171	0.02435	0.099	1.390
-75	16.96897	2.75520	0.00908	0.12879	0.245	3.647

Table 5.0 Margin Table for Kainji station (cont'd)

$\mathbf{M_m}$	λ_m^+	λ_m^-	$\mathbf{P_m}$	$\mathbf{F_m}$	$\mathbf{P_{cm}}$	$\mathbf{F_{cm}}$
-80	17.01897	2.75520	0.00156	0.02232	0.096	1.343
-95	17.01897	2.75520	0.00171	0.02435	0.095	1.321
-110	16.81897	2.75520	0.00339	0.04772	0.074	1.071
-115	16.95230	2.75520	0.00766	0.10866	0.136	2.127
-120	16.81897	2.75520	0.00311	0.04374	0.067	0.980

-135	16.81897	2.75520	0.00339	0.04772	0.064	0.936
-150	17.01897	2.75520	0.00341	0.04869	0.041	0.657
-155	19.61737	2.29600	0.00535	0.07984	0.069	1.237
-160	17.01897	2.75520	0.00313	0.04464	0.035	0.564
-175	17.01897	2.75520	0.00341	0.04869	0.031	0.519
-190	17.01897	2.75520	0.00171	0.02435	0.018	0.355
-195	22.21577	1.83680	0.00209	0.03467	0.035	0.751
-200	17.01897	2.75520	0.00156	0.02232	0.015	0.309
-215	24.09989	3.04427	0.00180	0.02691	0.014	0.296
-235	24.81417	1.37760	0.00123	0.02883	0.022	0.511
-270	24.81417	1.37760	0.00030	0.00706	0.010	0.226
-275	24.81417	1.37760	0.00090	0.02118	0.021	0.476
-280	24.81417	1.37760	0.00028	0.00647	0.009	0.212
-295	24.81417	1.37760	0.00030	0.00706	0.009	0.206
-310	24.81417	1.37760	0.00030	0.00706	0.007	0.163
-315	24.81417	1.37760	0.00093	0.02177	0.010	0.235
-320	24.81417	1.37760	0.00028	0.00647	0.007	0.149
-335	24.81417	1.37760	0.00030	0.00706	0.006	0.143
-350	24.81417	1.37760	0.00060	0.01412	0.003	0.064
-355	24.81417	1.37760	0.00055	0.01294	0.002	0.050
-360	24.81417	1.37760	0.00055	0.01294	0.001	0.037
-375	24.81417	1.37760	0.00060	0.01412	0.001	0.024
-395	32.60937	0.00000	0.00004	0.00131	0.000	0.007
-435	32.60937	0.00000	0.00002	0.00052	0.000	0.006
-475	32.60937	0.00000	0.00003	0.00114	0.000	0.005
-510	32.60937	0.00000	0.00003	0.00105	0.000	0.004
-515	32.60937	0.00000	0.00003	0.00096	0.000	0.003
-520	32.60937	0.00000	0.00003	0.00096	0.000	0.002
-535	32.60937	0.00000	0.00003	0.00105	0.000	0.001

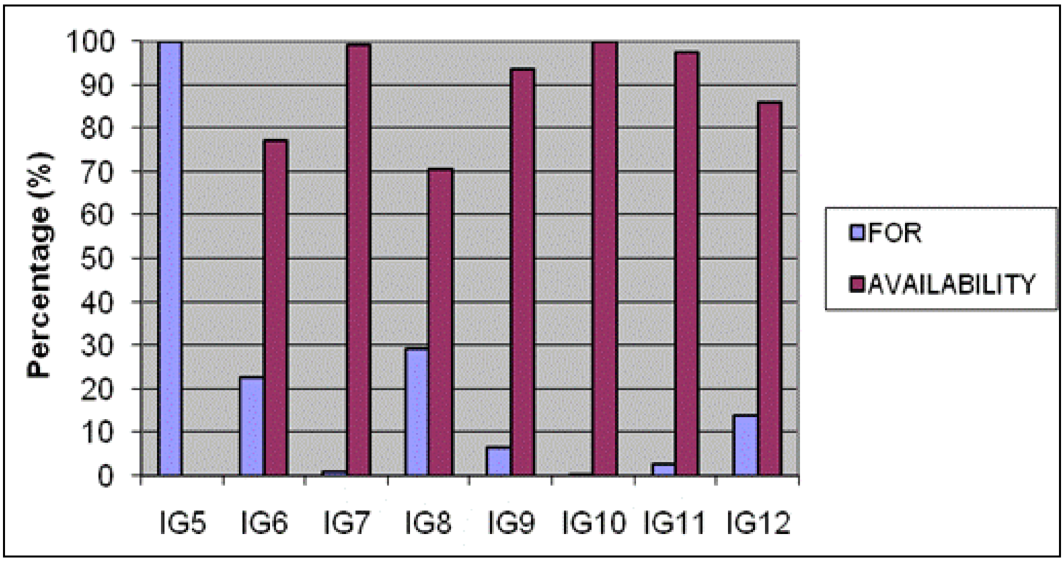

Figure 1.0 FOR and Availability of Kainji Power Station for 2004-2007

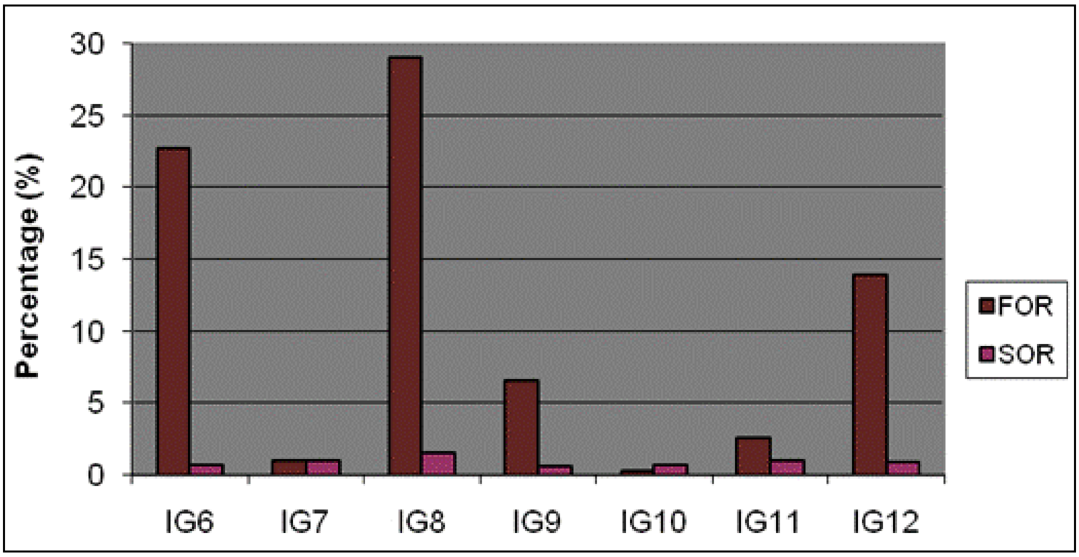

Figure 2.0 Variation of SOR and FOR of Kainji Power Station for 2004-2007

4.2 Discussion of Results

Generally, typical values for Forced Outage Rates (FOR) tend to range between 0.3% and 29% which depends on other factors such as unit type, size and age of plant. Though, unit 5 did not fall between these ranges as it was not available throughout the period of study, hence having Force Outage Rate (FOR) of 100%.

Low values of force outage rates are expected for hydro units since they are supposed to be very reliable.

The result obtained shows the poor performance of Kainji Hydro Station. However, one can say that the performance of the station is below expectation since it can be observed that the constituents' performance is below expectation.

Maintenance which is the backbone of successful performance has not been properly done for Kainji units. Sizes directly influence the overall system reliability thus requiring greater maintenance for larger units than the smaller ones. Hydro units are generally known to be large and since maintenance is not properly done, the reliability could fall.

Unit 5 was not available throughout the period of study as can be seen in Table 1 making its FOR to be 100% and Availability to be Zero (0) showing that it is the worst unit in the station in terms of its reliability. Unit 10 appears to be the most adequate unit between 2004 and 2006 under study, (refer to Table 1). This also shows that unit 8 was more adequate for the period 2006 to 2007.

Between 2004 and 2007, analysis show that unit 5 is the least since not available at all during the period of study follow by unit 8 with the lowest among others that were available during the period. This can be shown in Table 1 or Fig. 1. A look at the period under consideration revealed that, the availability reached its worst level in 2007 corresponding to unit 12 when it was on its greatest forced outage. (Refer to Table 1). It should be observed also that unit 5 was not in service over the period of study.

There are several factors responsible for these outages. The major causes of outages are the surge and system swing. System swing refers to sudden drop followed by rise in frequency. Other major cause of outages is unknown owing to faulty indicators and/or no relay indications. The outages associated with these cause are quite frequent.

In order to actually evaluate the Reliability of the Station as a whole, the margin Table (Table 5) is developed by the convolution of the Generation and Load models of Table 3 and 4. The Margin Table yield the overall probability and frequency of failures including the magnitude of the capacity deficiency involved, that is, the ability of the capacity generation not meeting the load demand. This is shown by the negative margins. The cumulative negative margin state corresponds to load loss greater than or equal to the specified margin, the zero margin being the break-even point between the failure and success or vice-versa.

From the margin Table 5, the system failure probability (P_F) is 0.13. The system failure frequency (F_F) is 1.75 per year (corresponding to system failure duration of 0.57 year or 6.85 months). Also, the mean duration of system failure (T_F) is 0.07 year (corresponding to system mean failure duration of 3.80 weeks). The mean loss of load (MLOL) is 9.87MW.

This analysis generally, shows the effect of negative margin on a station. Wider margin assures a more reliable performance.

Also, the result obtained as compared with that using the LOLP method, shows that, LOLP is 0.18 (corresponding to 66.58 day/year) also, the Reliability of Kainji is 23.91%.

5. Conclusion

This research was aimed at evaluating the reliability performance of Kainji hydro electric power station of Nigeria. The results obtained are presented and fully discussed. The overall stations reliability is evaluated by the lump-ability (convolution) of the generation and load models, using the Frequency and Duration (F&D) approach. The margin table so formed gave the probabilities and frequencies (including cumulative states) of various margin states. The system failure probability (P_F) and frequency (F_F), the mean duration of system failure (T_F), loss of load probability (LOLP) and the mean loss of load (MLOL) were obtained. The Reliability of the station was also computed for the period of study (2004-2007). Reliability indices were obtained for the These provided information on the knowledge and mean time of encountering certain available capacity and margin states based on the probability and frequency of system failure. The frequent outages (forced and scheduled) greatly affected the reliability of the stations. The main result of our analysis here, when compared with the corresponding results in some other countries, indicates that Kainji power station has so far performed below expectation. The study generally showed that the generating units at Kainji hydro power station have not been adequately maintained, which led to frequent and delayed forced outage rates indicating unreliable performance of the individual units. Also to be considered is the fact that most of the generating units are old enough to be replaced. The overall station mean loss of load (MLOL) is 9.87MW which is high indicating an unreliable station performance, the reliability of the station is low (23.91%) from the reliability computation as against the 37% when the time of operation equals the MTBF. This then shows that the station as a whole did not meet up to its expectation and hence cannot sustain the demand from the consumers.

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