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Optimization of maintenance intervals preventive and repair of gas turbines. Case of Algerian gas pipelines

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1. Introduction

The optimal frequency of preventive maintenance means an exploitation of gas turbines, with a required reliability, a guaranteed availability and a minimum cost during the period of operation.

The operating system of the gas turbines is based on the maintenance and preventive repairs supposed to eliminate the risks of the forced stops.

We assume that as a result of maintenance, the machine is restored to its original state; it is to say that after each repair the frequency between 2 preventive repairs will be again planned on the basis of the deterioration of the state of the machine.

Planning of maintenance of a fleet of machines is the subject of several disciplines each of them rich in an impressive number of references. In the thesis [1] gathered a series of works on the theme of this paper. We can also mention the work of Volkovas (and alls) on adaptable monitoring vibration [2, 3]. and The stress strain state of mechanically heterogeneous welded joints by Bražėnas, A**.** and alls [4] which may affect the operation of the pipeline machines.

In this paper our contributions is the formulation of the problem of the determination of the period of preventive maintenance of machinery component installed along the Algerian gas pipeline compressor stations in relying on models from Markov processes part of the stochastic models expressing the ageing of equipment.

The determination of the number of the preventive repairs for machines for a given period, in the majority of the practices cases, is based on the knowledge of the essential parameters obtained from the statistics such as:

– mean life time of the equipment;
– mean Time To First Failure (MTTFF);
– mean Time Between Failures MTBF;
– intensity of renewal of the depot of machines.

2. Development of theory

Let's look the case of machines in continuous operation case which would be stopped only for preventive or curative repair. The operating period to the curative or preventive repair is a random variable.

For each function of distribution we can write [5]:

$$f(t)=\frac{dF(t)}{dt}=\lambda_r(t)e^{-\int_0^t\lambda_r(x)dx}=\lambda_r(t)R(t);\;\; p(t)=\frac{dP(t)}{dt}=\lambda_p(t)e^{-\int_0^t\lambda_p(t)dx}=\lambda_p(t)P_o(t), \tag{1}$$

where r designates the number of curative repairs and p those preventive; $F(t)$ and $f(t)$ - function and density of the distribution of the operating time to the failure; $P(t)$ and $p(t)$ - function and density of the distribution of the operating time to the preventive repair; $\lambda_r(t)$ - intensity of failure of the machine; $\lambda_p(t)$ - intensity of request of scheduled repairs; $R(t)$ - reliability between $(0, t)$; $P_o(t)$ – Probability that there is not a preventive repairs during the period $(0, t)$.

In these conditions the alternate process, (compounds of the forced shutdown of the machine and its stop for the scheduled repairs), form 2 related flows between them and influencing the one on the other. From these assumptions we can determine the intensity of the flow of the request for the curative repairs ρ_r, prophylactic ρ_p and the total flow of requests ρ.

The total number of the machine stops (M_s), caused by failures and the preventive repairs in the time interval $(t, t + dt)$ will be proportional to the intensity of the total flow of requests $\rho(t)$ and to the interval dt.

$$M_s=\rho(t)\,dt. \tag{2}$$

M_s can be calculated otherwise. If the machine is put into operation at the time $\tau = 0$, then the conditional probability of its breakdown in the interval $(t, t + dt)$ is written:

$$\psi(t)=\left[f(t)P_0(t)+p(t)R(t)\right]dt. \tag{3}$$

$\psi(t)$ can be interpreted as the number of failure per hours from the beginning of operations of the machine at time $\tau = 0$. Each start-up of the machine at the time τ $(0 < \tau < t)$ will involve $\psi(t-\tau)dt$ breakdowns in the interval $(t, t + dt)$. The number total of the machine stops in the interval $(t, t + dt)$ is equal to [5]:

$$M_s=\psi(t)dt+\int_0^t\rho(t-\tau)\,d\psi(\tau)dt. \tag{4}$$

By equalizing the two expressions of M_s we get the expression of the total flow of requests (ρ):

$$\rho(t)=\psi(t)+\int_0^t\rho(t-\tau)d\psi(\tau). \tag{5}$$

For the resolution of the Eq. (5) we used the Laplace transforms, and by applying the convolution theorem. [6, 7] we obtain in the expression of the function of renewal:

$$\rho(t)-\psi(t)=\int_0^t \rho(t-\tau)d\psi(\tau) \quad \text{(Originals)} \tag{6}$$

$$\left.\begin{aligned}&\phi(z)-F(z)=F(z)\phi(z) \ \ (Images) \Rightarrow\\ &\phi(z)=\frac{F(z)}{1-F(z)};\ \phi_r(z)=\frac{F_r(z)}{1-F_r(z)};\\ &\phi_p(z)=\frac{F_p(z)}{1-F_p(z)},\end{aligned}\right\} \tag{7}$$

where (images) $\phi(z)\to\rho(t)$; $\phi_r(z)\to\rho_r(t)$; $\phi_p(z)\to\rho_p(t)$; $F(z)\to\psi(t)$; $F_r(z)\to\psi_r(t)$; $F_p(z)\to\psi_p(t)$.

Knowing the Laplace transforms, the Mellin formula of inversion is written (original) [7]:

$$\left.\begin{aligned}&\rho(t)=\frac{1}{2\pi i}\int_{\sigma-i\infty}^{\sigma+i\infty}e^{zt}\phi(z)dt\\ &\rho_r(t)=\frac{1}{2\pi i}\int_{\sigma-i\infty}^{\sigma+i\infty}e^{zt}\phi_r(z)dt\\ &\rho_p(t)=\frac{1}{2\pi i}\int_{\sigma-i\infty}^{\sigma+i\infty}e^{zt}\phi_p(z)dt\end{aligned}\right\} \tag{8}$$

With $\phi(z)=\int_0^\infty e^{-zt}\rho(t)dt;\ \phi_r(z)=\int_0^\infty e^{-zt}\rho_r(t)dt;$

$\phi_p(z)=\int_0^\infty e^{-zt}\rho_p(t)dt;\ F(z)=\int_0^\infty e^{-zt}\psi(t)dt;$

$F_r(z)=\int_0^\infty e^{-zt}\psi_r(t)\,dt;\ F_p(z)=\int_0^\infty e^{-zt}\psi_p(t)\,dt.$

For the determination of the optimal duration of the operation of the machine between 2 prophylactic interventions the criterion of optimization should be a maximum duration of operation of the machine.

A machine in operation, with the difference of a machine in reserve, can to be in one of the 3 possible states: in operation (E_0), in curative repair (E_2) or in preventive repair (E_1).

The probability for the machine to be found in one of those states mentioned above will be expressed through P, P_r, P_p respectively.

The passages of the machine from one state to another, under the condition that there is not interruption of operation between 2 general planned revisions, represent the Markov process [8, 9]. By applying the basic principles for these processes we can write (Fig. 1):

$$\left.\begin{aligned}&\frac{dP(t)}{dt}=-P(\rho_r+\rho_p)+P_p\mu_p+P_r\mu_r;\\ &\frac{dP_r(t)}{dt}=-P_r\mu_r+P\rho_r;\\ &\frac{dP_p(t)}{dt}=-P_p\mu_p+P\rho_p.\end{aligned}\right\} \tag{9}$$

For the stationary case when $t\to\infty$; $\frac{dP_i(t)}{dt}=0$; $\rho_r(\infty)=\rho_r$, the solution of the system is:

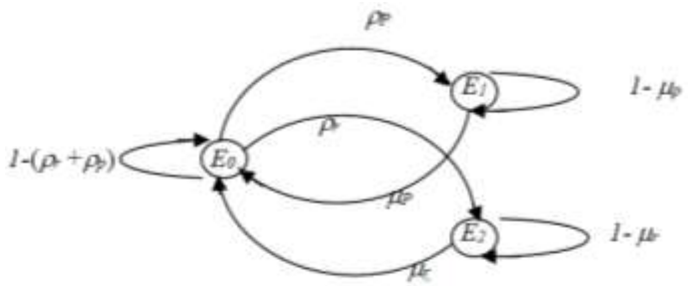

Fig. 1 Graph of the states of the system

$$P=\frac{1}{1+\frac{\rho_r}{\mu_r}+\frac{\rho_p}{\mu_p}} \text{ - Probability to be in operation.}$$

$$P_r=\frac{\frac{\rho_r}{\mu_r}}{1+\frac{\rho_r}{\mu_r}+\frac{\rho_p}{\mu_p}} \text{ - Prob. to be in curative repair.} \tag{10}$$

$$P_p=\frac{\frac{\rho_p}{\mu_p}}{1+\frac{\rho_r}{\mu_r}+\frac{\rho_p}{\mu_p}} \text{ - Prob. to be in preventive repair.}$$

With $\sum P_i=1$, where $\mu_p=\frac{1}{MTTPR}$; $\mu_r=\frac{1}{MTTR}$. In the other side $\lambda_p=\frac{1}{MTBPR}$; $\lambda_r=\frac{1}{MTBF}$; *MTTR* - Mean Time to Repair; *MTTPR* - Mean Time to Preventive Repair (average duration of preventive repairs); *MTBPR* - Mean Time between Preventive Repairs (average duration of operation between the preventive repairs); *MTBF* - Mean Time between Failure.

By replacing in Eq. (10) ρ_r and ρ_p by their value we gets the value of the operating time depending on the settings of the distribution functions $F(t)$ and $P(t)$ which, in their turn are expressed through the characteristics of these functions.

Considering the average duration of operation between 2 preventive repairs (*MTBPR*) as characteristic of the function $p(t)$:

$$MTBPR = \int_0^\infty \tau \, p(\tau) d\tau .$$

The optimal value of *MTBPR* corresponding to the maximum time of operation (P-probability to be in operation) is determined by the conventional methods of research of extremes of the functions.

In the case of the gamma distribution [10] where (Eq. 1):

$$f(t) = \frac{\lambda_r (\lambda_r t)^{r-1}}{(r-1)!} e^{-\lambda_r t}; \qquad (11)$$

$$p(t) = \frac{\lambda_p (\lambda_p t)^{p-1}}{(p-1)!} e^{-\lambda_p t}. \qquad (12)$$

The Laplace transform of $f(t)$ can be written [1]:

$$\int_0^\infty \frac{\lambda_r^r t^{r-1}}{(r-1)!} e^{-\lambda_r t - zt} dt = \frac{\lambda_r^r}{(z+\lambda_r)^r}.$$

The solution is:

$\alpha = lim\, F_r(z)$, when $z \to 0$,

$$\alpha = \sum_{n=0}^{p-1} \frac{(r+p-1)!}{n!(r+p-1-n)!} \lambda_r^{r+p-1-n} \lambda_p^n ;$$

$\beta = lim\, F_p(z)$, when $z \to 0$,

$$\beta = \sum_{k=0}^{r-1} \frac{(r+p-1)!}{k!(r+p-1-k)!} \lambda_r^k \lambda_p^{r+p-1-k} ;$$

$\delta = lim\, F(z)$, when $z \to 0$,

$$\delta = (\lambda_r + \lambda_p)^{r+p-1}.$$

$$\varphi = \frac{r}{\lambda_r}\left[(\lambda_r+\lambda_p)^{r+p-1} - \lambda_p^{r+p-1} \right] + \sum_{k=0}^{r-1} \frac{(r+p-1)!}{(r+p-1-k)!(k+1)} \left[p - r(r+p-1) + k(r+p) \right] \lambda_r^k \lambda_p^{r+p-1-k}.$$

For the case $r = k$ and $p = 1$ (r - number of repair; k - number of failures; p - number of preventive repair) we have: $\alpha = \lambda_r^r$; $\beta = (\lambda_r + \lambda_p)^r - \lambda_r^r$; $\delta = (\lambda_r + \lambda_p)^r$;

$$\varphi = \frac{(\lambda_r+\lambda_p)^r - \lambda_r^r}{\lambda_p}.$$

Then we can write:

$$\left.\begin{aligned}
\rho &= \frac{\delta}{\varphi} = \frac{\lambda_p (\lambda_r+\lambda_p)^r}{\left[(\lambda_r+\lambda_p)^r - \lambda_r^r\right]} = \frac{1}{MTBPR} \frac{1}{1-\left(\dfrac{ry}{1+ry}\right)^r};\\
\rho_r &= \frac{\alpha}{\varphi} = \frac{\lambda_p . \lambda_r^r}{\left[(\lambda_r+\lambda_p)^r - \lambda_r^r\right]} = \frac{1}{MTBPR} \frac{1}{\left(\dfrac{1+ry}{ry}\right)^r - 1};\\
\rho_p &= \frac{\beta}{\varphi} = \frac{\lambda_p\left[(\lambda_r+\lambda_p)^r - \lambda_r^r\right]}{\left[(\lambda_r+\lambda_p)^r - \lambda_r^r\right]} = \lambda_p = \frac{1}{MTBPR} = \frac{1}{MTBF}\frac{1}{y}.
\end{aligned}\right\} \qquad (13)$$

By replacing in Eq. (10) the expressions of ρ, ρ_r, ρ_p from Eq. (13) we obtain:

$$P = \frac{1}{\dfrac{\tau}{y}\left[\Phi + 1\Big/\left(\left(\dfrac{1+ry}{ry}\right)^r - 1\right)\right] + 1}, \qquad (14)$$

where

$$\tau = \frac{MTTR}{MTBF}; \quad \Phi = \frac{MTTPR}{MTTR}; \quad y = \frac{MTBPR}{MTBF}. \qquad (15)$$

The expression of optimal periodicity between 2 preventive repairs corresponding to a maximum duration of operation of the machine will be obtained when $\dfrac{dP}{dy} = 0$, then:

$$\Phi = \frac{1 - \dfrac{1+r(y-1)}{1+ry}\left(\dfrac{1+ry}{ry}\right)^r}{\left[\left(\dfrac{1+ry}{ry}\right)^r - 1\right]^2}. \qquad (16)$$

In order to facilitate the calculations of $\Phi = \Phi(y, r)$ we can represent in the following table the values of Φ for $1 \le r \prec \infty$ and $0 \le y \le 2$ (Table 1).

3. Results and discussions

1. This last expression allows to determine the optimal duration of operation until the next preventive repair of the machine, according to its technical state (r and *MTBF*) as well as the capabilities of repair (*MTTR*, and *MTTPR*) of the repair station, with a guarantee to have a

maximum level of the use coefficient of the compressor plant.

2.

$$\left.\begin{array}{l} \Phi \to 0 \text{ when } y \to 0 \\ \quad\quad \text{and} \\ \Phi \to 0.5\left(1-\dfrac{1}{r}\right) \text{ when } y \to \infty. \end{array}\right\} \quad (17)$$

3. The analysis of the function shows that:

- The optimal period between 2 consecutive preventive repairs depends on the duration of repair and of the number of failures *r*.
- The limit value for the duration of repair is equal to:

$$\Phi_{max} = \frac{MTTPR}{MTTR} = \frac{1}{2}\left(\frac{r-1}{r}\right). \quad (18)$$

Table 1

Values of $\Phi = \Phi(y, r)$

r	*y*										
	0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
1	0	0	0	0	0	0	0	0	0	0	0
2	0	0.049	0.091	0.114	0.137	0.160	0.169	0.178	0.187	0, 192	0.197
4	0	0.065	0.125	0.175	0.220	0.245	0.270	0.285	0.300	0.308	0.311
6	0	….	….	….	0.248	0.276	0.297	….	….	….	0.341
8	0	0.100	0.175	0.230	0.270	0.310	0.330	0.340	0.350	0.355	0.360
…	… …	… …	… ….	… ….	… ….	… ….	… ….	… ….	… ….	… …	… ….
∞	… …	… …	0.190	0.250	0.300	0.340	0.37	0.390	0.410	… …	0.430

Table 2

Values of availability (calculated by Excel formula next ($A = 1/1 + MTTR\ \omega$))

ω (1/h)	*MTTR* (hours)							
		50	72	100	150	200	250	300
0.00002		0.999001	0.99856207	0.99800399	0.99700897	0.99601594	0.99502488	0.99403579
0.00006		0.99700897	0.99569858	0.99403579	0.99108028	0.98814229	0.98522167	0.98231827
0.0001		0.99502488	0.99285147	0.99009901	0.98522167	0.98039216	0.97560976	0.97087379
0.00014		0.99304866	0.99002059	0.98619329	0.97943193	0.97276265	0.96618357	0.9596929
0.00018		0.99108028	0.98720581	0.98231827	0.97370983	0.96525097	0.9569378	0.9487666
0.00022		0.98911968	0.98440699	0.97847358	0.96805421	0.95785441	0.9478673	0.9380863
0.00026		0.98716683	0.981624	0.97465887	0.99974007	0.95057034	0.93896714	0.92764378
0.0003		0.98522167	0.9788567	0.97087379	0.9569378	0.94339623	0.93023256	0.91743119

4. Conclusion

The expression (16) indicates the need for making a preventive repair in order to eliminate the risks from a stop forced during the exploitation of the machine. It allows to find the expression of the MTBPR (mean time between preventive repair) The theory developed allows determining, according to the data of the problem (number of *r* and *p*), the optimal intervals between the following preventive, repairs: current preventive repair, partial or general. This will allow the operations teams to provide:

- the necessary equipment for this type of repair. Equipment redundancy to the time of the repair:
- the required number of spare parts for this repair;
- the costs induced by this kind of repair.

Example of application

It is asked to determine the optimal duration of operation of the turbine in Algerian gas pipeline, up to the preventive repair ($p = 1$ - number of preventive repair) for the following data of a number of turbines type General. Electric, installed in a compressor plant: The average time to curative repair $MTTR = 70$ h, to the preventive repair $MTPR = 20$ h $\to \Phi = \dfrac{MTTPR}{MTTR} = 0.285$; the number of machines in observation $N = 4$. The required coefficient of availability $A = 0.99$; the period of observation $T = 7500$ h. Solution: The *MTBF* depending on the coefficient of availability.

$MTBF = \dfrac{MTTR \times A}{1-A} = 6930$ hours. The flows of failures is determined by: (Fig. 1)

$\omega = \dfrac{1}{MTBF} = \dfrac{r}{\sum TBFi} = \dfrac{1-D}{D \cdot MTTR} = 0.144 \cdot 10^{-3}$ failure per hour for a machine (average). For all of the machines, for the period of observation, then:

$r^{tot} = \omega\ N\ T = 0.144 \times 4 \times 7500 \approx 4$ failures expected.

By replacing in Eq. (16) the value of $r^{tot} = 4$ and for $\Phi = 0.285$ there is: $y = \dfrac{MTBPR}{MTBF} = 1.4$ (Table 1). From this expression we calculate $MTBPR = 1.4 \times 6930 = 9702$ hours. This value represents the optimal periodicity of preventive repair.

The proposed contribution not took into account the problem of the management of the stock (spare parts).

The optimal determination of the number necessary of spare parts has been studied in [11]. In [12] investigated Optimization of Preventive Repair in a Dynamic System of Machines.

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DUJŲ TURBINŲ PROFILAKTINIO APTARNAVIMO IR EINAMOJO REMONTO INTERVALŲ OPTIMIZAVIMAS: ALŽYRO DUJOTIEKIO ATVEJIS

R e z i u m ė

Šio tyrimo tikslas yra nustatyti dujų turbinų profilaktinio aptarnavimo periodą, siekiant užkirsti kelią priverstiniams sustabdymams ir atstatyti pradinę komponentų techninę būseną. Tam yra pasitelkta tiek atnaujinimo teorija tiek Markovo procesas pagrįstas patikimumo teorija priklausomai nuo stebėjimų rezultatų ir eksploatacijos statistinių duomenų apdorojimo.

Valdant sistemos sukurtos šio tikslo pasiekimui operacijas yra garantuojamas sistemos išlaikymo tam tikrą periodą iki profilaktinio remonto patikimumas. Kiekis atsarginių dalių reikalingų aptarnavimui yra mažinamas kaip ir remontų laikas. Aptarnavimo darbo periodo planavimas priklauso nuo mašinų techninio stovio, kurio kitimas laike yra dilimo pobūdžio ir greičio funkcija. Mašinų techninis aptarnavimas vaidina svarbų vaidmenį jų patikimumui t.y. mašinos būviui. Sprendžiant profilaktinio aptarnavimo dažnio optimizavimo uždavinį būtina įvertinti visus veiksnius bloginančius būvį (senėjimas, dilimas, deformacijos) ir gerinančius jį (valdymas ir testavimas, profilaktika ir remontas). Darome prielaidą, kad po kiekvieno einamojo remonto mašina yra atstatoma iki originalaus būvio, t.y. po kiekvieno remonto dviejų aptarnavimų dažnis bus planuojamas pasitelkiant mašinos nusidėvėjimo būseną.

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OPTIMIZATION OF MAINTENANCE INTERVALS PREVENTIVE AND REPAIR OF GAS TURBINES. CASE OF ALGERIAN GAS PIPELINE

S u m m a r y

The purpose of this study is to determine the period of preventive repairs for a gas turbines, to prevent the forced stops and to restore the initial technical state of components. Has this effect we use the renewal theory and the Markov process based on the theory of reliability depending on the results of observation and processing of statistical data of exploitation.

Manage the operation of a system designed to achieve a given work is to guarantee the possibility of having the system in operation for a specified period before the preventive repair with high reliability. The quantity of spare parts for this repair, available at the level of the maintenance service, is also to reduce the time of the repairs of the machines.

The planning of the period of maintenance work depends on the technical condition of the machines, which the variation in time is a function of the type and of the speed of wear. The maintenance of the machine plays an important role on its reliability i.e. on the state of the machine. To solve the problem of optimization of the frequency of preventive repairs it is necessary to take into account all the factors; deteriorating state (aging, wear, deformation) and the improving (control and testing; prevention and repair.)

We suppose that after each maintenance repair, the machine is restored to its original state; t.e. after each repair the frequency between 2 preventive repairs will be again planned on the basis of the deterioration of the state of the machine.

Keywords: maintainability, availability, Markov process, Laplace transforms, optimization.

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