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Reliability, Availability and Performance Evaluation of Gilgel Gibe I & Gilgel Gibe II Hydro Power Stations

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Abstract: ***Generation system reliability is an important factor in the long term planning for future capacity expansion of systems to make sure that the total installed capacity is sufficient to support demand for new customers. The planning process utilizes reliability indices as criteria to decide on new investments in new generation capacities. Due to the high rate electricity demand of the country, stable and continuous supply of electrical power required to the consumers. Hence, improvement of the operational performance of a nation's electric supply is vital for its socioeconomic developments. Gilgel Gibe I and Gilgel Gibe II hydropower generation systems are part of grid systems and supplies power for the entire Consumers in the country. Numerical and analytical methods are used to assess and evaluate the reliability, availability and performance index parameters.***

Keywords: Reliability, Availability, Failure rate, Repair rate, Service hour

1. Introduction

Gilgel Gibe I and Gilgel Gibe II hydropower plants are installed in Gibe River. Gilgel Gibe I was installed and generate power in 2004 and have three generation units with generating capacity of 70 MW each, whereas Gilgel Gibe II was installed and generate power in 2010 and have four generating units with 105 MW generating capacity each.

Electricity has been the driving force for economies of any country by providing day-to-day necessity for customers. If the electricity is generated from renewable energy, then it plays a significant role in meeting energy demand, boosting energy security, addressing environmental issues and climate change as well as contributing to other aspects of social development. Hydropower generation is one of renewable energy technology that received great attention from the power industry. It becomes the leading source of renewable energy by providing more than 86% of all electricity generated by renewable sources worldwide. Other sources, including solar, geothermal, wind and biomass, account for less than 14% of renewable electricity production [1].

Ethiopia's path toward development is constrained by its limited range of natural resources. The major country's economically exploitable energy resource is hydropower, which offers the potential for generation of more than 45GW. However; when we see the existing power generation, Hydro Power covers 1978 MW out of 2268MW electric energy generated [17]. The rest are diesel Power 112 MW, geothermal Power 7 MW and wind Power 171 MW.

Ethiopia has Africa's greatest hydropower potential, second only to Democratic Republic of the Congo. Now the government of Ethiopia plans to meet customers demand by constructing huge generating power plants like renascence hydro power plant dam.

In addition to the discrepancy of the existing electric power generation and customer demands, the existing Hydro power plants are not that much working efficiently. The interruption of power is common in Ethiopia everywhere, even though the extent varies. The problems of power interruption arise at the Generation power plant, transmission power system and distribution power system at large. In order to satisfy customers' demand these power systems must be reliable and efficient.

2. Review of Literature

Reliability can be expressed in different ways and in power system, it is mainly defined as the ability of the components in generation, transmission and distribution systems to perform a required function, under given environmental and operational conditions and for a stated period of time [5]. Several techniques have been used in the reliability evaluation of power generation, transmission and distribution systems, which considers different approaches for different plants and using different models [7].

A modern power system is complex, highly integrated and very large. Fortunately, the system can be divided into appropriate sub-systems or functional zones that can be analyzed separately [2]. These functional zones are generation, transmission and distribution.

Generation system reliability is an important aspect in the planning of future capacity expansion. It provides a measurement of reliability or adequacy to make sure that the total generation system capacity is sufficient to provide adequate electricity when needed [1].

Power generation companies, research centers and consultants, have investigated the best economical means of affecting the upgrade of hydropower plants [6]. The traditional objective of electric system planning is to supply electricity demand at minimum cost and with acceptable long-term reliability that Supply continuously with wave quality.

Whenever a discussion of power system reliability occurs, it always involves a consideration of system states and whether they are adequate, secure, and can be attributed an alert, emergency, or some other designated status [11]. The concept of adequacy is considered as the existence of enough facilities within the system to satisfy the consumer demand [12]. These facilities include those necessary to generate sufficient energy and the associated transmission and distribution networks required to transport the energy to the actual consumer load points.

The reliability of a generating station is a function of the reliability of the constituent generating units [14]. Accurate estimates of the reliability of generating unit are needed for generating, capacity planning and to aid improved criteria for future designs and operations. Reliability assessment of a generating system is fundamentally worried with predicting if the system can meet its load demand adequately for the period of time intended [9]:

Based on reliability analysis, the standard requires the development of root cause analysis aiming at defining the basic cause; mostly it can be the failure of a component of an undesirable behavior of equipment of a processing plant. This analysis should support the application of maintenance plans developed to maximize plant availability [15]. By using the functional tree, a failure mode and effect analysis of all systems and components can be done. This analysis allows the evaluation of the equipment considered critical for the interruption of power generation, either from the point of view of the excessive time to repair the failure or due to the high frequency of occurrence of a fault. This equipment considered critical should have their maintenance prioritized with the aid of the functional tree and estimated reliability of the most critical equipment [16].

3. Materials and Methods

Reliability analysis of electrical generation system is the main tool in order to provide better quality of service for the customers in planning and expansion of supply to be cost effective [10]. The evaluation of reliability may be inappropriate as a measure for continuously operated systems that can tolerate failures. The measure used for such repairable systems; which are characteristics of components used in a hydro power station like generator, transformer, turbine etc is availability [8]. Availability of a repairable device is defined as the ratio of time ready for service per specified period. Availability is also interpreted as the probability of finding the component/device/system on the operating status at any time into the malfunction [9].

There are two main categories of reliability evaluation techniques, namely analytical and simulation. Analytical techniques represent the system by a mathematical model and evaluate reliability indices by mathematical solutions. Simulation on the other hand, like Monte Carlo simulation methods, estimates the reliability indices by simulating the actual progression and random performance of the system. Therefore, the method treats the problem as a series of real experiments conducted in simulated time. It estimates probability of the events and indices by counting the number of times an event occurs.

The main difference between these methods is in the way the methodology uses the input data in which the reliability indices are evaluated [10].

This research is done by using both analytical and numerical methods. For the analytical method of evaluation, Markov model is used having its own characteristics such as memoryless and stationary. The different states will be defined from the collected data and the type of failures occurred in each unit are called Markov states. Based on this, reliability indices like mean time to repair (MTTR), mean time to failure (MTTF), mean time between failures (MTBF), repair rate (μ), failure rate (λ) are evaluated for each generating unit.

The evaluation of Markov models used to obtain unit reliability and availability for the year 2013/14 and 2014/15. The data of each unit for each year is collected at a time scheduled with different type of failure taking into account. According to the classification, Markov states are defined. The reliability indices of each unit are found from the classified data.

To drive the Markov model of a Hydro-unit; the failure and repair rates are assumed exponentially distributed and there is no transition between the scheduled and force outages. Each unit after repairing is instantly returning to up state.

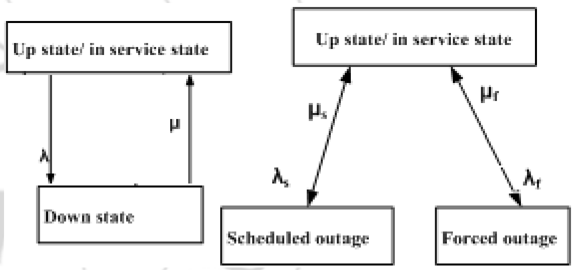

Figure 3.1: Two states and three states Markov Modeling

Failures of components, units and systems occur randomly and the frequency, duration, and impact of failures vary from year to year [8]. The information is recorded daily during any power interruption at each generation unit. The data used for this research at both hydro power plants for the last two years were:

- Yearly frequency of scheduled and forced outage for each generating unit
- Yearly duration of scheduled and forced outage for each generating unit
- Monthly maximum and minimum power generated at the generating units
- Maximum actual power generating capacity of generating units

According to the definition of reliability the reliability (R) is considered as the probability of the unit in the state of operation/up state and in state of scheduled/ maintenance outage whereas availability (A) is considered as the probability of the unit in service state [18].

The relationship between unit outages and reliability parameters are specified in a number of literatures [19, 20].

$$MTTR = \frac{FOH}{N} \quad \text{------------------------------------} \quad (1)$$

$$\mathrm{MTTF} = \frac{\mathrm{SH}}{\mathrm{N}} \quad \text{--- (2)}$$

$$\mathrm{MTBF} = MTTR + MTTF \quad \text{------------------------- (3)}$$

$$\mu = \frac{1}{\mathrm{MTTR}} \quad \text{-- (4)}$$

$$\lambda = \frac{1}{\mathrm{MTTF}} \quad \text{-- (5)}$$

$$R = \frac{SOH + SH}{8760\ hr} \quad \text{-- (6)}$$

$$A = \frac{SH}{8760\ hr} \quad \text{-- (7)}$$

In case of Monte Carlo simulation process, the first step is the generation of uniformly distributed random numbers using a uniform random number generator. The random numbers, thus generated are converted into values representing a non-uniform probability distribution. There are three basic methods in doing so. These are - the inverse transforms; composition and acceptance-rejection techniques [21].The following equation is used in order to convert a uniformly distributed function into exponentially distributed using inverse transform.

From its probability density function of uniformly distributed random number, the cumulative distribution function will be expressed in the following manner.

$$\mathrm{F}_{\mathrm{U(u)}} = \mathrm{U} \quad 0 \le \mathrm{U} \le 1 \quad \text{--------------------------- (8)}$$

The cumulative probability distribution function of exponential distribution function from its probability density function is derived as follows.

$$\mathrm{F_U(u)} = \int_0^t \lambda e^{-\lambda u} du = 1 - e^{-\lambda t} \quad \text{------------------- (9)}$$

Then, by equating, the cumulative uniformly distributed random function with cumulative exponentially distributed random function and using inverse transformation the generated random number will convert to another type of random number.

$$\mathrm{U} = 1 - e^{-\lambda t}$$

$$1 - \mathrm{U} = e^{-\lambda t} \quad \text{---------------------------------- (10)}$$

$$\mathrm{T} = \frac{-\ln(1-\mathrm{U})}{\lambda} \quad \text{--------------------------------- (11)}$$

Since U and 1-U described as the same way and the same type of distribution

$$\mathrm{T} = \frac{-\ln \mathrm{U}}{\lambda} \quad \text{---------------------------------- (12)}$$

Where U is uniformly distributed random variable and T is exponentially distributed random variable

The time sequential Monte Carlo simulation is adopted in this paper as an efficient method for the determination of the system reliability indices. In time sequential simulation, an artificial history that shows the up and down times of each element of the system is generated in chronological order using random number generators and the probability distribution of the element failure and restoration parameters [19]. A sequence of operating-repair cycles of the system is obtained from the history of the components using the relationship between the element states and the system states.

$$\mathrm{TTF} = -\mathrm{MTTF} * \ln \mathrm{U} \quad \text{-------------------------- (13)}$$

$$\mathrm{TTR} = -\mathrm{MTTR} * \ln \mathrm{U}' \quad \text{--------------------------- (14)}$$

Where U and U' are two uniformly distributed random number sequences between [0, 1] and MTTF is the mean time to failure and MTTR is the mean time to repair. The procedure carried out in this paper to calculate the reliability indices using the adopted simulation method are summarized as follows:

Step 1: Generate a random number for the units.

Step 2: Convert these random numbers into times to failures (TTF) corresponding to the probability distribution of the element parameters.

Step 3: Generate a random number and convert this number into the repair time (TTR) of the unit with minimum TTF according to the probability distribution of the repair time.

Step 4: Calculate the three basic load point indices caused by each unit operating history using the following equations:

$$\lambda = \frac{\mathrm{N}}{\sum \mathrm{TTF}} \quad \text{---------------------------------- (15)}$$

$$\frac{\mathrm{N}}{\sum \mathrm{TTR}} \quad \text{---------------------------------- (16)}$$

$$\mathrm{U} = \frac{\sum \mathrm{TTR}}{\sum \mathrm{TTF} + \sum \mathrm{TTR}} \quad \text{------------------------------ (17)}$$

Where N is the number of transitions between up and down states during the given year

Step 5: Evaluate the reliability and availability of each unit using equations (6) and (7)

4. Results and Tables

The reliability indices of Gilgel Gibe I and Gilgel Gibe II hydro power stations were computed for each unit between the fiscal years 20013 and 2015. The fiscal year in Ethiopia is from July to June. The reliability indices evaluated from the collected and analyzed data of each unit of the two-hydropower plants is as follows.

Table 4.1: Frequency and duration of forced outage

Generation power plant	Generating unit	Yearly forced outage frequency (N)		Yearly total forced outage hours (FOH) (Hrs)	
		2013/ 2014	2014/ 2015	2013/ 2014	2014/ 2015
Gilgel Gibe I	Unit 1	20	42	25.95	89.53
	Unit 2	24	91	411.15	844.75
	Unit 3	28	34	165.63	314.03
Gilgel Gibe II	Unit 1	57	145	1704.9	630.38
	Unit 2	72	218	1627.82	1366.92
	Unit 3	46	138	790.67	666.07
	Unit 4	55	111	2571.04	1286.52

Table 4.2 Frequency and duration of Scheduled outage

Generation power plant	Generating unit	Maximum generation capacity ()	2013/2014		2014/2015	
			Max. load (MW)	Min. load (MW)	Max. load (MW)	Min. load (MW)
Gilgel Gibe I	July	210	150	30	184	20
	Aug		190	30	185	0
	Sept		190	0	210	70
	Oct		190	40	195	0
	Nov		190	0	190	55
	Dec		180	30	190	15
	Jan		140	18	180	16
	Feb		140	0	210	40
	Mar		160	0	170	0
	Apr		120	0	90	0
	May		160	40	210	10
	June		170	0	210	45

Table 4.3: Monthly maximum and minimum power generation of Gilgel Gibe I

Generation power plant	Generating unit	Yearly scheduled outage frequency (N_S)		Yearly scheduled outage hour (SOH) in (Hrs)	
		2013/ 2014	2014/ 2015	2013/ 2014	2014/ 2015
Gilgel Gibe I	Unit 1	4	17	5.88	310.37
	Unit 2	3	7	12.17	116.27
	Unit 3	7	19	96.12	363.67
Gilgel Gibe II	Unit 1	1	14	17.83	55.55
	Unit 2	1	27	1.35	366.43
	Unit 3	0	13	0	49.35
	Unit 4	0	22	0	338.15

Forced outage hour (FOH), Service hour (SH), Scheduled outage hour (SOH), Forced outage frequency (N) and scheduled outage frequency (N_S) are the main inputs to derive all reliability indices. Mean time to repair (MTTR), Mean time to failure (MTTF), Mean time between failures (MTBF), Repair rate (μ), Failure rate (λ), reliability (R) and availability (A) of each generating unit of Gilgel Gibe I and Gilgel Gibe II hydropower plants is tabulated in table 3.5.

Table 4.4: Monthly maximum and minimum power generation of Gilgel Gibe II

Generation Power plant	Generating unit	Maximum generation capacity (MW)	2013/2014		2014/2015	
			Max. load (MW)	Min. load (MW)	Max. load (MW)	Min. load (MW)
Gilgel Gibe II	July	420	270	0	420	27
	Aug		420	0	390	0
	Sept		300	0	390	60
	Oct		300	0	385	0
	Nov		330	0	380	80
	Dec		320	0	380	0
	Jan		320	0	380	40
	Feb		300	0	370	45
	Mar		330	0	360	0
	Apr		290	0	300	0
	May		350	20	380	0
	June		360	0	420	60

Table 4.5: Analytical reliability indices

Generation popup plant	Generating unit	2013/2014							2014/2015						
		MTTF (hr)	MTTR (hr)	MTBF (hr)	μ (/hr)	λ (/hr)	R %	A %	MTTF (hr)	MTTR (hr)	MTBF (hr)	μ (/hr)	λ (/hr)	R %	A %
Gilgel Gibe I	Unit 1	436.4	1.3	437.7	0.769	0.002	99.70	99.64	199.1	2.1	201.2	0.476	0.005	98.98	95.43
	Unit 2	347.4	17.1	364.5	0.058	0.003	95.31	95.17	85.7	9.3	95.0	0.108	0.012	90.36	89.03
	Unit 3	303.5	5.9	309.4	0.169	0.003	98.11	97.01	237.7	9.2	246.9	0.109	0.004	96.42	92.26
Gilgel Gibe II	Unit 1	123.5	29.9	153.4	0.033	0.008	80.54	80.33	55.7	4.3	60.0	0.233	0.018	92.80	92.17
	Unit 2	99.0	22.6	121.6	0.044	0.010	81.42	81.40	32.2	6.3	38.5	0.159	0.031	84.40	80.21
	Unit 3	173.2	17.2	190.4	0.058	0.006	90.97	90.97	59.3	4.8	64.1	0.208	0.017	92.40	91.83
	Unit 4	112.5	46.8	159.3	0.021	0.009	70.65	70.65	64.3	11.6	75.9	0.086	0.016	85.31	81.45

Table 4.6: Relaibility indices using Monte Carlo simulation

Generation power plant	Generating unit				
		μ (/hr)	λ (/hr)	μ (/hr)	λ (/hr)
Gilgel Gibe I	Unit 1	0.77	0.0021	0.479	0.007
	Unit 2	0.059	0.003	0.11	0.015
	Unit 3	0.18	0.0029	0.108	0.004
Gilgel Gibe II	Unit 1	0.035	0.0078	0.235	0.019
	Unit 2	0.042	0.009	0.16	0.033
	Unit 3	0.055	0.0065	0.206	0.016
	Unit 4	0.025	0.01	0.089	0.015

Generally, the typical values for Forced Outage Rates of generating units tend to range between 0.3% and 29.4%, which depends on other factors such as unit type, size and age of plant components. Generating unit 1 of Gilgel Gibe I had a minimum forced outage rate in both years.

The result obtained shows the poor performance of Gilgel Gibe I and Gilgel Gibe II Hydropower station and the performance was too low for Gilgel Gibe II. Even though scheduled maintenance is a backbone of successful performance, the frequency was high for all generating units in 2014/15 compared to 2013/14. Compared to other units, unit 1 of Gilgel Gibe I was the most reliable and available in both years.

The major causes of outages are forced outages, which are resulting from emergency conditions. It results from improper operation of equipment or employee error and due to external factors of generating units such as shortage of water and silt content.

5. Conclusion

This research was aimed at evaluating the reliability, availability and performance of Gilgel Gibe I and Gilgel Gibe II hydroelectric power station in Ethiopia. The detail result is presented and discussed. The Reliability and availability of each unit were computed for the period of study. The frequent outages greatly affected the reliability and availability of each unit. Even though Gilgel Gibe I was installed earlier, its performance is better than Gilgel Gibe II. Both the scheduled and forced outage frequency and duration of each unit was increased from 2013/14 to 2014/15. The main result of this research analysis here, when compared with the corresponding results in some other countries, the two hydro power stations so far performed below expectation. Even though these power plants supply power to the customers through the grid system, their outage leads to power interruption at any place of the country. Due to this, when power outage happened at these power generations or others, the government urged to use unplanned power outage at some distribution substations to minimize the effect. Since this unplanned distribution substation outage will be done alternatively, it will have high impact to customer satisfaction.

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