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ANALYSIS OF CAPACITY OUTAGE PROBABILITY TABLE (COPT): A CASE STUDY OF AFAM THERMAL POWER STATION, NIGERIA

[1]Okakwu, I.K., [2]Olabode, O.E., [3]Ade-Ikuesan, O.O., [4]Oluwasogo, E.S. and [3]Osifeko M.O.

[1]Department of Electrical/Electronic Engineering, Faculty of Engineering, University of Benin, Benin City, Nigeria.
[2]Department of Electronic/Electrical Engineering, Ladoke Akintola University of Technology, Ogbomoso, Nigeria.
[3]Department of Computer and Electrical Engineering, Olabisi Onabanjo University, Ago Iwoye, Nigeria.
[4]Department of Electrical and Computer Engineering, Kwara State University, Malete, Nigeria.
*igokakwu@yahoo.com

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ABSTRACT

Power generation model is a basic criterion for generation system reliability assessment, and one of such models is capacity outage probability table. Capacity outage probability table is a good indicator that determines the future capacity expansion in a bid to ensure that the plants' total installed capacity is adequate to provide uninterrupted electricity as required by the end-users. This paper presents a probabilistic approach and analytical approach to Capacity Outage Probability Table (COPT) using: a case study of Afam thermal power station, Nigeria. The results of the analysis showed that as the number of unit outage increases, the capacity outage (MW) also increases while capacity available (MW), individual state probability and cumulative probabilities decreases.

1. INTRODUCTION

Since its inception, electricity has proven to be the driving force for sustainable socio-economic growth of nations across the globe (Islam, 2017). There is no gainsaying that industrialized nations of the world at the moment are channeling their effort in ensuring secured electricity supplies at competitive prices while third world countries like Nigeria who are at the verge of experiencing sustainable economic growth are in dire need of reliable electric power supply to support her economic growth and provide basic energy services to her people for their day-to-day activities (Ameh and Idoniboyeobu, 2012; Kumar *et al., 2013*). Presently in Nigeria, hydro-thermal power plants are used to generate electricity, while the integration of renewable energy sources into national grid is as good as paper proposal. Ideally, these power plants ought to generate electricity continuously without failure (Adhikary *et al.*, 2010). However, the reverse is the case as far as the supply of electricity is concerned and incessant power failures are common occurrences. It needs to be pointed out that availability of a complex power plant system is strongly associated with its component's reliability and maintenance policy (Adhikary *et al.*, 2010).

Electrical power plant reliability is the probability that it will not only generate electricity for its end-users without interruption but also, in an acceptable quality subject to design specifications (Etebu *et al.*, 2016). Reliability of power generation system is a good indicator in planning for capacity expansion geared towards ensuring that the total installed capacity is sufficient to deliver adequate electricity as required (Allan and Billinton, 1996). It is also a useful tool employed by power system engineers in the design, operation and maintenance of electric power system (Kumar *et al.*, 2013). Reliability as applied to generation system places keen interest on reliability of generators used in power systems (Kumar *et al.*, 2013). Power plant adequacy and security are the two core indices on which generation power system reliability assessment rest. Plant adequacy implies a state of having sufficient facilities to generate the required power demand by the end-users under static conditions while power plant security connotes the capability of the plant to absorb both dynamic and transient disturbances prevalent in bulk power supply system (Akhavein et al., 2011; Etebu *et al.*, 2016).

Generally, a power system is characterized by a probabilistic generation model of the existing system and this system generation model is usually presented in the form of capacity outage probability table (COPT) (Ahmed, 2011; Kumar *et al.*, 2013; Groissböck and Gusmao, 2015). COPT comprises of the available or unavailable capacity levels and their corresponding probabilities (Ahmed, 2011). Literature survey shows that COPT has been created using different approaches and these approaches can be broadly grouped into two; analytical methods and Monte Carlo simulation (MCS) techniques (Allan and Billinton, 1996; Gubbala and Singh, 1996). The MCS method is expensive in computational time, hence, very slow.

This paper presents probabilistic approach and analytical approach to COPT: a case study of Afam thermal power station, Nigeria. The analysis was implemented in MATLAB environment, and Afam thermal power station, Nigeria was used as a case study.

2. METHODOLOGY

2.1. Study Area

Afam thermal power station is located in the oil rich town of Okoloma in the Ndoki clan of Qyigbo Local Government Area of Rivers State, Nigeria. The power station was privileged to be the first major gas-turbine station built in Nigeria and the station with its auxiliary units were built and installed by Brown Boveri with the first phase; Afam 1 having four generating units (GT1– GT4) each with installed capacity of 10.3MW was constructed and commissioned in1963. Exponential local economic growth experienced in the seventies justified the need for Afam II having additional four generating units, each with an installed capacity of 23.9MW commissioned in 1976. Two years later, Afam III having four gas turbines of 27.5 MW as the installed capacity of each unit was commissioned in 1978 and in the year 1982, six generating units with installed capacity of 75 MW each were added to the station this known as Afam IV. Afam V was commissioned in the year 2002 with two generating units, each having installed capacity 138MW (Eti *et al.*, 2004).

2.2. Data Collection

The data below was obtained from Afam Power Station:

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Afam 1:

-	Number of generating units	-	4 Nos
-	Total install capacity	-	41.2MW
-	Capacity on each unit	-	10.3MW
-	Forced outage rate	-	0.03

Afam 2:

-	Number of generating units	-	4 Nos
-	Total install capacity	-	95.6MW
-	Capacity on each unit	-	23.9MW
-	Forced outage rate	-	0.02

Afam 3:

-	Number of generating units	-	4 Nos
-	Total install capacity	-	110MW
-	Capacity on each unit	-	27.5MW
-	Forced outage rate	-	0.025

Afam 4:

-	Number of generating units	-	6 Nos
-	Total install capacity	-	450MW
-	Capacity on each unit	-	75MW
-	Forced outage rate	-	0.04

2.3. Mathematical Modelling

The two basic input parameters required for this generation system reliability analysis are the capacity and the failure probabilities of individual generating units. Consider the operation of a unit under two-state model, its failure probability known as its unavailability U is given as:

$$U = \frac{\lambda}{\lambda+\mu} \quad (1)$$

Where: $\lambda =$ unit failure rate; $\mu =$ unit repair rate; $U =$ unit unavailability.

The state space diagram for the system showing the transition rate from state 0 to state 1 is λ and the transition rate from state 1 to state 0 is μ and is as showed in Figure 1 where: the state 0 represent the operating state and state 1 stands for the failed state.

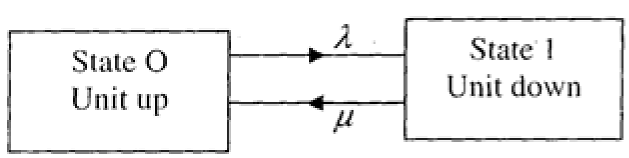

Figure 1: State space diagram showing rate of transition between failure and repair per unit time

Forced outage rate (FOR) stands for unit availability and is given as:

$$FOR = \frac{Forced\ outage\ hours}{IN-Service\ hours+Forced\ outage\ hours} \quad (2)$$

Considering a generation system having $n-$identical units with availability of each designated as A and unavailability(FOR) of each unit represented with F. The number of failed units is denoted as g such that the different states of the systems are defined by $g = 0, 1, 2, \ldots, n$ while the total number of states equals$(n + 1)$. Then probability$\left(P_g\right)$ of a state g (i.e., probability of having g units of n failed can be expressed using binomial distribution expansion given as:

$$P_g = {}^nC_g(F)^g.(A)^{(n-g)} \quad (3)$$

Where: P_g = Probability of having g-units out; n = number of units; F = F.O.R or unavailability; A = availability; g = number of failed units

To obtain the capacity model for the system both the capacity and availability of the individual units has to be combined where each generating unit is represented by its nominal capacity (C_i) and its corresponding unavailability as (U_i). If the capacity or the outage capacity is represented by X, then the individual state probability is expressed as:

$$P(X = x_i) = \begin{cases} 1 - q, & x_i = C_i \\ q, & x_i = 0 \end{cases} \quad (4)$$

To obtain the cumulative state probability the individual state probability for all capacity less than x_i will be summed up thus;

$$P(X = x_i) = \begin{cases} 0 & x_i < 0 \\ q & 0 \le x_i \le C_i \\ 1 & x_i \ge C_i \end{cases} \quad (5)$$

Implementing the above equations on real-time data, the Capacity Outage Probability Table (COPT) that represents the probability of different capacity outages of the system can be generated.

2.4. Analytical Approach

For a system with n generating units which can either be "in service" or "out of service", the total number of system states is 2^n and the total probabilities of these states must be equal to 1.0. Each unit is represented by one bit with a value of "1" or "0" which corresponds to "in service" or "out of service" state. The probability of the units in these two states is given by:

$$Prob = \begin{cases} 1 - FOR & if\ in\ service = 1 \\ FOR & if\ out\ of\ service = 0 \end{cases} \quad (6)$$

The individual state probability is calculated using:

$$P_g = \prod_{g=1}^{n} P_g \quad (7)$$

For Afam-I with 4 units, the possible state is 16 which is presented in Table 1.

Table 1: System possible state for Afam I

System state	Unit 1	Unit 2	Unit 3	Unit 4
1	1	1	1	1
2	0	1	1	1
3	0	0	1	1
4	0	0	0	1
5	0	0	0	0
6	1	0	1	1
7	1	1	1	0
8	1	0	0	0
9	1	0	0	1
10	1	1	0	1
11	0	1	0	1
12	1	1	0	0
13	0	1	1	0
14	1	0	1	0
15	0	0	1	0
16	0	1	0	0

It can be seen from Table 1 that states 2,6,7 and 10; 3,9,11,12,13 and 14; and 4,8,15 and 16 are identical states which corresponds to 30.0MW, 20.6MW and 10.3MW all "in service" respectively. State 1 corresponds to 41.2MW in service, while state 5 correspond to 0MW "out of service". Equation 7 was used to calculate the individual states probabilities. The final step was to rearrange the states and merge the states with same capacity level.

3. RESULTS AND DISCUSSION

The proposed approach was implemented in MATLAB environment; it was run on a portable computer with an Intel Core2 Duo (1.8GHz) processor, 2GB RAM memory and MS Windows 8 as an operating system. The obtained COPT for Afam-I-IV is as showed in Tables 1 to 4. As can be observed from the Table 2, Afam-I consists of four units and as the number of unit increases progressively during the analysis, the system capacity output (MW) increases approximately in equal proportion while capacity available (MW) decreases approximately in equal proportion. The probability of individual state being failed decreases as the unit increases, a slight difference in between unit 0 and 1 was observed, while an exponential decrease was observed with units 3 and 4 compared to 0 and 1. The cumulative probability obtained for Afam-I also decreases as the system unit increases such that cumulative probability of unit 4 tends to be insignificant in value.

From Table 3, Afam-II consists of four units and as the number of unit increases progressively during analysis, the system capacity output (MW) increases while capacity available (MW) decreases. The probability of individual state being failed decreases as the unit increases, a slight difference in between unit 0 and 1 was observed, while an exponential decrease was observed with units 3 and 4 compared to 0 and 1. It can be deduced that the results for Afam-II followed the same trend with Afam-I.

Table 4 for Afam-III shows the same trends of results as the number unit increases progressively during the analysis, the system capacity output (MW) increases while capacity available (MW) decreases. The probability of individual state being failed decreases as the unit increases, a slight difference in between unit 0 and 1 was observed, while an exponential decrease was observed with units 3 and 4 compared to 0 and 1.

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Table 2: Capacity outage probability table (COPT) for Afam-1

No. of unit out (g)	Capacity out (MW)	Capacity available (MW)	Probabilistic approach		Analytical approach	
			Individual state probability (Pg)	Cumulative probability (CP)	Individual state probability (Pg)	Cumulative probability (CP)
0	0	41.2	0.88529281	1	0.88529281	1
1	10.3	30.9	0.10952076	0.11470071	0.10952076	0.11470719
2	20.6	20.6	0.00508086	0.005179995	0.00508086	0.00518643
3	30.9	10.3	0.00009828	0.00009909	0.00010476	0.00010557
4	41.2	0	0.00000081	0.00000081	0.00000081	0.00000081

Table 3: Capacity outage probability table of Afam-II

No. of unit out (g)	Capacity out (MW)	Capacity available (MW)	Probabilistic approach		Analytical approach	
			Individual state probability (Pg)	Cumulative probability (CP)	Individual state probability (Pg)	Cumulative probability (CP)
0	0	95.6	0.92236816	1	0.92236816	1
1	23.9	71.7	0.07529536	0.07763184	0.07529536	0.07763184
2	47.8	47.8	0.00230496	0.00233648	0.00230496	0.00233648
3	71.7	23.9	0.00003136	0.00003152	0.00003136	0.00003152
4	95.6	0	0.00000016	0.00000016	0.00000016	0.00000016

Table 4: Capacity outage probability table of Afam-III

No. of unit out (g)	Capacity out (MW)	Capacity available (MW)	Probabilistic approach		Analytical approach	
			Individual state probability (Pg)	Cumulative probability (CP)	Individual state probability (Pg)	Cumulative probability (CP)
0	0	110	0.90368789	1	0.90368789	0.999999995
1	27.5	82.5	0.09268594	0.09631211	0.09268594	0.096312105
2	55	55	0.00356484	0.00362617	0.003564844	0.003626165
3	82.5	27.5	0.00006093	0.00006133	0.00006093	0.000061321
4	110	0	0.00000039	0.00000039	0.000000391	0.000000391

Table 5: Capacity outage probability table of Afam-IV

No. of unit out (g)	Capacity out (MW)	Capacity available (MW)	Probabilistic approach		Analytical approach	
			Individual state probability (Pg)	Cumulative probability (CP)	Individual state probability (Pg)	Cumulative probability (CP)
0	0	450	0.78275778	1	0.78275778	1
1	75	375	0.19568945	0.21724221	0.19568945	0.21724221
2	150	300	0.02038432	0.02155276	0.02038432	0.02155276
3	225	225	0.00113246	0.00116845	0.00113246	0.00116845
4	300	150	0.00003538	0.00003598	0.00003538	0.00003598
5	375	75	0.00000059	0.00000059	0.00000059	0.00000059
6	450	0	4.10E-09	4.10E-09	4.10E-09	4.10E-09

Unlike Afam-I-III, Afam-IV has six units with total installed capacity of 450MW, during the analysis, as the number of unit increases, capacity output (MW) also increases while the capacity available (MW) decreased marginally. The individual state probability and cumulative probability decreases exponentially and later tends to negligible value. It is observed from Tables 2-5 that both the individual state probability and cumulative probability increases as the capacity available increases. The trend observed was as a result of increases in the number of “unit outages” in the system. Although in practice, the probability of having large amounts of capacity output due to the outage of several units is very low then the capacity outage table can be truncated for probability below a specified amout (e.g. 10^{-7}), i.e. the capacity outage is zero.

4. CONCLUSION

This paper presents an effective method to determine the COPT of a generating station. The probabilistic and analytical approaches were used to obtain the reliability indices of the generating station. The probabilistic approach has significant advantages over the analytical approach. The analytical approach requires more mathematic modelling of the generating units compared to the probabilistic method. The proposed technique proves to be an effective means of building a COPT. The models are applied to Afam thermal power station in Nigeria.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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