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A Markov model of generator performance at the Kainji hydro-power station in Nigeria

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ABSTRACT

The Kainji hydropower station is a seven turbo-alternator station that for many years served as the base load supply for the Nigerian power grid. Over 200,000 pieces of data about the performance of the machines were used to estimate values of the failure and repair rates for each machine and a Markov steady-state model of the plant was constructed to determine the probability output of the turbines. This result showed that Kaplan turbine (KT) 12 is prone to failure compared to any other KT unit in the hydropower plant. Also, the clusters of probability that define the system state due to the different output capacities of the units show that the hydropower plant has not performed to its maximum capacity, further evaluation shows that 60% of the KT machine units are operating which is consistent with the observed robustness of the output. The model not only conforms to observations but reasonably provide a means of studying the effects of different actions that may be taken to improve the performance of hydropower plant.

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1. INTRODUCTION

Electricity has always been a driving force in every country's economy for meeting customers day-to-day needs. When power is created from renewable energy sources, it helps to meet energy demand, improve energy security, address environmental challenges climate change, and contribute to other elements of social development [1], [2]. Hydropower generation is a renewable energy technology that has attracted a lot of interest from the power industry. Hydropower plant accounts for over 86% of all renewable energy generated globally. Other renewable energy sources, such as solar, geothermal, wind, and biomass; account for less than 14% of total output [3], [4].

The Kainji hydropower plant, which was envisioned as the nucleus of Nigeria's power system, had a capacity of 960 MW and was to be powered by 12×80 MW Kaplan turbines. The station was commissioned in 1968 with two 80 MW Kaplan turbo-alternators. Subsequently, other types of turbines of varying sizes were installed. By 2010, six additional units consisting of two 80 MW and two 100 MW Kaplan turbines and two 120 MW Francis turbines were installed bringing the installed capacity to 760 MW. The consultant, Balfour Beatty-Netherland Engineering Consult (NEDECO) designed the Kainji Dam to generate at a full capacity of 760 MW. In reality, all the units have never been fully installed due to problems arising from serious shortfalls in the expected inflows into the reservoir due to drought [5], [6]. The operators of the facility, Nigeria electricity power authority (NEPA), deviated from the original plan and introduced Francis turbines (which are more sensitive to head conditions than the original Kaplans) and even increased the rated capacity of individual units from 80-100 MW and 120 MW. The information obtained from various sources indicates that the actual generating capacity of the dam was reduced as a result of under performance by the enlarged units and overall unsuitability of the Francis turbines for this situation.

Between February 1964 and August 1968, the Kainji Dam, a multipurpose project planned for power generation, improved river navigation, flood management in the Niger Valley, and fishery output of over 10,000 tons annually, was built. The Kainji reservoir stretches about 136 km upstream of Kainji Dam, and it has two flood seasons known as the white and black floods [7]. White flood is due to local rain that begins around July/August and peaks in September. The black flood which is around November to February and peaks in January is due to rain that has fallen in places like Senegal, Guinea and Sierra Leone that takes about six months before arriving at Kainji Lake. Having flowed over a long distance, all its debris has settled before arriving at Kainji, hence, the water is cleared [8], [9].

The rising rate of electricity demand in Nigeria necessitates a constant and reliable supply of electricity to users. As a result, improving a country's electric supply's operational effectiveness is critical for its economic and social development. Also, due to its twenty-four (24) hour usage per day it has become increasingly essential in our day-to-day activities. Likewise, it has been discovered by [10]–[14] that the energy provided by Nigeria's largest hydroelectric power plants does not fulfil demand. Electricity consumers in Nigeria (domestic and industrial) have been looking forward to the power holding company of Nigeria (PHCN) in meeting their required demand. The Electricity sector in Nigeria is divided into three sectors (generating companies, transmission companies and distribution companies and all the sector activities are regulated by Nigerian electricity regulating commission (NERC). However, the distribution companies relate with the end users of electricity in Nigeria. Many researchers have stated that the generating capacity of the Nigeria grid is low to the demand of the consumers and most of the existing generating stations were not operating at installed capacity [2]. Therefore, reliability evaluation of generating station needs to be carried out.

Reliability evaluation of a generating system is predicting if the system can meet its load demand without failure for the period of time required. Accurate estimates of generating unit reliability are needed for generating capacity planning and to aid improved criteria for future designs and operations [15]–[17]. Due to the fact that the Kanji hydropower plant is not operating at its maximum capacity, there is a need to model the probability output of the generators in order to know the state of the hydropower plant.

2. METHOD

Over 200,000 items of data (generation output, hydrological information, problems, and relevant matters) were obtained from Kainji hydropower station, collated and verified from National Control Centre (NCC) where some forms of reports have been filed daily by the generating stations, and then entered into a compatible format for a structured query language (SQL) server database. The principal difficulty encountered was the poor archiving of the information. The paper addressed the information from official generation sources and does not consider or include generation involving private organizations of which virtually all in the recent past have had to maintain a sizeable capacity and the small informal generating plants that have become the average person's response to the very inadequate power supply. The amount of electricity generated hydroelectric plants is proportional to the energy of the water at the top of the water column [18], [19]. Consequently, the electric power generated is proportional to the product of the head and the rate of flow and can be expressed as (1).

$$P = \eta.\rho.g.h.Q \tag{1}$$

where, P is power (J/s or watts), η is the turbine efficiency, ρ is the density of water (kg/m^3), g is the acceleration due to gravity (9.81 m/s^2), h is head (m), Q is the flow rate (m^3/s). A spreadsheet procedure was developed for evaluating the power developed based on the outflow (tailrace flow) for Kainji power station and the head as obtained from the database. This was carried done since it provides an insight into plant efficiency.

2.1. Development of the Markov process generator model

A power station in the context of this work is assumed to consist of a set of number (N_G) turbo-alternators where each machine is assumed to operate independently of others and experiences failures that are described by a simple exponential process. The state of the station at any given time will be described as per the condition of each of the machines. In this research only two conditions are recognized, a machine is said to be “UP” when it is fully functional and capable of producing up to its rated output and “DOWN”

(DN) is the condition when the turbo-alternator has been shut down for whatever reason and has failed to deliver its expected rated output. This implies that for an NG generator station the state at any given time can be expressed as an NG-tuple of "UP"s and "DOWN"s depending on the condition of the machine associated with that position in the NG-tuple. The "UP"s and "DOWN"s time of generating station is depicted in Table 1.

Table 1. Commissioning date, uptime and downtime of the generators

	UP T KT 6	DN T KT 6	UP T KT 7	DN T KT 7	UP T KT 8	DN T KT 8	UP T KT 9	DN T KT 9	UP T KT 10	DN T KT 10	UP T KT 11	DN T KT 11	UP T KT 12	DN T KT 12
Year of Installation	1978		1968		1968		1969		1969		1976		1976	
Sum	732	364	649	447	810	286	870	226	987	109	951	145	654	442
Number (N)	11	10	11	11	13	13	16	15	13	12	15	14	20	19

For convenience's sake and since the field for representing the condition has only two entries, it may be mapped onto the binary field. The "UP" condition been represented as a "1" and the "DOWN" as a "0". The condition of the station may then be represented as a binary vector or n-tuple. In other words, a station with 5 generators that has a condition (1, 0, 0, 1, 1) implies that generators 1, 4 and 5 are "UP" while generators 2 and 3 are down. The complete set of all possible conditions is referred to as the Markov transition set [20]–[23].

The set is characterized by transitions which depend on the probability of failure and repair of the individual machines. The set thus created has properties which are developed below. Unlike a proper state space, this set does not satisfy the necessary requirements to qualify as space since there is no notional null element or the additive inverse that would enable addition to lead to the null element. Nonetheless, the set is characterized by basic properties that determine the transition between states and rules that govern that process. Since the set is binary, it has a dimensionality of 2^{N_G} and the elements of the station condition vector may then be represented logically as the set of binary numbers between 0 and $2^{N_G} - 1$. The important operation was fully defined in the nature of transitions between states. From the theory of probability and reliability, the probability of a failure occurring in an interval due to a failure process λi for the infinitesimal time element, Δt [24] may be expressed as (2):

$$P\ (\lambda_i) = \lambda_i \Delta t \quad (2)$$

Also, the probability of two such events occurring in the same time duration was expressed as (3).

$$P\left(\lambda_j\ \lambda_i\right) = \lambda_j \lambda_i \Delta t^2 \quad (3)$$

Since Δt is very small Δt^2 is smaller still and negligible when compared with the single failure or repair event. This precludes multiple failures and provides significant simplification in the transition [25]. Indeed, the transitions reduce from $2^{N_G}!$ (which is the number of transitions when any state may be the terminal condition for a starting point) to 2^{N_G}. The set of possible states can be arranged as a sequence that reshaped and reorganized. The problem to be addressed is to determine the relevant transitions and use this information to design efficient routines for calculating the Markov state probabilities.

$$Let\ N = \{Sk :\ all\ possible\ combinations\ of\ Machine\ conditions\} \quad (4)$$

Since only one state change may occur during transitions, the N can be partitioned into a number of subsets containing states that never have transitions between them but have a similar structure. For an N_G generator stations the subset of states with one machine down consists of ${}^{Ng}C_1$ states and will be represented as N_1. Then,

$$N = \cup_{m=1}^{N_g} N_{m,}\ m = 0,1,2, \ldots\ N_g \quad (5)$$

The cardinality of the subsets N_G is given by Pascal's triangle for different N.

$$\prod m = Nc_m \quad (6)$$

where N_m={q_k: $k=1, 2\ldots N_g$; over the binary field} and q_k is the N_m – tuple that define the state of the station at the given time. Note that $m=\sum q_k$ since it defines the number of functioning machines.

The representation so far implies that for any given number of machines in a station, it may be partitioned into a number of subsets defined by the number of working machines and (7).

$$N_m \cap N_i = \emptyset = null\ set \tag{7}$$

These outputs are very useful in extracting the Markov probabilities for large numbers of stations with machines as shall be evident in the next few paragraphs. The output implies that transitions can only occur when a station migrate from one subset to another which has either one more machine up or down. This can be best expressed by the following definition. Nr+ is a successor set to Nr if and only if all states in the former have one generator more operating than in the latter. Similarly, Nr- is a predecessor set to Nr if and only if the latter has one less functional machine than the latter. Clearly successor and predecessor states are subsets of the total number of states and will determine how the probabilities are related to each other. Figure 1 is the decomposition of the machine states into operational subsets and from which the transitions can be determined.

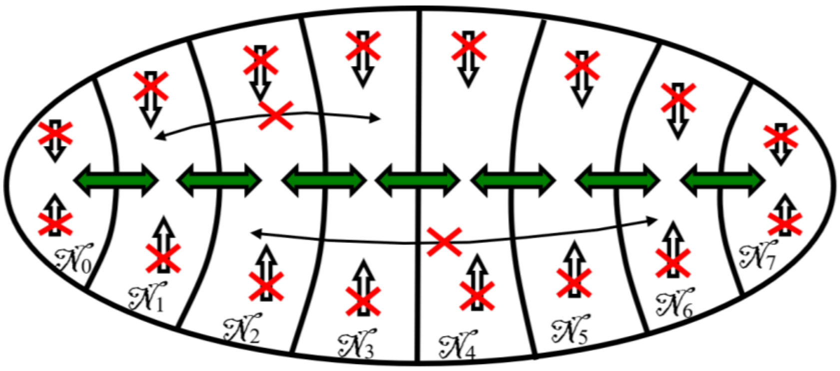

Figure 1. Decomposition of the machine states into operational subsets

These definitions provide a rationale for the automatic generation of the Markov transition matrix. The resulting rational process can be generalized and made efficient by exploiting some of the results that become evident from the transition properties. Applying the above definitions to the station it is clear that N_0 has no predecessor state while N_{Ng} has no successor state. Hence,

$$N_{0^-} = N_{N_g{}^+} = \emptyset \tag{8}$$

The next step is to determine how these considerations facilitate the generation of the transition matrix and simplify the calculation of the probabilities by exploiting the apparent sparseness of the transition matrix.

Consider an arbitrary state S_k and N_m, then it has a number of successor and recessor states. The number of successor states is the number of machines that can be repaired one at a time. Hence for the Ng machines there will be $\prod_m{}^{+}={}^{Ng}C_{(Ng\ -\ Nm)}$ successor states in its successor subset and $\prod_m{}^{-}={}^{Ng}C_{(Nm)}$ in its recessor subset. The implication is that all other transitions are not feasible and will not play a role in the dynamical considerations of the state in the Markov sense. It also implies that the only $[{}^{Ng}C_{(Ng\ -\ Nm)}+{}^{Ng}C_{(Nm)}+1]$ elements will be non-zero in the row corresponding to S_k in the transition matrix. Let P_k be the probability of the station being in S_k the rate of change of the probability with respect to time is the conditional probability of all migrations from the state minus the combined probabilities of all the states that will terminate at S_k. Transitions into recessor states will be failures of a machine and hence the probability of such a transition involving say the repair of a machine q can be expressed as (9).

$$\Delta Pkq = pr\{\, k\ \to v | station\ is\ in\ S_k |\}.Pk \tag{9}$$

where the first term is the conditional probability of a transition taking place. In practice when all transitions take place independent of the present state, the system can be described as a homogeneous system and all transitions to progressor states will be μ_ζ where ζ is the machine repaired and λ_υ and υ is the machine which was the successor state in the regressor subset. Clearly this may not always be true since stations tend to have a fixed maintenance crew whose time-to-repair may increase as the number of machines in the repair queue increases. This aspect can be relatively realistically reflected by using non-homogeneous values for the different repair rates and failure rates. The algorithm developed here would simply reflect this in computing transition matrix entries using appropriately defined transition probabilities. The situation is illustrated in Figure 2. The transition matrix elements a_{kj} corresponding to the transitions to and from S_k can thus be written as (10).

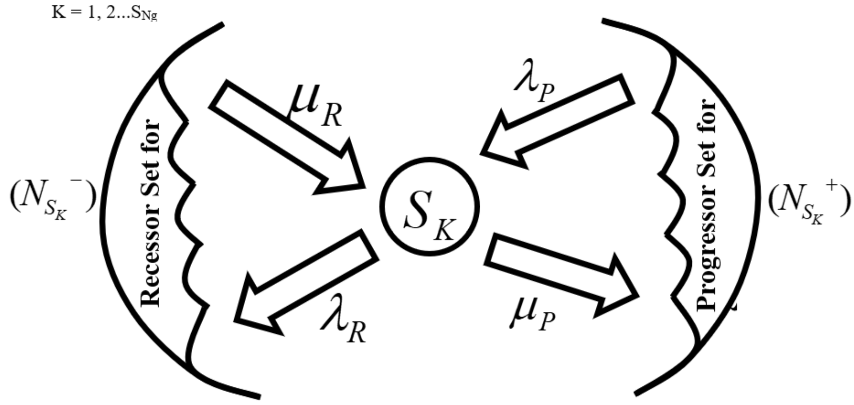

Figure 2. Transition possibilities

$$\frac{dP_k}{dt} = \sum^{\nu e N_k^+} \mu_\nu \, p_k + \sum^{\nu e N_k^-} \lambda_\nu \, p_k - \sum^{\tau e N_k^+} \lambda_\tau \, p_\tau - \sum^{\nu\gamma e N_k^+} \mu_\gamma \, p_\nu \quad (10)$$

In the steady-state, the system state probabilities are unchanging and the derivative is zero. Also, since all the states constitute the only possible conditions for the power system, hence the total probability must be unity. Hence,

$$\sum_{k-1}^{S_{Ng}} Pk = 1 \quad (11)$$

The (11) may be rewritten in the matrix form as (12):

$$Ap = 0 \quad (12)$$

where p is the row-vector of the long run probabilities p_k and the elements satisfy the relation

$$a_{kk} = \sum^{\nu \in N_k^+} \mu_\nu + \sum^{\nu \in N_k^-} \lambda_\nu \quad (13)$$

$$a_{ij} = \begin{cases} -\lambda_\tau \; if \; \tau \; is \; a \; progressor \; state \\ \mu_\gamma, if \; \gamma \; is \; a \; regressor \; state \end{cases} \quad (14)$$

As shown in (13) depends on whether the link is related to a progressor state or regressor state. The output result confirms the second very important observation that renders such problems tractable. $|a_{kk}| \geq |a_{kj}|$ the matrix A is thus diagonally dominant and hence it tends itself to resolution by iterative methods [26]. The above results provide the entire basis for developing suitable codes for the automatic generation of the Markov transition matrices for some power stations.

3. RESULTS AND DISCUSSION

The model is implemented in Excel VBA and the results of the transition state are depicted in Figure 3. Table 2, shows the failure rate and repair rate of the Kaplan turbine generator set. Also, Figures 4 and 5 show the model of the output state probabilities of the hydroelectric plant and the state probability of the generator respectively.

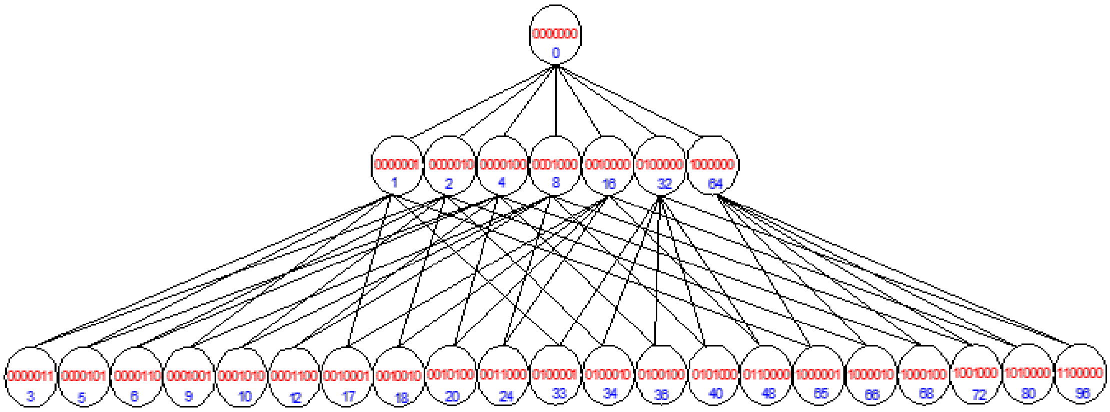

Figure 3. A section of the KHPS state transition diagram

Table 2. Failure rate and repair rate of generators

	UP T KT 6	DN T KT 6	UP T KT 7	DN T KT 7	UP T KT 8	DN T KT 8	UP T KT 9	DN T KT 9	UP T KT 10	DN T KT 10	UP T KT 11	DN T KT 11	UP T KT 12	DN T KT 12
Mean (hr)	1597	873.6	1416	975.3	1495	528	1305	361.6	1822	218	1522	248.6	784.8	558.3
λ (/yr)	5.485		6.186		5.858		6.713		4.807		5.757		11.16	
μ(/yr)		10.03		8.982		16.59		24.23		40.18		35.24		15.69
UP T/DN T		2.011		1.452		2.832		3.85		9.055		6.559		1.48
TOTAL		1096		1096		1096		1096		1096		1096		1096

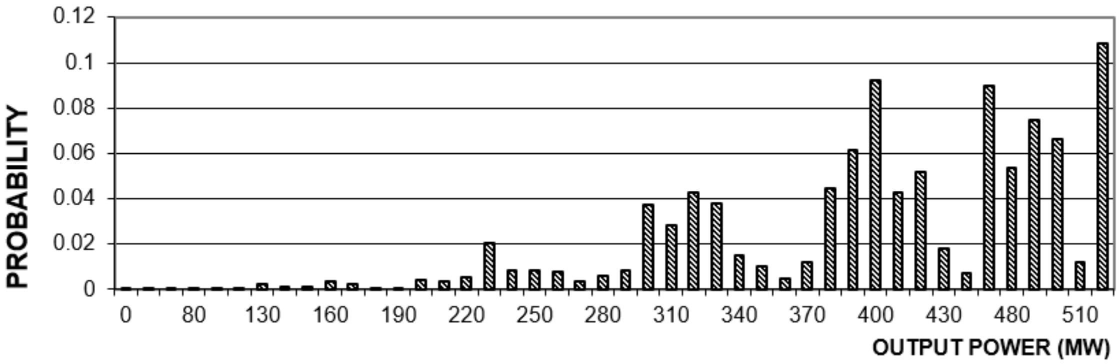

Figure 4. Output state probabilities of Kainji Markov model

This result showed that the failure rate of the KT 6 to KT 12 varies from 4.807 to 11.16 per year in which KT 10 indicating the least failure rate while KT 12 shows the highest failure rate. This implies that KT 12 is prone to failure compared to any other KT unit in the hydropower plant. Also, the rate at which the KT units are repaired shows that it takes more time to restore KT 10 to UP mode from down mode compared to other unit in the station this implies that the faults that occurred in KT 10 may be a severe fault which may takes longer time. However, KT 7 shows the least repair rate this implies that the factors that leads to downtime in KT 7 may be repair easily compared to other unit.

The result, which is shown in Figure 4 yielded clusters of probability that define the system state due to the different output capacities of the units which indicate that power output of all the KT unit in the station varies from 80 to 510 MW this implies that the hydropower plant has not performed to its maximum capacity. A further assessment performed by aggregating the probabilities and the number of functioning machines resulted in Figure 5. From, the results the probability that none or only one of the KT unit is UP is 0 but the probability that five or six KT units are working is 33 and 30% respectively, this approach suggests that for almost 60% of the time, 5 or 6 machines are operating which is consistent with the observed robustness of the output. The model not only conforms to observations but also indicates that although individual plant reliability is a far cry from what is expected from usually very reliable hydro power plants, the aggregate behavior is quite insensitive. The most likely output from the station is however considerably lower than the maximum value. This implies that considerable benefits may accrue if the system is refurbished and proper maintained.

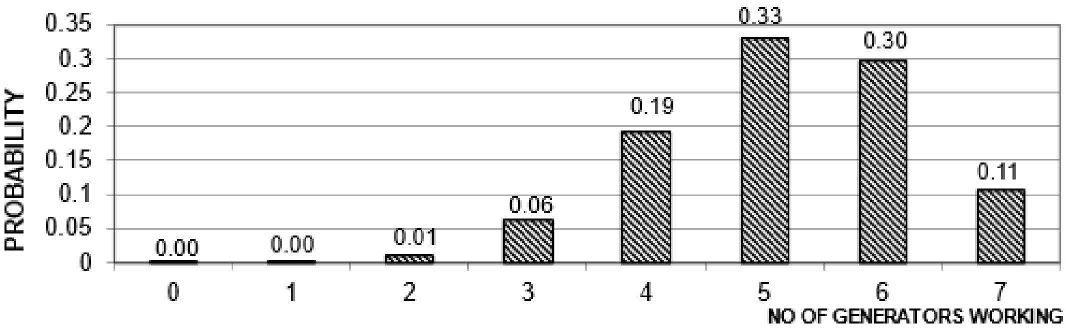

Figure 5. State probability of generators at the Kainji power station

4. CONCLUSION

Having created the database, the effort was focused on the Kainji hydropower station. Using information derived from the database, estimates of unit failure and repair rates were determined. The result was then used to initialize a 128-state Markov model constructed using EXCEL-VBA as the platform. In spite of the complexity of the problem, it was possible to automatically generate the transition matrix and solve the relatively large system by iteration and decomposition. This approach eliminated the need for proprietary software since EXCEL-VBA is available on virtually every contemporary laptop. As a result, the state probabilities were calculated. The outcome indicated that although the station was operating at about 60% of its maximum output capacity, more than five machines tended to be functional most of the time. Furthermore, it was revealed that the station is in dire need of refurbishing and simulations confirm the marked improvement that will prevail should this be properly undertaken.

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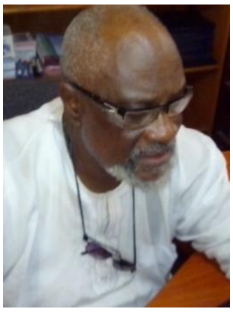

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