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Analysis of the reliability, availability and maintainability of a group of tidal turbines in production by the state space method (Markov process)

Faliniaina Jhon Eldiss Jeannot, Dr Jaomiary Antonio
[1,] *Student, University of Antananarivo, Madagascar*
[2,] *Research professor at the University of Antsiranana, Madagascar*

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ABSTARCT: The study of the safety of operation of an energy system is a very vast field. This work focuses on FMD analysis (Reliability, Availability, Maintainability) a group of tidal turbines in production to give users and technicians the tools or data to help them improve their production system if necessary. For this type of analysis, several tools are available. But the most used are: the tree of causes, the tree of events, the diagram of reliability, the method of space of states. In our case, the focus will be on analytical and graphic techniques using the MEE (State Space Method) by dividing the **n** entity of the group into **m** sub-group in order to avoid having an overabundant number of differential equations to solve because of the huge size of the transition matrix, and it also facilitates the creation of the Markov graph. Depending on the data, as well as the configuration or structure concerning the components, the results of the latter can be calculated, analysed and evaluated on the basis of adequate probability functions. Mathematical models are presented in order to see the behaviours of the system's FMD parameters study with simulations in the form of curves or histograms. It is from the reading of the figures or the results obtained either by calculation or by simulation that the appropriate type of maintenance is foreseen.

KEYWORDS: Tidal turbine-FMD-Markov-Simulation.

I- INTRODUCTION

The current trend is to build wind farms and water Turbine with large production capacities, consisting of a large number of entities. The concept of reliability and availability for an energy production system is classified in two broad categories as predictive reliability, operational reliability. The objective here is to analyse the reliability, availability, operational of n tidal turbines in production using MEE (State Space Method). Using the Markov graph, we can see the transitions of each possible state as a function of n and the state variables.

1- Background to the work

Our chapter focuses on the mathematical modelling of the FMD of the energy production of 10 (ten) tidal turbines using the state space method (Markov process) as a tool. The transition probabilities from state i to state j are the status variables considered.

The figure below gives us a rough idea of the structure of the system that we will break down in this study.

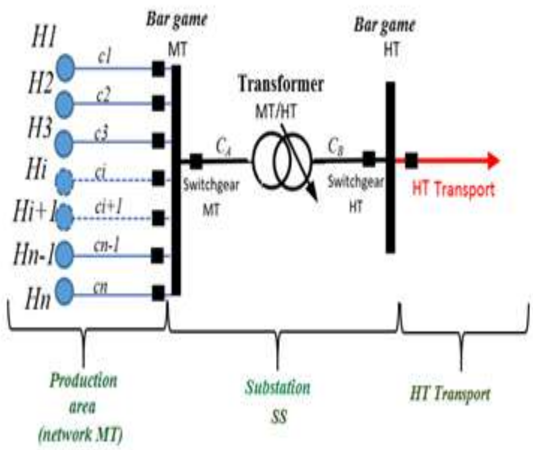

Figure 01: Topology of n parallel mounted water Turbine.

II- METHODOLOGY

Emphasis will be placed on analytical and graphic techniques. These methods are sufficient to

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provide users and technicians with the results needed to make objective decisions about the use and improvement of the system if necessary. Analytical methods can be qualitative or quantitative. The most used are: the tree of causes, the tree of events, the diagram of reliability, the method of space of states. But in this thesis, we focus on the use of MEE (Markov process) in order to better understand the evolution as well as the behaviour of the components and the overall system itself.

1- Model based on state space method (Markov process)

[2].A system consisting of repairable elements each having its own probability of states is considered.

$E = \{State\ Ei\ of\ système\}$

It is said that a process is Markov if:

- Given n+1 any dates

$t1 < t2 < .... < tn < t < t\max$

- Given n+1 any states

$E1, E2, ...En, E$

$$\Pr\begin{Bmatrix} X(t) = E / X(tn) \\ = En, X(t) = X(tn-1) \\ = En-1, ..., X(t1) = E1 \end{Bmatrix} = \Pr\begin{Bmatrix} X(t) = E / X(tn) \\ = En \end{Bmatrix} \quad (1.01)$$

A Markov process whose state space is discrete is called the «Markov chain».

III- PERFORMANCE ANALYSIS

1-Modelling

The probability of state Ei of a system is given by:

$$P_r = 2^n \quad (1.02)$$

So, for n=10, we have

$$P_r = 2^{10} = 1024$$

$$X(t) = P(E1(t), E2(t), ..., E1024(t)) \quad (1.03)$$

If n is very high, as in our case, it is very difficult to create the Markov graph according to the transition probability without forgetting the overabundant number of equations to solve at the same time. So one of the solutions is to break n down into several subgroups.

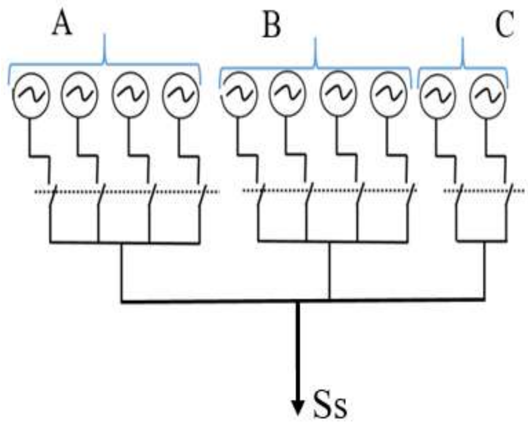

Figure 02: Breakdown into three subgroups

Subgroup A: H1, H2, H3, H4
Subgroup B: H5, H6, H7, H8
Subgroup C: H9, H10

In order to better understand the evolution and likely behaviours of the entire system analysed, we will first break down a three-part production line. (See figure below).

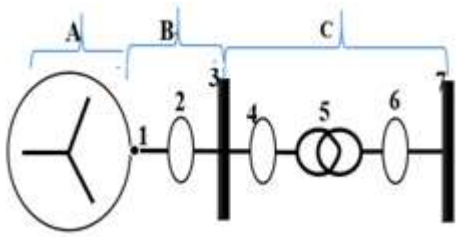

Figure 4.03: Graph of a production line

Part A: Source tidal turbine
Part B: Cable connection from generator connection to Ss input (part C)
Part C: all the components of the Ss
1: Connecting the cable to the generator
2, 4, 6: Link cable
3, 7: Bar set
5 : transformer

a- Performance of Part A

Part A is the Tidal Source (Hi). The failure rate λ_{Hi} is the sum of all the failure rates of components that make up a tidal entity because its components are in serial configuration.

With the Markov process, we have:

$$X(t): \begin{cases} 1 \Rightarrow Hi \rightarrow good\ condition \\ 0 \Rightarrow Hi \rightarrow defaulting \end{cases}$$

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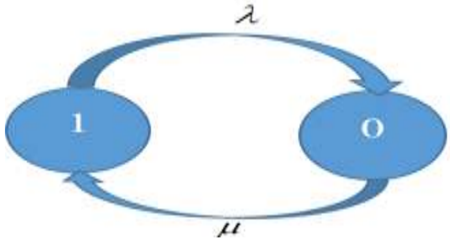

Figure 04: State Model

With the Markov graph above we obtain the following transition matrix:

$$M = \begin{pmatrix} -\lambda_{H1} & \lambda_{H1} \\ \mu_{H1} & -\mu_{H1} \end{pmatrix} \quad (1.04)$$

We develop this relationship to calculate $\prod_1(t)$
By asking:

$$\prod' = \prod(t)M \quad (1.05)$$

The following relationship is the Chapman-Kolmogorov process state equation or equation. And its resolution tells us about the entire probability of occupation of each state.

$$\prod_1 = A = \frac{\mu}{\lambda+\mu} \quad \prod_0 = \overline{A} = \frac{\lambda}{\lambda+\mu}$$

(1.06)

A: Availability $\overline{A}$: Unavailability

b- Link Cable Analysis Model (Part B)

Each link consists of one cable and two "SG-switchgear" shielding cells on both ends (see figure below).

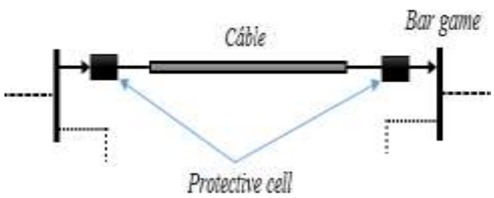

Figure 05: Link cable model

The failure rate of the cables depends on their respective lengths

$$\lambda_{B_i}(t) = \lambda_{B_i}.l_{cable} + 2\lambda_{SG_i} \quad (1.07)$$

With the approach on the state space method like that of the previous one, we obtain:

$$\overline{A}_{Bi} = \frac{\lambda_{Bi}}{\mu_{Bi}} = \left[\left(1+\frac{\lambda_{C_{Bi}}}{\mu_{C_{Bi}}}\right)\left(1+\frac{\lambda_{SG_{Bi}}}{\mu_{SG_{Bi}}}\right)^2 - 1\right]$$

(1.08)

$$A_{Bi} = 1 - \overline{A}_{Bi} \quad (1.09)$$

c- Reliability of n entities of parallel subgroups

The subgroup **(**A and B) is a serial-parallel configuration. With the figure below, we obtain the overall model.

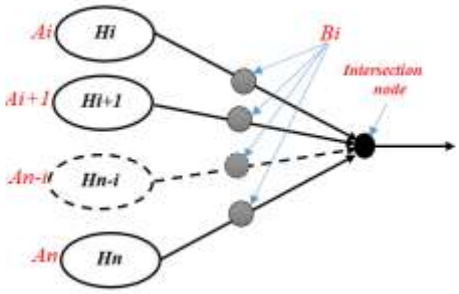

Figure 06: A and B Configuration

For a branch we have $(A_i \rightarrow B_i)$ that is in series, so we obtain models of $R_i(t)$:

$$R_i(t) = \exp(-\lambda_i.t) \quad (1.10)$$

$$R_{Hi}(t) = R_{Ai}(t).R_{Bi}(t) \quad (1.11)$$

On the other hand, for an analysis of the entire group entity or branches, we have:

$$(A_i \rightarrow B_i)//(A_{i+1} \rightarrow B_{i+1})//... \\ ...//(A_{n-i} \rightarrow B_{n-i})//(A_n \rightarrow B_n) \quad (1.12)$$

From where

$$R_{T_{Ai\rightarrow Bi}}(t) = 1 - \prod_{j=1}^{p}\left(1 - \prod_{j=1}^{nj} R_{ij}(t)\right) \quad (1.13)$$

As shown in Figure 02 concerning the breakdown of n tidal turbines of the group into three subgroups (ABC), we have four entities for the subgroups (A B) and two for C each of them have their own probabilities of transitions as well as probabilities of states (Ei).

$$X(t) = P_r(E1, E2, E3, ...E8) \quad (1.14)$$

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Using the availability rate and unavailability of each subgroup as a status variable, we have the following probabilities:

$$E1 = A_{G_A}(t).A_{G_B}(t).A_{G_C}(t) \quad (1.15)$$

$$E2 = \overline{A_{G_A}(t)}.A_{G_B}(t).A_{G_C}(t) \quad (1.16)$$

$$E3 = A_{G_A}(t).\overline{A_{G_B}(t)}.A_{G_C}(t) \quad (1.17)$$

$$E4 = A_{G_A}(t).A_{G_B}(t).\overline{A_{G_C}(t)} \quad (1.18)$$

$$E5 = \overline{A_{G_A}(t)}.\overline{A_{G_B}(t)}.A_{G_C}(t) \quad (1.19)$$

$$E6 = \overline{A_{G_A}(t)}.A_{G_B}(t).\overline{A_{G_C}(t)} \quad (1.20)$$

$$E7 = A_{G_A}(t).\overline{A_{G_B}(t)}.\overline{A_{G_C}(t)} \quad (1.21)$$

$$E8 = \overline{A_{G_A}(t)}.\overline{A_{G_B}(t)}.\overline{A_{G_C}(t)} \quad (1.22)$$

d- substation performance (Ss)

Even if there are several components that make up Ss, there are only two possible states (running and failing) because, Ss only works if all its components work.

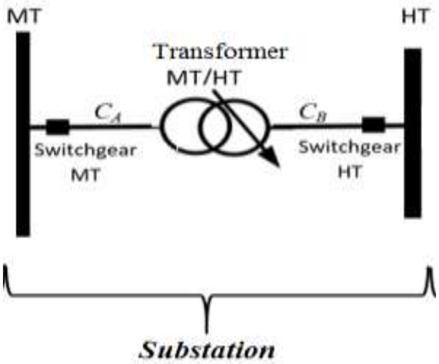

Figure 07: Substation (Part C)

The components of Ss is in series, so we can evaluate the performance of the latter using the following properties:

$$\lambda_{SS} = \lambda_{C_{SS}\_MT} + \lambda_{C_{SS}\_HT} + \lambda_{t_{SS}} + 2\lambda_{SG_{SS}} \quad (1.23)$$

$$\lambda_{SS} = \sum \lambda_{SS_i} \quad (1.24)$$

Reliability and availability as well as unavailability are:

$$R_{SS}(t) = R_{C_{SS}\_MT}(t).R_{C_{SS}\_HT}(t).R_{t_{SS}}(t).2R_{SG_{SS}}(t) \quad (1.25)$$

$$A_{SS}(t) = A_{C_{SS}\_MT}(t).A_{C_{SS}\_HT}(t).A_{t_{SS}}(t).2A_{SG_{SS}}(t) \quad (1.26)$$

$$\overline{A_{SS}(t)} = 1 - A_{SS}(t) \quad (1.27)$$

By combining the three parts (A B C) of Figure 03, we obtain the overall system reliability assessment properties below:

$$R_{Global}(t) = R_{A \to B}(t).R_{SS}(t) \quad (1.28)$$

Or

$$R_{Global}(t) = R_{Gr(A//B//C)}(t).R_{SS}(t) \quad (1.29)$$

e- Global System MEE Model

Now the system is analysed as a single repairable entity whose state space diagram is shown in the figure below:

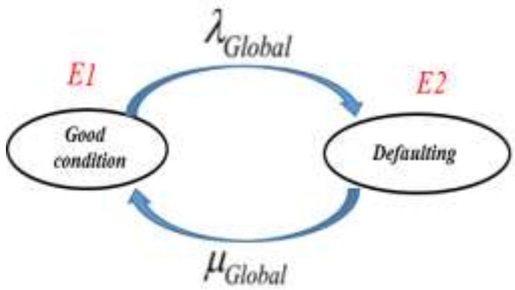

Figure 08: State Space Diagram

$$X(t) = P_r\left(E1(t), E2(t)\right) \quad (1.30)$$

As mentioned above, one of the interests of this method is its ability to create probability of states at time t.

The transition matrix:

$$M = \begin{pmatrix} -\lambda_{Global} & \lambda_{Global} \\ \mu_{Global} & -\mu_{Global} \end{pmatrix} \quad (1.31)$$

The failure rate and repair for the final analysis are:

$$\lambda_{Global} = \lambda_{Gr(A//B//C)} + \lambda_{SS} \quad (1.32)$$

$$\mu_{Global} = \frac{\lambda_{Global}}{\left[\left(1 + \frac{\lambda_{(Gr_A//Gr_B//Gr_C)}}{\mu_{(Gr_A+Gr_B+Gr_C)}}\right).\left(1 + \frac{\lambda_{SS}}{\mu_{SS}}\right)\right]} \quad (1.33)$$

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Hence, the models for analysing and evaluating the performance of our system are:

$$R_{Global}(t) = \exp(-\lambda_{Global}.t) \quad (1.34)$$

$$A_{Global} = P_{r(E1)} = \frac{\mu_{Global}}{\lambda_{Global} + \mu_{Global}} \quad (1.35)$$

$$\overline{A_{Global}} = P_{r(E2)} = \frac{\lambda_{Global}}{\lambda_{Global} + \mu_{Global}} \quad (1.36)$$

f- Global System Status Frequency and Duration

[9].With the transition probabilities of the i and j states that exist in the system, we can define the frequencies as well as the duration of occurrences as a function of time by:

$$F_{r(E1)} = P_{r(E1)}.\lambda_{Global} \quad [occ/an] (1.37)$$

$$F_{r(E2)} = P_{r(E2)}.\mu_{Global} \quad [occ/an] (1.38)$$

$$D_{(E1)} = \frac{P_{r(E1)}.8760}{F_{r(E1)}} \quad [h/occ] \quad (1.39)$$

$$D_{(E2)} = \frac{P_{r(E2)}.8760}{F_{r(E2)}} \quad [h/occ] (1.40)$$

g- Average temporal quantities

[4].The mean temporal quantities are defined as analyses of the cycles. The values of the latter are calculated in a wider time interval.

$$MTTF_{Global} = \int_0^{\infty} R_{Global}(t)dt \quad (1.41)$$

$$MTTR_{Global} = \int_0^{\infty} \left[1 - M_{Global}(t)\right]dt \quad (1.42)$$

h- Maintainability

[7].Maintainability is the probability that the entity will be repaired in an interval of time $t_r(0, t)$. When we consider that the damage rates are constant, we are faced with corrective maintenance after the failure is discovered. Preventive Maintenance has no effect on $R_{Global}(t)$ whether $\lambda_{Global}(t)$ is constant because, you intervene as a prevention only if you detect degradation on the system.

The maintenance function is given by:

$$M(t) = \exp(\mu.t) \quad (1.43)$$

For corrective actions per production unit, we have:

$$M_{Hi}(t) = \exp(\mu_{Hi}.t) \quad (1.44)$$

$$T_{M(Hi)}(t) = \frac{d(1 - M_{Hi}(t))}{dt} \quad (1.45)$$

So for our system, we get the probability of being maintained at t by:

$$M_S(t) = \exp(\mu_S.t) \quad (1.46)$$

$$T_{M(S)}(t) = \frac{d(1 - M_S(t))}{dt} \quad (1.47)$$

IV- APPLICATION

We will now run simulations using the various models presented above in order to see and analyse the possible scenarios.Some of the component data below is taken from [1] [3] [5] [7].

Table 1 Simulation data

Designations	$\lambda(occ/an)$	$\mu(occ/an)$
Hi (Part Ai)		
tidal turbine	0,318	18,56
Submarine Cable (Part Bi)		
Cable MT (1 km)	0,0150	9.96
SG-switchgear	0,001	8.6
Under Electrical Station (Part C)		
MT Circuit Breaker	0,032	12,17
HT Circuit Breaker	0,032	12,17
HT Disconnect	0,012	12,17
Transformer HT	0,013	3.161
Cable MT (1 km)	0,0150	9.96
Cable HT (1 km)	0,0150	9.96

For the following data, it is considered that there are nodes on each cable link to another component.

$$l_{Bi} = [1{,}5 \;\; 1 \;\; 1{,}25 \;\; 1{,}5 \;\; 2 \;\; 1{,}75 \;\; 1 \;\; 0{,}5 \;\; 0{,}75 \;\; 0{,}5] \quad (km)$$

a- Reliability

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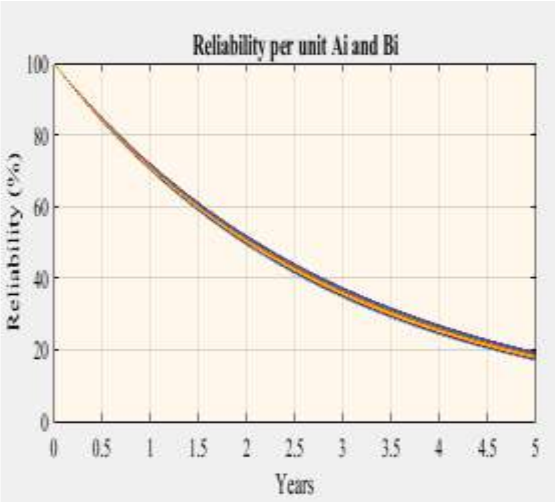

Figure 09: R(t) per unit $Ai \rightarrow Bi$

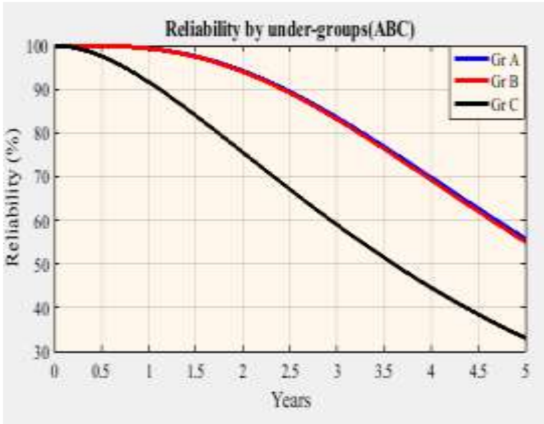

Figure 10: R(t) of subgroups

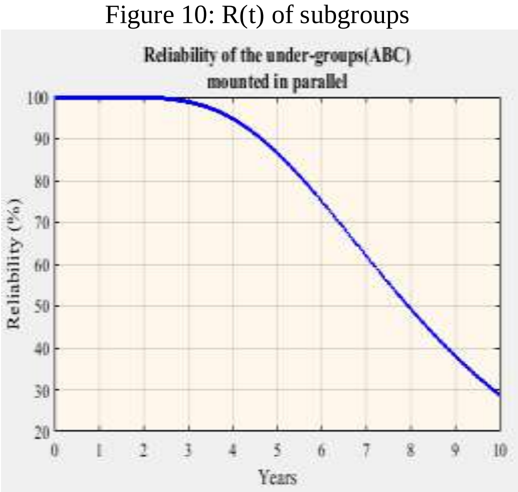

Figure 11: R(t) of all subgroups

The figure below is the overall R(t) look with Ss.

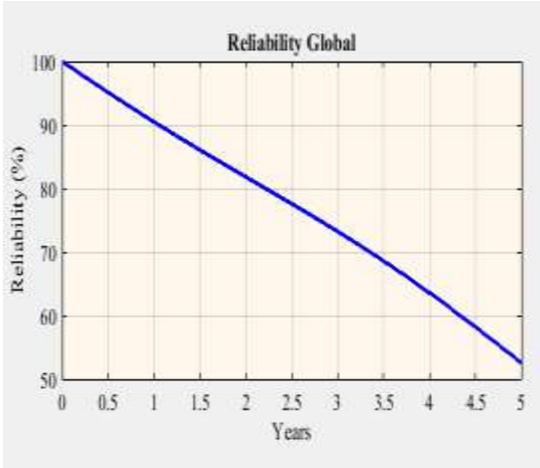

Figure 12: Overall R(t) including Ss

b- Availability

If the degradation of the system over time is not taken into account, the calculation results for the availability rates are presented in the table below.

Table 2 Availabilities per production unit

Availabilities $Ai \rightarrow Bi$ (%)			
$A_1 \rightarrow B_1$	97,4	$A_6 \rightarrow B_6$	97,2
$A_2 \rightarrow B_2$	97,6	$A_7 \rightarrow B_7$	97,3
$A_3 \rightarrow B_3$	97,6	$A_8 \rightarrow B_8$	97,9
$A_4 \rightarrow B_4$	97,9	$A_9 \rightarrow B_9$	97,8
$A_5 \rightarrow B_5$	97,7	$A_{10} \rightarrow B_{10}$	97,7

The indices of the limit availabilities of each subgroup according to the rates of failures and repairs are presented in the figure below:

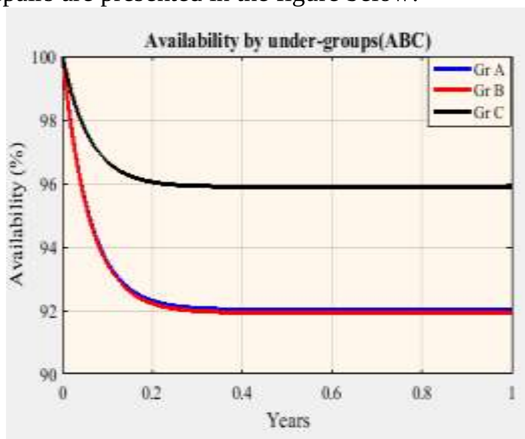

Figure 13: Subgroup availability

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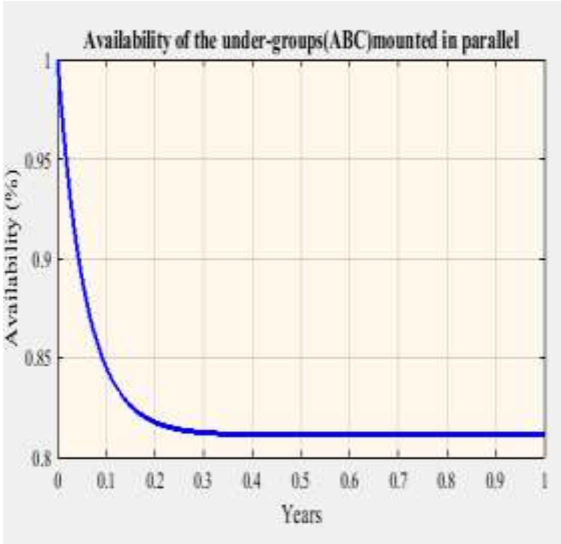

Figure 14: Availability global

c- Maintenance action

Here, we focus on corrective maintenance according to MTTF and MTTR. The table below shows the results of the calculations using equation (1.41)and (1.42).

Table 3 Average operation and repair quantities

Hi	MTTF (years)	MTTR (years)				
H1	2.8944	0.061	H6		2.8249	0.059
H2	2.9674	0.062	H7		2.8592	0.060
H3	2.9304	0.061	H8		3.0130	0.063
H4	3.0441	0.064	H9		2.9674	0.062
H5	3.0053	0.063	H10		2.8944	0.061

The corrective maintenance action of an entity starts at t equal to the upper MTTF interval and ends at t equal to the upper MTTR interval. The figure below shows the start and duration of H1.

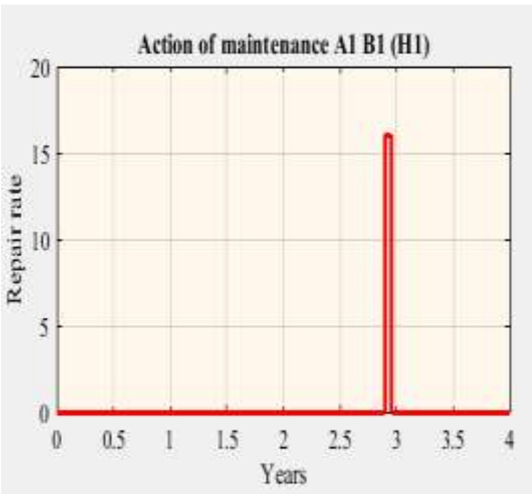

Figure 15: H1 Corrective Maintenance Action

The figure below shows the system-wide repairs.

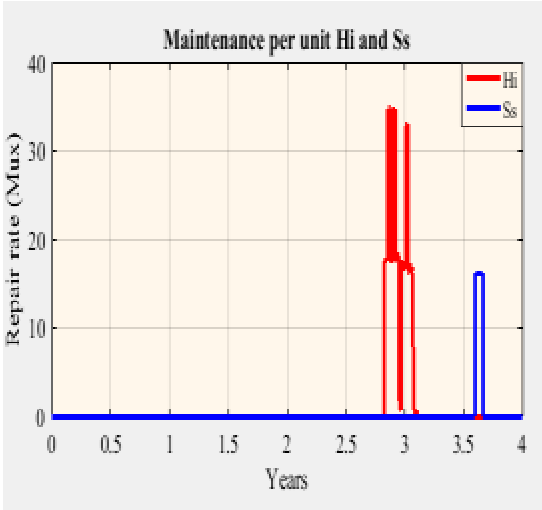

Figure 16: Overall view of all maintenance actions of the global system

The figure below shows the total production time as well as the time of the malfunction (action of the corrective maintenance) of the system for a period of 10 years.

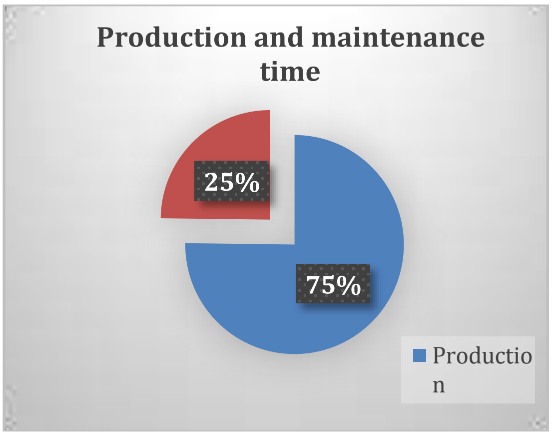

Figure 17: Total production and repair time

For the production time interval of 0 to 10 years, 25% of this time which is equivalent to 2.5 years is the non-production time because it is the sum of the times of the corrective maintenance while 75% of this 10 years or 7.5 years is the production time.

1- Analysis of results

As mentioned above, we analysed, evaluated the reliability and availability of ten (10)

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tidal turbines in production based on probability functions.

a- reliability

The reliability function in this work is an exponential function. With the help of equation (1.09), we have been able to show with the help of figure 09 obtained by simulation the speed of the curves $R_{Hi}(t)$. We can see that the percent reliability rates of each entity are decreasing very quickly. These exponential decreases are due to the magnitude of the sum of the failure rates of (λ_{Hi}) their constituent components.
Let us take as an example the case of H1

$$H1:\begin{cases} t=2\ ans \to R_{H1}(2\ ans)=50\% \\ t=4\ ans \to R_{H1}(4\ ans)=25\% \end{cases}$$

Over a period of two years, R_{H1} the rate of decline has increased from 50% to 25%, including a 25% deterioration. The percentage rate of R(t) increases if another parallel entity is added to it. This is the case for the R(t) indices presented in Figure 10 concerning the reliability of sub-groups (ABC).

For example, group A

$$R_{GrA}(t):\begin{cases} t=2\ ans \to R_{GrA}(2\ ans)=94\% \\ t=4\ ans \to R_{GrA}(2\ ans)=69\% \end{cases}$$

These results confirm that the R index improves with the increase of n if the configuration is in parallel. The overall analysis of our ten lines $Ai \to Bi$ is shown in Figure 11, which has very high time-percentage rates. By combining the results of the analyses $R_{T_{Ai \to Bi}}(t)$ with that of the substation $R_{SS}(t)$, the indices fall again (see figure 12) because, the configuration between the latter is in series. So the overall reliability of our system is shown in figure 12.

$$t=2\ ans \to R_{Global}(2\ ans)=82\%$$

$$t=4\ ans \to R_{Global}(4\ ans)=64\%$$

b- Availability

The results of the calculations concerning the percentage rates of availabilities presented in this work are limit values because we have assumed that the damage rates as (λ_{Hi}) well as repair (μ_{Hi}) are independent of time t. one of the reasons for this choice is that this hypothesis is based on another hypothesis concerning the return of the initial state of the system or sub-system after each maintenance. In contrast to the reliability indices $R_{Hi}(t)$, the availability rates $A_{Hi}(t)$ decrease with the increase in n.

Take the case of Figure 13:
The three curves presented on this are the A_{GrA} A_{GrB} A_{GrC}. It is clear that the availability rate of Group C, which is composed of two entities, is higher than that of A and B of which n=4.

$$A_{GrC}=96\%\ \ A_{GrB}=92\%\ \ A_{GrC}=92,2\%$$

The reason is that the greater the n, the greater the number of possible transitions. Even if the number of entities n of subgroup A is equal to that of subgroup B without forgetting the characteristics of the turbines used which are identical, the small difference between A_{GrA} and A_{GrB} is caused by the lengths l of the cables of the links because the rate of failure of a cable is a function of its length. The overall availability of the system including A_{SS} is 82% (see Figure 14).

c- Maintenance

The corrective maintenance action of an entity starts at t equal to the values of the results of the MTTF calculations of each entity and ends at t equal to the upper MTTR interval (see Table 3).

Take the case of H1:

According to Figure 15, H1 ($A_1 \to B_1$) operates until its first failure at t= 2.89 years. So, from there, the $t_r=0,061\ ans$ maintenance action begins for 498 hours or 22 days. According to the results presented in Table 3, H6 is the first entity that fails. So it is she who undergoes the first maintenance intervention.

With the 10 production lines $Ai \to Bi$ and the substation, figure 16 illustrates the repair rates and times of each entity according to their μ_i respective ones. We note that they have probabilities of finding themselves in the state of failure successively around t=[2.82 to 3.6 years] because of the identical physical characteristics of the tidal turbines installed except for the lengths of the cables.

d- Productivity time

Once the failure times and maintenance times of each component of the entire system are known, the total productivity time and the downtime of the overall system can be determined by adding these multiplied by its frequency in a time interval. As shown in Figure 17, for a time interval of 0 to 10 years, 25% of this time which is equivalent to 2.5 years is non-production time because it is the sum of corrective maintenance times and 75% or 7.5 years is the production time.

V- CONCLUSION

In this work, we had analyzed, evaluated the reliability as well as the availability of ten (10) tidal turbines in production based on probability functions and distribution laws by the state space method. Our approach is to study and model them by first dissecting a production line $Ai \rightarrow Bi$ of the group, starting with the part (Ai) which is the tidal turbine (Hi) source and the part (Bi) which concerns the cables of the links. Then the ten entities of the group are broken down into three sub-groups (ABC) for very specific reasons.

The results of the calculation of the global reliability indices $R_{Global}(t)$ as well as the availability $A_{Global}(t)$ obtained by breaking it down are exactly equal to the results obtained if the breakdown is not carried out on the basis of a direct analytical calculation. But with the use of the MEE, it is more advantageous to break it down because it is easier to see the probabilities of the transitions between the states Ei.

Recommendations

- ✓ As we had spoken only of corrective maintenance as interventions after each failure, it is rather necessary to intervene as prevention. By using the reliability degradation rate as a function of time, we can organize preventive maintenance actions because, with this type of intervention, we can improve reliability as well as its availability.
- ✓ As the downtime of our system for corrective actions according to MTTF and MTTR accumulates in a small time interval, systematic maintenance is recommended.
- ✓ During a corrective intervention, it is necessary to change if possible the faulty components with the one which has the lower rate of damage in order to increase the performance of the system.

Perspective

- ✓ Make an evaluation of the powers P produced according to the probabilities of states.
- ✓ Determination of the number N of optimal preventive interventions in order to reach an objective R(t) index.

REFERENCES

[1]. Ouahid DAHMANI, « Modeling, Optimization and Reliability Analysis of AC electrical topology of offshore wind farms». Thesis defended November 25, 2014 from the University of Nantes. Specialization in Electrical Engineering.

[2]. IDDER Samira, « Reliability of systems: Markov and Weibull-Markov models». Master's thesis defended on June 23, 2013 by Universityof BejaiaA. Mira.

[3]. Gabriel Antonio Perez Castaneda, « Evaluation by simulation of the SDF of systems in a hybrid dynamic context». Thesis defended on March 30, 2009 from the National Polytechnic Institute of Lorraine. Automatic specialty and signal processing.

[4]. Romain Bernard, « Multi-system SDF analyses». Doctoral thesis Defended on November 23, 2009. Doctoral school of mathematics and computer science of the University of Bordeaux.

[5]. Timothée KOMBE, «Modeling fault propagation in production systems». Doctoral thesis Defended on June 30, 2011 from the National Institute of Applied Sciences of Lyon and the National Polytechnic School of Yaoundé.

[6]. Anthony LEGENDRE, « System Engineering and Dependability: Methodology for Synchronizing Architecture Models and Risk Analysis». Doctoral thesis Defended on December 15, 2017 from the University of Paris-Saclay prepared at the Supélec central school

[7]. Andrea Bianca OCNASU, « Evaluation of the dependability of distribution networks by Monte Carlo simulation: application to optimal maintenance strategies». Thesis defended on October 10, 2008 by the Polytechnic Institute of Grenoble. Electrical Engineering Specialty.

[9]. Malik MEGDICHE"Operating safety of distribution networks inpresence of decentralized generation". Thesis defended on December 13, 2004 at the National Polytechnic Institute of Grenoble.