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Optimization of the availability of a group of tidal turbines using a maintenance organization obtained by the state space method (Markov process)

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ABSTRACT: following my previous publication entitled «Analysis of the reliability, availability and maintainability of a group of tidal turbines in production by the state space method (Markov process)», Volume 2, Issue 1, pp: 01-05, ISSN: 2395-5252, this article focuses on the organization of optimal maintenance of the entire system by the state space method (MEE). Here we propose an optimization algorithm based on decision parameters from a random variable. To do this, costs associated with the different types of maintenance and energies will be introduced in the resolution.
Keywords: Tidal turbine-Markov Maintenances

I- INTRODUCTION

Frequent interruptions caused by faults or troubleshooting are one of the factors that cause losses on a production system. For an operational system, preventive maintenance is organized according to the historical knowledge of the components or by feedback from the concerned engineer. To better understand our theme, the figure below illustrates the architecture of the system to be studied.

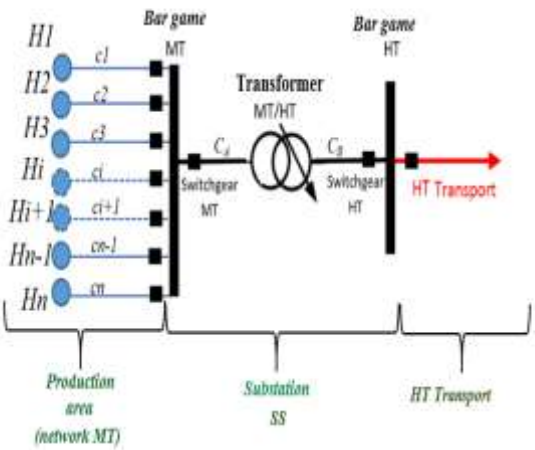

Figure 01: Network architecture.

The reliability, availability indices we use here are derived from [1].

Our goal is to determine the intervention time and the optimal frequency of maintenance to have the maximum availability of the system.

1- Approach

By analogy, maintainability is the probability that the entity will be repaired in an interval of time $t_r(0, t)$.

Two types of maintenance will be considered:

- Corrective Maintenance (Mc)
- Conditional Planned Maintenance (Mp)

For resolution and organization, we propose two approaches.

- 1st approach: Actions are carried out in case of failures (Mc)
- 2nd approach: The 1st action is carried out in case of failure (Mc), while the remain by imposing a reliability threshold $R_{\min}(t)$ (Mp).

1- Modelling of maintenance by MEE

We consider three states (E1, E2, E3), whose decision variable for these three states is the default rate $\lambda(t)$. So we have one function:

$$X(t)=\begin{cases} E1 & \text{System works } \left(\lambda(t)\le\lambda_{moy}(t)\right) \\ E2 & \text{Mpc } \left(\lambda_{moy}(t)<\lambda(t)\le\lambda_{\max}(t)\right) \\ E3 & \text{Mc } \left(\lambda(t)\ge\lambda_{\max}(t)\right) \end{cases}$$

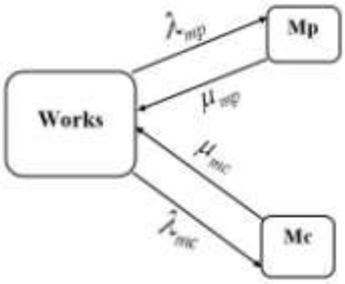

Figure 02: Status graph

With the figure above, we obtain the following transition matrix:

$$M=\begin{pmatrix} -\left(\lambda_{mp}+\lambda_{mc}\right) & \lambda_{mp} & \lambda_{mc} \\ \mu_{mp} & -\mu_{mp} & 0 \\ \mu_{mc} & 0 & -\mu_{mc} \end{pmatrix} \quad (1.03)$$

With $Ei'(t)=MEi(t)$

$$S=\begin{cases} E1'(t)=-\left(\lambda_{mp}+\lambda_{mc}\right)E1(t)\ldots \\ +\mu_{mp}E2(t)+\mu_{mc}E3(t) \\ E2'(t)=\lambda_{mp}E1(t)-\mu_{mp}E2(t) \quad (1.04) \\ E3'(t)=\lambda_{mc}E1(t)-\mu_{mc}E3(t) \\ E1(t)+E2(t)+E3(t)=1 \end{cases}$$

The permanent probabilities of state occupation are obtained by system resolution

(S) with the $Ei'(t)=0$

$$E1=\frac{\mu_{mp}\mu_{mc}}{\mu_{mp}\mu_{mc}+\lambda_{mp}\mu_{mc}+\mu_{mp}\lambda_{mc}} \quad (1.05)$$

$$E2=\frac{\lambda_{mp}\mu_{mc}}{\mu_{mp}\mu_{mc}+\lambda_{mp}\mu_{mc}+\mu_{mp}\lambda_{mc}} \quad (1.06)$$

$$E3=\frac{\mu_{mp}\lambda_{mc}}{\mu_{mp}\mu_{mc}+\lambda_{mp}\mu_{mc}+\mu_{mp}\lambda_{mc}} \quad (1.07)$$

2- Cost models

In order to have an optimal organisation of maintenance, we need data on the costs associated with maintenance calculated from the cost models. The stopping frequencies (Fr) of each component will be determined by the MEE. Concerning the output power of each unit, we keep the concept of material range by choosing a range of average power Pi between 1 and 1.5 MW. Depending on the stops, we will assign a cost to each END energy of the respective components because, the constraint we inject into the algorithm concerns this END.

$$END_i=\overline{A_i(t)}*\left(P_i*t\right) \quad (1.01)$$

$$END_{ref\_i}\ge END_i \quad (1.02)$$

The price of the energy we will use is under price reference in Madagascar which is equal to 740[Ariary/kWh]. The other associated costs are taken arbitrarily.

The cost models are time-dependent as well as two parameters including the maintenance frequency (Nm) and λ_m.

$$C_{Mc\_i}(t)=Fr_{mc\_i}\left(t,\ N_{mc\_i},\ \lambda_{mc\_i}\right)* \left[C_{mc\_i}(0)+C_{mr\_i}(0)\right] \quad (1.09)$$

$$C_{Mp\_i}(t)=\left[\begin{matrix} Fr_{mp\_i}\left(t,\ N_{mp\_i},\ \lambda_{mp\_i}\right)* \\ C_{mp\_i}(0) \end{matrix}\right] \quad (1.10)$$

$$C_{Inter}(t)=z*Fr_{Inter}^{\ 2}(t)* P_i+u*END_i(t) \quad (1.11)$$

To fully define the optimization problem, we will impose the following objective function and constraint condition:

$$Min\left(C_{Global}\right)=\sum_{t=0}^{T}\begin{bmatrix}C_{Mc}\left(t\right)+\\ C_{Mp}\left(t\right)+C_{Inter}\left(t\right)\end{bmatrix} \quad (1.12)$$

II- APPLICATION

Table 1 Simulation data

Designations	$\lambda(occ/an)$	$\mu(occ/a$
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
Transform HT	0,013	3.161
Cable MT (1 km)	0,0150	9.96
Cable HT (1 km)	0,0150	9.96

Length of Link Cables

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

Average output power P of each turbine

$$Pi=[1{,}2\ \ 1{,}4\ \ 1{,}3\ \ 1{,}25\ \ 1{,}35\ \ 1{,}15\ \ 1{,}45\ \ 1{,}4\ \ 1{,}3\ \ 1{,}2] \quad [MW]$$

With MEE we have the following frequencies and durations:

Table 01:Fr(T), Dr, A(T)

Hi	**Fr(T)**	**Dr[h]**	**A(T)%**
H1	3,5	1789	97,9
H2	3,7	1883	97,8
H3	3,6	1832	97,9
H4	3,3	1673	98,1
H5	3,8	1968	97,7
H6	3,5	1712	98
H7	3,4	1680	98,1
H8	3,3	1713	97,9
H9	3,3	1759	98
H10	3,4	1768	98
Ss	2,8	1304	99,2
$\sum$	37,6	18496	78,8

Power

The powers shown in the figures below are average powers. In case of unit failure, the power concerned is equal to 0 (zero) during the downtime.

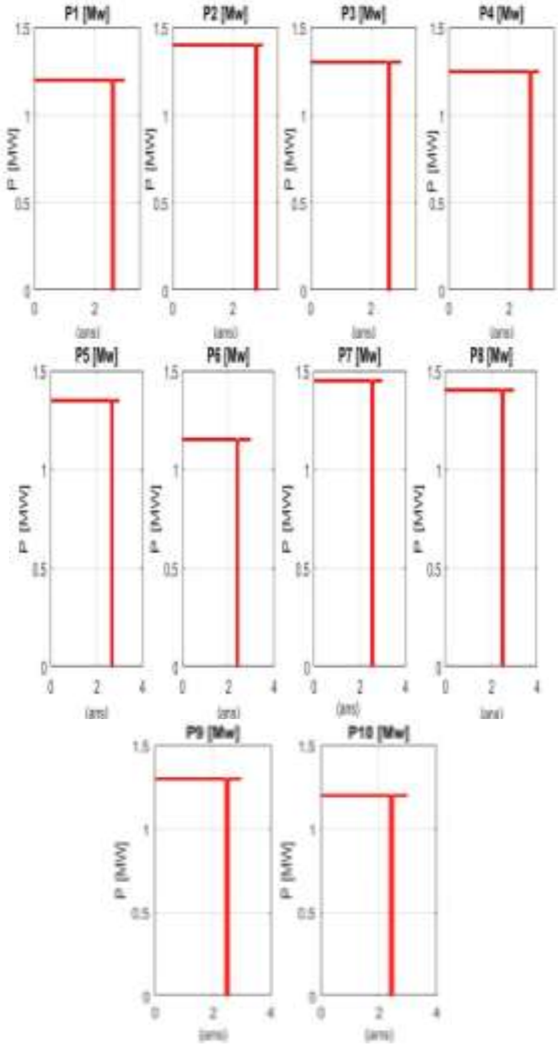

Figure 03: Power per unit

Depending on the frequency of interruption of each tidal turbine, the figure below shows the overall system P scenario.

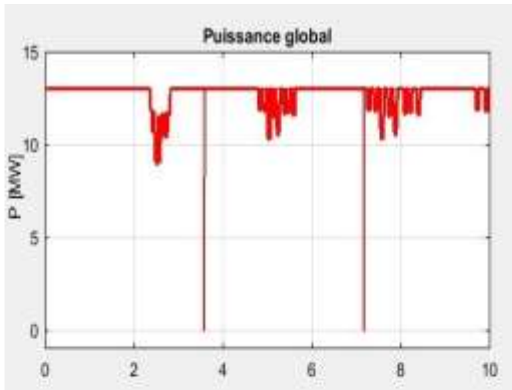

Figure 03: Overall power as a function of stop probabilities and duration of occurrence

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a- Undistributed energy (END(T))

Table 02: Dr(T), ENDi(T) as a function of state probabilities

Hi	ENDi(T)	Dr[h]	A(T)%
H1	2316	1789	97,9
H2	2813	1883	97,8
H3	2542	1832	97,9
H4	2244	1673	98,1
H5	2795	1968	97,7
H6	2197	1712	98
H7	2691	1680	98,1
H8	2517	1713	97,9
H9	2338	1759	98
H10	2223	1768	98
Ss	-	1304	99,2
By introducing the unavailability of the substation, we have $END_{Global}(T) = 33286\ MW$ $A_{Global}(T) = 78,8\ \%$			

b-Resolution of the optimization algorithm
Procedures:
Step 1: Simulation of the initial organisation
Step 2: Creating analytical models
Step 3: Objective function
Step 4: Optimization algorithm
Step 5: Analysis of the result

For the 1st approach, the tasks are determined by the Markov method by assigning two variables [0 1] to Fr(t) which is the function that determines the frequency of the states. Without forgetting of course the decision variable $\lambda_{mc}(t)$.

For the second approach, we impose $R_{min\_Hi}(t) = 55\%$ and $R_{min\_Ss}(t) = 45\%$, for the reason that according to the results of the assessment calculations in [1],the tidal turbines have most of the probabilities of failure around their respective 50% and 39% for the substation [1].

Below are the results concerning the optimal numbers of maintenance actions and the optimal default rates at which maintenance must be operated according to the two approaches mentioned above.

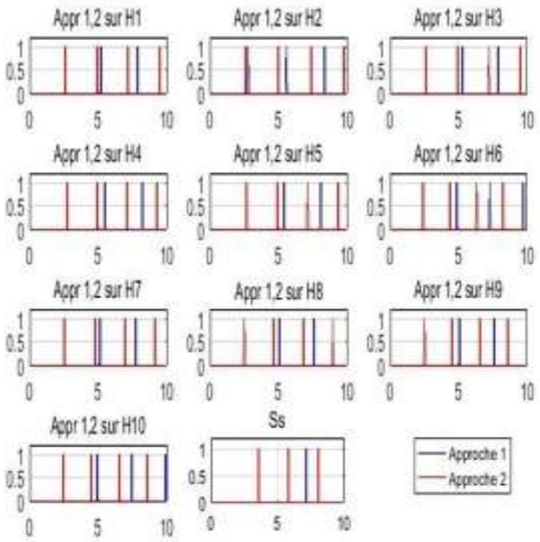


Figure 04: Component maintenance tasks on both approaches

Optimum default rates to which maintenance must be operated for only a few units.

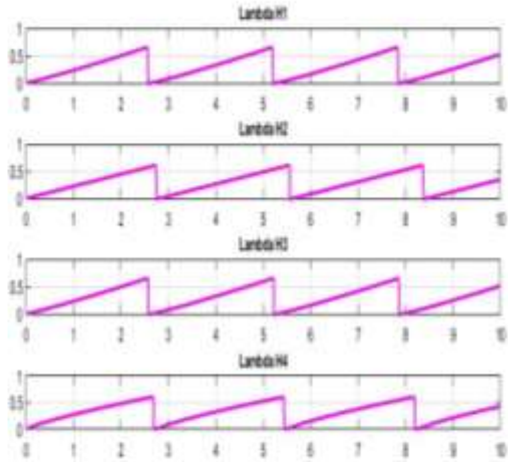


Figure 05: λ_{m-opt} (Optimum Failure Rate at which Corrective Maintenance Actions Begin)

Table 03: Optimal Frequency and Default Rates

	λ_{m-opt}	$Fr(T)$	λ_{m-opt}	$Fr(T)$
	Cas1		Cas2	
H1	0,56	3	0,46	4
H2	0,61	3	0,50	4
H3	0,65	3	0,54	4

H4	0,61	3	0,5	4
H5	0,63	3	0,52	4
H6	0,7	4	0,6	4
H7	0,66	3	0,56	4
H8	0,68	3	0,58	4
H9	0,66	3	0,56	4
H10	0,65	4	0,55	4
Ss	0,31	2	0,22	3

Interpretation:

For the 1st approach (case 1), the majority of units undergo three (03) maintenance actions in 10 years of production, except for H6 and Ss

The figures above and the results on the table above show that for the second approach, maintenance actions are more frequent because, it does not wait for the components to fail.

For tidal turbines installed at the bottom of the sea, there is no difference between TIc, TIps and TIpc in terms of downtime, labor. So in order to have less financial loss in terms of maintenance, we chose conditional preventive maintenance based on the data concerning the first evaluation.

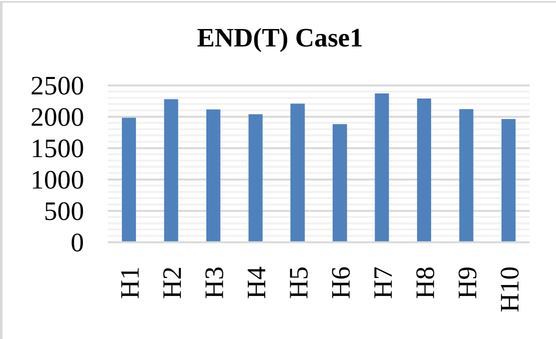
d- Cost assessment by case

Table 04: Maintenance costs

	$Fr(T,N)$	$C_M(T,\lambda,I$ **$*10^6$ [Ariary]**	$Fr(T$	$C_M(T,\lambda,N)$ **$*10^6$ [Ariary]**
	Case 1		**Case 2**	
H1	3	50,4	4	27,6
H2	3	54,9	4	30
H3	3	58,5	4	32,4
H4	3	54,9	4	30
H5	3	56,7	4	31,2
H6	4	84	4	48
H7	3	59,4	4	33,6
H8	3	61,2	4	34,8
H9	3	59,4	4	33,6
H10	4	78	4	44
Ss	2	18,6	3	8,8
C_{Total}	30	**636**	43	**354**

It is clear from the result presented above that the cost of the second approach (case 2) is cheaper than that of the first approach (case 1) because the costs are based on the default rates. Even if the frequency of action is higher.

Interruption costs are associated with undistributed energy (ENDi). The figures below show the NGS for each tidal turbine.



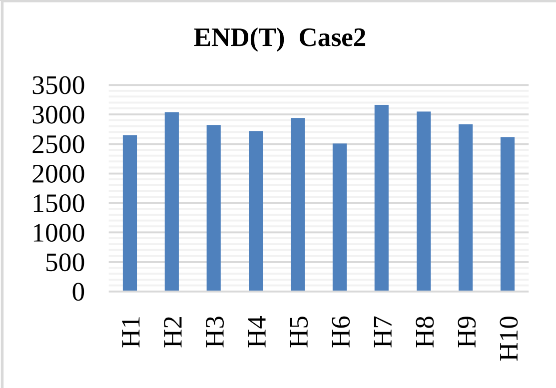


Figure 07: END by Fr

Table 05: Interruption Costs

	$END(T)$ [MW]	$C_{Int}(T,N$ **$*10^8$ [Ariary]**	$END(T$ [MW]	$C_{Int}(T,N$ **$*10^8$ [Ariary]**
	Case 1		**Case 2**	
H1	1987	14,70	2649	19,60
H2	2281	16,88	3042	22,51
H3	2118	15,68	2824	20,91
H4	2040	15,10	2720	20,13
H5	2207	16,33	2942	21,77
H6	1883	13,93	2511	18,58
H7	2374	17,57	3165	23,43
H8	2289	16,94	3051	22,58
H9	2125	15,73	2833	20,97
H10	1962	14,52	2616	19,36
C_{Total}		**212,1**		**243,4**

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e-Final Availability

For the evaluation of availability, we will compare the results for the following axes:

- END(T) next (appr 1, 2) in relation to total system output without interruption.
- Next unavailability (appr 1, 2) in relation to time T

Table 06: Availability and unavailability

	$A(T)$ %	$\overline{A(T)}$ %	$A(T)$ %	$\overline{A(T)}$ %
	Case 1		**Case 2**	
H1	98,14	1,86	97,4	2,6
H2	98,14	1,86	97,5	2,5
H3	98,15	1,85	97,5	2,5
H4	98,14	1,86	97,6	2,4
H5	98,13	1,87	97,5	2,5
H6	97,5	2,5	97,3	2,7
H7	98,13	1,87	97,6	2,4
H8	98,14	1,86	97,6	2,4
H9	98,21	1,79	97,5	2,5
H10	97,7	2,3	97,5	2,5
Ss	99,5	0,8	99,2	0,8
Global	**83,3**	**14,7**	**79**	**21%**

Table 07: Summary and Comparison of Results

	Before	After
	Case 1	
$A(T)\%$	**78,8 %**	**83,3 %**
$TP\ (ans)$	**7.8 years**	**8.3 years**
$END(T,N)$ [MW]	**33286**	**27416**
$C_M(T,\lambda,N)$ [Ariary]	-	**636*10⁶**
$C_{Int}(T,N)$ [Ariary]	**24,62*10⁹**	**21,21*10⁹**
	Case 2	
$A(T)\%$	**78,8 %**	**79 %**
$TP\ (ans)$	**7.8 years**	**7.9 years**
$END(T,N)$ [MW]	**33286**	**32952**
$C_M(T,\lambda,N)$	-	**354*10⁶**
$C_{Int}(T,N)$	**25,62*10⁹**	**24,34*10⁹**

By comparing the overall availability index before optimization which is equal to 78.8% (see Table 02) with the results of the availabilities after optimization in the table above, we clearly see that there is a difference of 5.5% between the index of A(T) for the first approach (Case 1).

However, for the second approach (Case 2), this difference is only 0.2%. The reason for this small difference is that, even if we have optimized according to the second approach, the frequency of interruptions still remain high compared to that of the first approach because, the optimal failure rates resulting from the algorithm at which maintenance is operated are very low compared to that of case 1. Hence the progress of intervention times. So in terms of availability, the first approach is more beneficial.

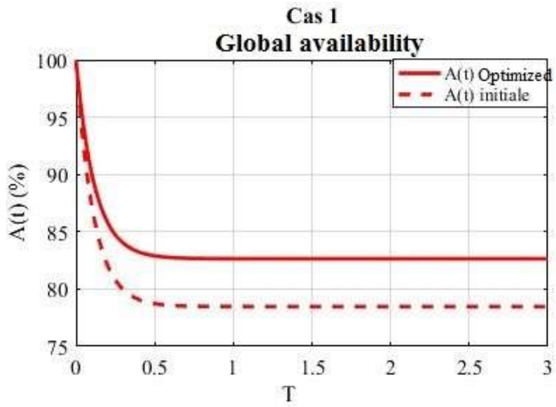

Figure 7: Global Availablity case 1

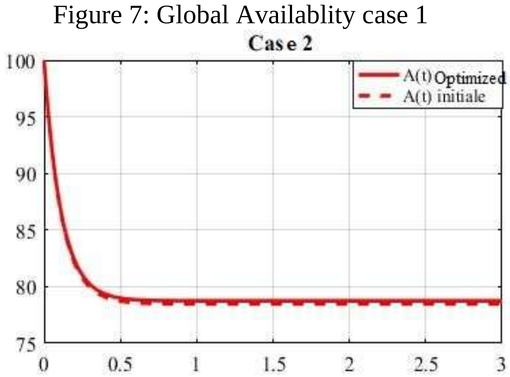

Figure 9: Global Availablity case 2

Effect of maintenance actions on R(t)

Case 1

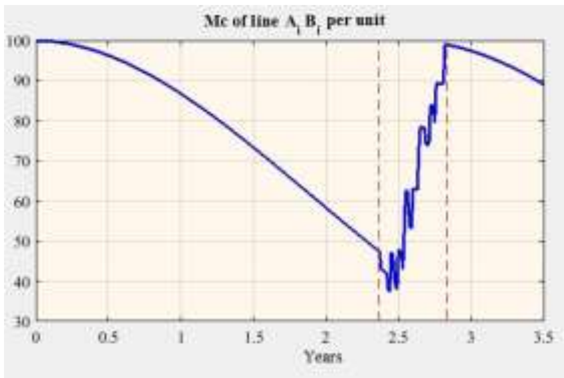

Figure 10: Mc of ten tidal turbines as a function of MTTF and MTTR

Case 2

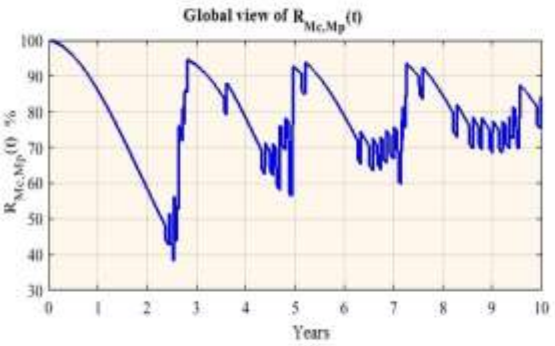

Figure 11: Global view $R_{Mc,Mp}(t)$

3-Analysis of results

Using MEE, we were able to see the probabilities as well as the frequencies of the states of each component whose results are presented in Table 01. With the different probabilities of states and transitions between the turbines, without forgetting the substation, our overall system is available at79.8%. That is 20.2% unavailability. In order to verify the veracity or to validate these values, we subtracted the chosen study time (T=10 years) by the sum of the stopping times multiplied by their Fr(T), we obtained the production time TP=7.88 years which is 78.8% of the study time (T). There's a small 1% difference. This difference is normal because with MEE, for the overall A(t) assessment of our system, there are 1024 transitions probabilities. Therefore, as our calculation is based on a probabilistic function, there is a small margin of precision error. We calculated the NGS based on the overall unavailability, at 33286 [MW] lost due to failures. By associating this NGS with the energy cost in Madagascar which is equal to 740 [Ariary/KWh], we have a loss of $24.62*10^9$ [Ariary]. With the resolution of the proposed algorithm, we were able to minimize this loss by organizing the optimal maintenance actions from the objective function by imposing a condition regarding the END of each source. Table 04shows the maintenance costs $C_M(T,\lambda,N)$ which are based on the maintenance numbers (N) and the optimum failure rates λ at which maintenance is performed. It is found that case 1 which is equal to $636*10^6$ [Ariary] is more expensive compared to case 2 equal to $354*10^6$ [Ariary]. Comparing the two prices, the choice is on case 2 because, it is the cheapest one with a difference of $282*10^6$ [Ariary]. Table 05 deals with interruption costs. The case 1 END is equal to 27416[MW], equivalent to $21.21*10^9$ [Ariary] and 32952 [MW] equivalent to$24.34*10^9$ [Ariary] for case 2. In this situation, case 1 is more beneficial because it is the cheapest of which a difference of $3.13*10^9$ [Ariary]. By comparing the two price differences, the choice is on the 1st approach (cas1) even if they are both optimization results.

In the end, by comparingalso the twopricedifferencesconcerning the END before and the ENDresultingfrom the optimization, wesee by the resultobtainedthat the price the NGS beforewhichisequal to$24.62*10^9$ [Ariary] issuperiorcompared to$21.21*10^9$ [Ariary] (END Prize). This confirmsthatouralgorithmworks. See Table 07 for comparisons of resultsobtainedbefore and afteroptimization.

III- CONCLUSION

In this article, we focused on the application of models related to the organization of maintenance. The results in figures and tables are obtained by simulation by introducing under Matlab programming the models obtained using the state space method (MEE). Based on these results, we were able to move to the resolution of an algorithm to optimize the availability of our system by starting with the frequency of action and the failure rates at which maintenance is operated from an objective function. The results for validation of the proposed algorithm are presented in **tables (04, 05, and 06).** At the end, we presented the effect of its maintenance actions on component reliability. The maintenance action has no effect on the reliability index of our system unless we change the component concerned by another more reliable model.

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