A Methodology of Availability Assessment for Complex Manufacturing Systems

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Abstract: -The degree in which a system is operational in a given horizon of time is the key indicator of service quality perceived by business users. The availability of critical systems is a function of the system reliability, maintainability and accessibility of support resources. Based on a comparative analysis, selecting an adequate method of availability assessment requires typical structures identification, reliability indices characterization and evaluation of non-reliability impact of the parts on system availability. Frequently used, binomial method leads to optimistic results due to bivalent states of components (operating/fault). For serial or parallel reliability structures, a realistic evaluation of system availability is obtained by applying polynomial or direct analysis based on reliability block diagram. A complex structure implies a successive assessment of structural components allowed by Monte-Carlo simulation providing accurate indices values. The paper presents a method of availability evaluation using Monte-Carlo simulation techniques which allows a comparative analysis of component impact on the system availability.

Key-Words: - availability, assessment, simulation, structures, complex manufacturing system, operational and reserve parts

1 Introduction

Reliability and availability are valid measures of quality, performance and effectiveness of a complex manufacturing system. Machine tools continually increase in sophistication (higher levels of diagnostics, diagnostic and prediction capability,), inherent flexibility, and user friendliness. Environmental demands require an increase inherent flexibility regarding multiple subsystems support, and user friendliness.

Availability assures the ability of system or component to perform its required function at a stated instant or over a stated period of time. The availability management inputs deals with business impact analysis and availability requirements while the outputs are concerning risk assessment, reliability and maintainability monitoring, improvement plans. High availability focuses specifically on minimizing or masking the effects of a component failure within the system. Availability improvement needs establishing feedback and feed forward methods for continuous improvement regarding performance monitoring, life cycle management and effective corrective actions applied to component criticality assessment.

Due to the increasing complexity of systems, availability assumes implementation at each capability level. Concept development, determining product functionality based upon customer requirements, technological capabilities, and economic realities.

Design development, focusing on product and process performance issues necessary to fulfill the product and service requirements in manufacturing or delivery.

Design optimization, seeking to minimize the impact of variation in production and use, creating a “robust” design.
Design verification, ensuring that the capability of the production system meets the appropriate level.
Failure of one component interrelated with others may not impact availability if the system is designed to support such a failure, while failure of another component may cause system downtime and hence degradation in availability. Performance of equipment depends on reliability and availability of the equipment used, operating environment, maintenance efficiency, operation process and technical expertise of operator. The implementation and realization of a product or service are depending on the context of use. Availability is influenced by the component reliability, which measure the expected time between component failures and the system design regarding the manner in which components are interrelated to satisfy required functionality and reliability. In the design stage the availability can be enhance through use of redundancy in the arrangement of system components. Availability improvement requires establishing availability feedback and feedforward methods for continuous improvement regarding effective corrective actions, life cycle management and planning, performance monitoring and cost-effective corrective maintenance focusing proactively on component criticality assessment.
The expected return on investment is seen as being directly related to system capability, defined in terms of durability, performance, availability and reliability. A major part of any system operating costs is due to unplanned system stoppages for unscheduled repair of the entire system of components. Decreasing the impact of failure is a way to improve reliability and availability of a system. The aim of this paper is to describe a method of availability analysis of a repairable manufacturing system using Monte Carlo simulation.

2 Availability assessment methods

The plausibility of availability assessment results are determined by values of reliability indices of system and components, the applied method of reliability analysis and the accepted simplifying hypothesis.
Based on the function $X(t)$ which describes the status of a repairable system at time t:

$$X(t) = \begin{cases} 1, & \textit{if the system is up} \\ 0 & \textit{otherwise} \end{cases} \tag{1}$$

are identified four approaches of availability performance: the availability function, limiting availability, the average availability function and limiting average availability [1].
Instant availability at time t is the probability that the system is operational at time t, being defined as:

$$A(t) = P(X(t) = 1) \tag{2}$$

The steady-state availability of the system is the limit of the instantaneous availability function as time approaches infinity

$$A = \lim_{t\to\infty} A(t) \tag{3}$$

The steady-state availability depending on the definitions of uptime and downtime has at least four important aspects [2]:
a). inherent availability is the probability that a system or equipment, when used under stated conditions, is an ideal support environment which will operate adequately at any point in time as required It excludes preventive or scheduled maintenance action, logistic delay time, and administrative delay time and is expressed as:

$$A = \lim_{t\to\infty} A(t) = \frac{MTBF}{MTBF + MTTR} \tag{4}$$

Where:
MTBF is mean time between failures
MTTR is mean time to repair
Inherent availability is an equipment design parameter, based on the failure distribution and repair-time distribution [3].

b) achieved availability is very similar to inherent availability with the exception that preventive maintenance (PM) downtimes are also included. Specifically, it is the steady-state availability considering corrective and preventive downtime of the system [4].

$$A_a = \frac{MTBM}{MTBM + \overline{M}} \tag{5}$$

Where:
MTBM- the mean time between maintenance operations includes both unscheduled and preventive maintenance;
Maintenance can have a negative impact on the achieved availability even though it may increase the MTBF [3].
c) operational availability is the probability that a system or equipment, when used under stated conditions in an actual operational environment, will operate satisfactorily when called upon. The operational availability is defined by equation:

$$A_O = \frac{MTBM}{MTBF + MDT} \tag{6}$$

where:

MDT is the mean maintenance down time and includes maintenance time (M), logistics delay time, and administrative delay time.

For realistic evaluation of availability the components of system are modeled as multivalent states element applying the following analysis methods [5]:

- binomial method;
- direct analysis based on block reliability diagram and failure group for different degrees of availability;
- Monte Carlo simulation .

The binomial method is frequently used in availability assessment. The system has two characterizing states, operational with probability (p) and failure with probability (q). The probability of (n-k) operating elements, respectively (k) failed is written as:

$$P_n(k) = C_n^k \cdot p^{n-k} \cdot q^k \tag{7}$$

expression which corrresponds to the (k+1) from Newton's binom:

$$(p+q)^n = \sum_{k=0}^{n} C_n^k \cdot p^{n-k} \cdot q^k \tag{8}$$

Stochastic variable distribution for a different number of failure is:

$$P(K \le k) = \sum_{i=0}^{k} P_n(i) = \sum_{i=0}^{k} C_n^i p^{n-i} q^i \tag{9}$$

The mean and the variance of this variabile are:

$$M(K) = n \cdot q \tag{10}$$

$$D(K) = n \cdot p \cdot q \tag{11}$$

The initial hypothesis doesn't correspond to reality, thus the results have a limited acceptance and are used in computation of states probability, success probability indices and mean value of availability of simple subsystems.

3 Availability assessment on the basis of block reliability diagrams

Starting from the availability of related subsystems of turbogenerator [7] are presented in the following two methods of assessing the availability of turbogenerator group. In order to exemplify the availability assessment we consider the case of turbogenerator in a power plant.

The block diagram considered as a case study for parametric reliability analysis of a turbogenerator group presented in figure 1. The detailed analysis goes up to the level of aggregates: tank (TK), turbine (T) synchronous generator (SG), and the electrical power evacuation station (EPES).

In the analysis frame take into account the reliability behaviour of subsystems which works for group: tank feeding subsystem with water (WFS), coal (CFS) and air necessary for the burn (AFS) cooling water used by condenser (CWFS); subsystems burned gases evacuation (BGES), ashes and slag (ASES) condense (CES).

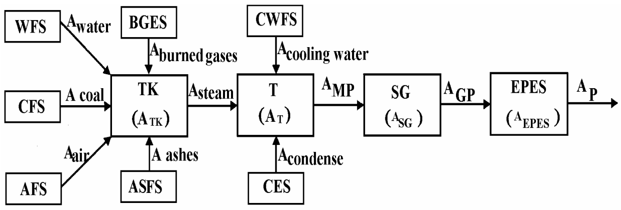


Fig.1 Block diagram for parametric reliability analysis of a tubogenerator

To evaluate the availability [8], of turbogenerator group are required:

- aggregates intrinsic availability (A_{TK}, A_T, A_{SG}, A_{EPES}),
- input availability (A_{CFS}, A_{WFS}, A_{AFS},)

- output availability (A_{BGES}, A_{SES}, A_{CES}). Subsystems included in the structure of turbogenerator are conditioning the operational regime of the the group. During the interval analysis (T_A) will be characterized by intermediate states (states of partial success), corresponding to the functional levels located between the extremes: defect (availability 0%) and the nominal level (100% availability). Modelling the evolution of the turbogenerator group through two states (availability 100%, respectively, 0%) is inaccurate and optimistic. A realistic stochastic modelling involves considering intermediary states of availability. Based on the results obtained previously on the availability of subsystems group [8], we can conclude that the levels of availability of the group are 100%) 83% 67% 50% 0%. Based on the results obtained previously on the availability of subsystems group, we can conclude that the levels of availability of the group are 100%) 83% 67% 50% 0%. Starting from the structure of the group turbogenerator from power plant II Oradea for each of these levels of availability is build the reliability block diagram, in which are considered the " failure groups " and based on are estimated reliability specific indicators [12].

Considering aggregates intrinsic availability evaluated between two states (operating, the subsystem assures the nominal flow /fault, the flow is zero) may be written as follows:

$$A_k = \begin{cases} 1,\ if\ t \in [0, \alpha_k(T_A)] \\ 0,\ if\ t \in [\alpha_k(T_A), T_A] \end{cases}, \quad (12)$$

$k \in \{A_{TK}, A_T, A_{SG}, A_{EPES}\}$

where: $\alpha_k(T_A) = \frac{\mu_k}{\lambda_k + \mu_k} \cdot T_A$ is mean operating time of aggregate k in considered analysis time (T_A=1year).

The block transformers, the auxiliaries and the bus-bars are serial connected in the structure of electrical power evacuation station.

Input and output subsystem availability is evaluated with Markov chain method [5].

Tank steam availability depending on intrinsic availability of tank and input subsystems is:

$$A_{steam} = \min\left(A_{TK}, A_{water}, A_{coal}, A_{gases}, A_{slag}\right) \quad (13)$$

Mechanical power availability at turbine generator system can be written as follows:

$$A_{MP} = \min\left(A_T, A_{steam}, A_{condense} A_{cooling\ water}\right) \quad (14)$$

Electrical power availability at generator clamps may be represented as follows:

$$A_{GP} = \min\left(A_{SG}, A_{MP}\right) \quad (15)$$

Electrical power availability at turbogenerator connection bar with electrical power system may be stated as follows:

$$A_B = \min\left(A_{EPES}, A_{GP}\right) \quad (16)$$

3.1 The availability of 100%

The reliability block diagram corresponding to this level of availability is presented in fig 2.

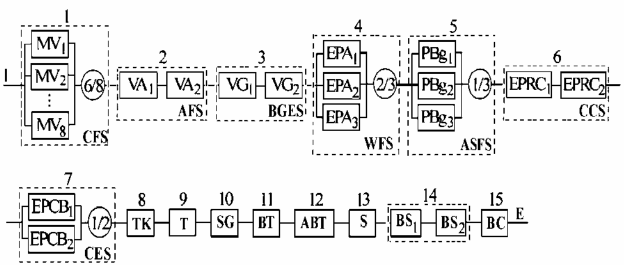


Fig. 2 Block diagram for parametric reliability analysis of a tubogenerator for 100% availability level CFS - coal feeding subsystem; AFS air feeding subsystem; BGES - burned gases evacuation subsystem; WFS - water feeding subsystem; ASES ashes and slag evacuation subsystem; cooling used by condenser subsystem; CES – condense evacuation subsystem; TK - tank; T - turbine; SG - synchronous generator; BT - block transformer; ABT – auxiliaries block transformer; S – swicher; BS - bars separator; CB - collector bars

For subsystems type "s of n" ("s" elements in function from a total of elements "n"), the failure and repair rate are calculated as follows:

$$\begin{cases} \lambda_C = \dfrac{\dfrac{n!}{(s-1)!\cdot(n-s)!} \cdot \dfrac{\lambda^{n-s+1}}{\mu^{n-s}}}{\sum\limits_{i=0}^{n-s} \left[\dfrac{n!}{i!\cdot(n-i)!} \cdot \left(\dfrac{\lambda}{\mu}\right)^i\right]} \\ \mu_C = (n-s+1)\cdot\mu \end{cases} \quad (17)$$

Using mean values for failure and repair rates, at the level of each subsystem, are obtained the following values:

$$\begin{cases} \lambda_1 = \dfrac{168 \cdot \dfrac{\lambda_{MV}^3}{\mu_{MV}^2}}{1 + 8\dfrac{\lambda_{MV}}{\mu_{MV}} + 28 \cdot \left(\dfrac{\lambda_{MV}}{\mu_{MV}}\right)^2} = 112 \cdot 10^{-4} h^{-1} \\ \mu_1 = 3 \cdot \mu_{MV} = 393 \cdot 10^{-4} h^{-1} \end{cases}$$

$$\begin{cases} \lambda_2 = 2 \cdot \lambda_{VA} = 2{,}6 \cdot 10^{-4} h^{-1} \\ \mu_2 = \mu_{VA} = 251 \cdot 10^{-4} h^{-1} \end{cases}$$

$$\begin{cases} \lambda_3 = 2 \cdot \lambda_{VG} = 6{,}8 \cdot 10^{-4} h^{-1} \\ \mu_3 = \mu_{VG} = 263 \cdot 10^{-4} h^{-1} \end{cases}$$

$$\begin{cases} \lambda_4 = \dfrac{6 \cdot \lambda_{EPA}^2}{3\lambda_{EPA} + \mu_{EPA}} = 4{,}3 \cdot 10^{-4} h^{-1} \\ \mu_4 = 2 \cdot \mu_{EPA} = 190 \cdot 10^{-4} h^{-1} \end{cases}$$

$$\begin{cases} \lambda_5 = \dfrac{3 \cdot \lambda_{PBg}^3}{\mu_{PBg}^2 + 3\mu_{PBg} \cdot \lambda_{PBg} + 3 \cdot \lambda_{PBg}^2} = 7{,}4 \cdot 10^{-4} h^{-1} \\ \mu_5 = 3 \cdot \mu_{PBg} = 333 \cdot 10^{-4} h^{-1} \end{cases}$$

$$\begin{cases} \lambda_6 = 2 \cdot \lambda_{EPRC} = 5{,}8 \cdot 10^{-4} h^{-1} \\ \mu_6 = \mu_{EPRC} = 35 \cdot 10^{-4} h^{-1} \end{cases}$$

$$\begin{cases} \lambda_7 = \dfrac{2 \cdot \lambda_{EPCB}^2}{3\lambda_{EPCB} + \mu_{EPCB}} = 0{,}41 \cdot 10^{-4} h^{-1} \\ \mu_7 = 2 \cdot \mu_{EPCB} = 70 \cdot 10^{-4} h^{-1} \end{cases}$$

$$\begin{cases} \lambda_{14} = 2 \cdot \lambda_{SB} = 0{,}014 \cdot 10^{-4} h^{-1} \\ \mu_{14} = \mu_{SB} = 400 \cdot 10^{-4} h^{-1} \end{cases}$$

Equivalent failure and repair rates at group level for the availability of 100%,are:

$$\begin{cases} \lambda_{e(100\%)} = \sum\limits_{i=1}^{15} \lambda_i = 181{,}76 \cdot 10^{-4} h^{-1} \\ \mu_{e(100\%)} = \dfrac{\lambda_{e(100\%)}}{\sum\limits_{i=1}^{15} \dfrac{\lambda_i}{\mu_i}} = 205{,}55 \cdot 10^{-4} h^{-1} \end{cases}$$

The probability of success for the availability of 100% is:

$$P_{S(100\%)} = \frac{\mu_{e(100\%)}}{\lambda_{e(100\%)} + \mu_{e(100\%)}} = 0{,}53072$$

Annual mean operating time of group in full capacity (100%) is:

$$M_{(100\%)}\left[\alpha(T_A)\right] = P_{S(100\%)} \cdot T_A = 4649\ h/year$$

Annual mean number of passages (failures) of the state group works at full capacity is:

$$M_{(100\%)}\left[\nu(T_A)\right] = P_{S(100\%)} \cdot \lambda_{e(100\%)} \cdot T_A = 84{,}5\ failures/year$$

3.1.1 Assessing subsystem availability

In order to assess the availability of subsystems is considered the example of burned gases evacuation subsystem. In this subsystem the identified main components are fans gas (VG) and (EF). The tank can be equipped with a VG (dimensioned 1x100%) or two (dimensioned 2x50 %). Electrofilters nonreliability directly don't influences on the tank availability, meaning that the tank is operational and if electrofilters are defect. But, in this case, the level of pollution overcomes the imposed limits, with unpleasant consequences on the environment. The recommend method of analysis for this subsystem is Markov chains with continuous time [5].

In the case of a group of power plant II Oradea, the tank is equipped with two fans gas, with a minimal flow unit of 80 m^3/s, designed 2x50%. The tank is configured with two electrofilters, designed in the version 2x50%, each being serial connected with fans gas. Block reliability diagram of subsystem is illustrated in fig. 3.

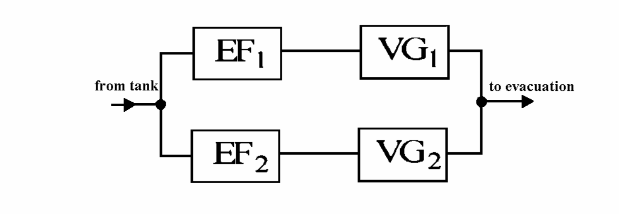


Fig.3 Block reliability diagram of subsystem

The mean failure and repair rates of fans gas and electrofilters (including electrical power supply installation) are:

$\lambda_{EF} = 0{,}4 \cdot 10^{-4}\ h^{-1}$; $\mu_{EF} = 350 \cdot 10^{-4}\ h^{-1}$

$\lambda_{VG} = 3{,}7 \cdot 10^{-4}\ h^{-1}$; $\mu_{EF} = 205 \cdot 10^{-4}\ h^{-1}$

The reliability analysis is detailed up to the states with double failures, the probability of the state with all elements function is:

$$P_1 = \frac{1}{1 + 2\frac{\lambda_{EF}}{\mu_{EF}} + 2\frac{\lambda_{VG}}{\mu_{EF}} \cdot \left(\frac{\lambda_{EF}}{2\mu_{EF}} + \frac{2\lambda_{VG}}{\mu_{VG} + \mu_{EF}}\right) + 2\frac{\lambda_{VG}}{\mu_{VG}}\left(\frac{\lambda_{VG}}{2\mu_{VG}} + \frac{2\lambda_{EF}}{\mu_{VG} + \mu_{EF}}\right)}$$

Applying the general solution method, based on Markov chains with continuous time are identified the possible states of the subsystem (Table 1).

Table 1 Possible states of subsystem

Analytical approach			
States number	Failure	States probability	Mean time yearly
1	-	P_1	$P_1 . T_A$
2	VG_1 or VG_2	$P_2 = 2P_1 \cdot \frac{\lambda_{VG}}{\mu_{VG}}$	$P_2 . T_A$
3	EF_1 or EF_2	$P_3 = 2P_1 \cdot \frac{\lambda_{EF}}{\mu_{EF}}$	$P_3 . T_A$
4	VG_1 and VG_2	$P_4 = 2P_1 \cdot \frac{\lambda_{VG}^2}{2\mu_{VG}^2}$	$P_4 . T_A$
5	EF_1 and EF_2	$P_5 = 2P_1 \cdot \frac{\lambda_{EF}^2}{2\mu_{EF}^2}$	$P_5 . T_A$
6	(VG_1 and EF_2) or (VG_2 and EF_1)	$P_6 = 2P_1 \cdot \frac{\lambda_{VG}\lambda_{EF}}{\mu_{VG}\mu_{EF}}$	$P_6 . T_A$

Operational numerical results				
States number	States probability	Mean flow.	Mean time yearly	Availa-bility
1	0,962656	160	8433	1
2	0,034749	80	304	0,5
3	0,0022	80	19	0,5
4	0,000313	0	2,7	0
5	0,000001	0	0,01	0
6	0,00004	0	0,4	0

Availability subsystem exhaust gas combustion (A_{gases}) is presented in graphic form fig 4.

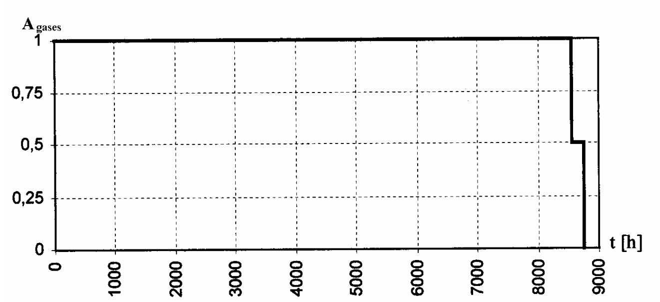


Fig. 4 Availability of subsystem

The likelihood of securing votes of the flow of burning gas is:

$$P_{S\ gases} = P_1 = 0{,}962656$$

Mean availability of burned gases evacuation system is:

$$A_M = 0{,}9891$$

3.2 The availability level of 83%

This level of availability is achieved if coal feeding subsystem (CFS) is located in the state "5 of 8", all other subsystems of the group being presented in reliability block diagram in fig. 2.

Failure and repair rates are calculated as follows:

$$\begin{cases} \lambda_1 = \dfrac{280 \cdot \dfrac{\lambda_{MV}^4}{\mu_{MV}^3}}{1 + 8\dfrac{\lambda_{MV}}{\mu_{MV}} + 28 \cdot \left(\dfrac{\lambda_{MV}}{\mu_{MV}}\right)^2 + 56\left(\dfrac{\lambda_{MV}}{\mu_{MV}}\right)^3} = 46{,}76 \cdot 10^{-4}\, h^{-1} \\ \mu_1 = 4 \cdot \mu_{MV} = 524 \cdot 10^{-4}\, h^{-1} \end{cases}$$

At the group level, the reliability indices are:

$$\begin{cases} \lambda_{e(83\%)} = 116{,}52 \cdot 10^{-4}\, h^{-1} \\ \mu_{e(83\%)} = 169{,}23 \cdot 10^{-4}\, h^{-1} \end{cases}$$

The probability that the availability of the group to be at least 83% is:

$$P_{S(\geq 83\%)} = \frac{\mu_{e(83\%)}}{\lambda_{e(83\%)} + \mu_{e(83\%)}} = 0{,}592231$$

The probability that the availability of the group to be 83% is:

$$P_{S(83\%)} = P_{S(\geq 83\%)} - P_{S(100\%)} = 0{,}061519$$

Annual mean operating time of group at 83% system availability is:

$$M_{(83\%)}[\alpha(T_A)] = P_{S(83\%)} \cdot T_A = 539\ h/\,year$$

Annual mean number of passages (failures) of the state group works at capacity 83% is:

$$M_{(83\%)}[\nu(T_A)] = P_{S(83\%)} \cdot \lambda_{e(83\%)} \cdot T_A = 6{,}3\ failures/\,year$$

3.3 The availability level of 67%

This level of availability is achieved if coal feeding subsystem (CFS) is located in the state "4 of 8", all other subsystems of the group being presented in reliability block diagram in fig. 1.

As a result:

$$\begin{cases} \lambda_1 = \dfrac{280\dfrac{\lambda_{MV}^5}{\mu_{MV}^4}}{1+8\cdot\dfrac{\lambda_{MV}}{\mu_{MV}}+28\left(\dfrac{\lambda_{MV}}{\mu_{MV}}\right)^2+56\left(\dfrac{\lambda_{MV}}{\mu_{MV}}\right)^3+70\left(\dfrac{\lambda_{MV}}{\mu_{MV}}\right)^4} = 13{,}76\cdot 10^{-4} h^{-1} \\ \mu_1 = 5\cdot\mu_{MV} = 655\cdot 10^{-4} h^{-1} \end{cases}$$

At the group level, the reliability indices are:

$$\begin{cases} \lambda_{e(67\%)} = 83{,}52 \cdot 10^{-4}\, h^{-1} \\ \mu_{e(67\%)} = 134{,}65 \cdot 10^{-4}\, h^{-1} \end{cases}$$

The probability that the availability of the group to be at least 67% is:

$$P_{S(\geq 67\%)} = \frac{\mu_{e(67\%)}}{\lambda_{e(67\%)} + \mu_{e(67\%)}} = 0{,}617179$$

The probability that the availability of the group to be 67% is:

$$P_{S(67\%)} = P_{S(\geq 67\%)} - P_{S(100\%)} - P_{S(83\%)} = 0{,}024948$$

Annual mean operating time of group at 67% system availability is:

$$M_{(67\%)}[\alpha(T_A)] = P_{S(67\%)} \cdot T_A = 219\ h/\,year$$

Annual mean number of passages (failures) of the state group works at capacity 67% is:

$$M_{(67\%)}[\nu(T_A)] = P_{S(67\%)} \cdot \lambda_{e(67\%)} \cdot T_A = 1{,}8\ failures/\,year$$

3.4 The availability level of 50%

This level of availability is achieved if coal feeding subsystem (CFS) is located in the state "4 of 8", all other subsystems of the group being presented in reliability block diagram states in fig. 5

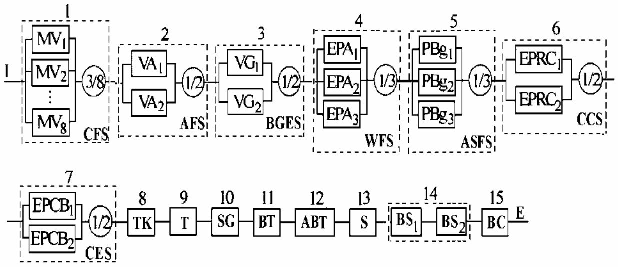


Fig. 5 Block diagram for parametric reliability analysis of a tubogenerator for 50% availability level

We mention the subsystems reliability indices values:

$$\begin{cases} \lambda_1 = \dfrac{168\cdot\dfrac{\lambda_{MV}^6}{\mu_{MV}^5}}{1+8\cdot\dfrac{\lambda_{MV}}{\mu_{MV}}+28\cdot\left(\dfrac{\lambda_{MV}}{\mu_{MV}}\right)^2+56\cdot\left(\dfrac{\lambda_{MV}}{\mu_{MV}}\right)^3+70\cdot\left(\dfrac{\lambda_{MV}}{\mu_{MV}}\right)^4+56\cdot\left(\dfrac{\lambda_{MV}}{\mu_{MV}}\right)^5} = \\ 2{,}59\cdot 10^{-4} h^{-1} \\ \mu_1 = 6\cdot\mu_{MV} = 786\cdot 10^{-4} h^{-1} \end{cases}$$

$$\begin{cases} \lambda_2 = \dfrac{2\cdot\lambda_{VA}^2}{2\cdot\lambda_{VA}+\mu_{VA}} = 0{,}013\cdot 10^{-4}\, h^{-1} \\ \mu_2 = 2\cdot\mu_{VA} = 502\cdot 10^{-4}\, h^{-1} \end{cases}$$

$$\begin{cases} \lambda_3 = \dfrac{2\cdot\lambda_{VG}^2}{2\cdot\lambda_{VG}+\mu_{VG}} = 0{,}025\cdot 10^{-4}\, h^{-1} \\ \mu_3 = 2\cdot\mu_{VG} = 526\cdot 10^{-4}\, h^{-1} \end{cases}$$

$$\begin{cases} \lambda_4 = \dfrac{3\cdot\lambda_{EPA}^3}{\mu_{EPA}^2 + 3\cdot\lambda_{EPA}\cdot\mu_{EPA} + 3\cdot\lambda_{EPA}^3} = 0{,}208\cdot 10^{-4}\, h^{-1} \\ \mu_4 = 3\cdot\mu_{EPA} = 285\cdot 10^{-4}\, h^{-1} \end{cases}$$

$$\begin{cases} \lambda_6 = \dfrac{2 \cdot \lambda_{EPRC}^2}{2 \cdot \lambda_{EPRC} + \mu_{EPRC}} = 0{,}41 \cdot 10^{-4} h^{-1} \\ \mu_6 = 2 \cdot \mu_{EPRC} = 70 \cdot 10^{-4} h^{-1} \end{cases}$$

At the group level, the reliability indices are:

$$\begin{cases} \lambda_{e(50\%)} = \sum_{i=1}^{15} \lambda_i = 53{,}51 \cdot 10^{-4} h^{-1} \\ \mu_{e(50\%)} = \dfrac{\lambda_{e(50\%)}}{\sum_{i=1}^{15} \dfrac{\lambda_i}{\mu_i}} = 139{,}1 \cdot 10^{-4} h^{-1} \end{cases}$$

The probability that the availability of the group to be at least 50% is:

$$P_{S(\geq 50\%)} = \frac{\mu_{e(50\%)}}{\lambda_{e(50\%)} + \mu_{e(50\%)}} = 0{,}722185$$

The probability that the availability of the group to be 50% is:

$$P_{S(50\%)} = P_{S(\geq 50\%)} - P_{S(100\%)} - P_{S(83\%)} - P_{S(67\%)} = 0{,}105006$$

Annual mean operating time of group at 50% system availability is:

$$M_{(50\%)}[\alpha(T_A)] = P_{S(50\%)} \cdot T_A = 920\ h/year$$

Annual mean number of passages (failures) of the state group works at capacity 50% is:

$$M_{(50\%)}[\nu(T_A)] = P_{S(50\%)} \cdot \lambda_{e(50\%)} \cdot T_A = 4{,}9\ failures/year$$

The results of calculations on the availability of the turbogenerator are presented in table 2.

Table 2 Reliability indices values of turbogenerator group

State number	Availability level	State Probability	Annual mean operating time]	Annual mean failures [failures/year]
1	100	0,530712	4649	84,5
2	83	0,061519	539	6,3
3	67	0,024948	219	1,8
4	50	0,105006	920	4,9
5	0	0,277815	2433	-

The available power during a year, at the bar turbogenerator connection with electroenergetic system is illustrated in fig. 6, (Pn = 60 MW). Energy availability of the turbogenerator group is:

$$D_W = \frac{P_n \cdot 4649 + 0{,}83 \cdot P_n \cdot 539 + 0{,}67 \cdot P_n \cdot 219 + 0{,}5 \cdot P_n \cdot 920}{P_n \cdot 8760} = 0{,}651039$$

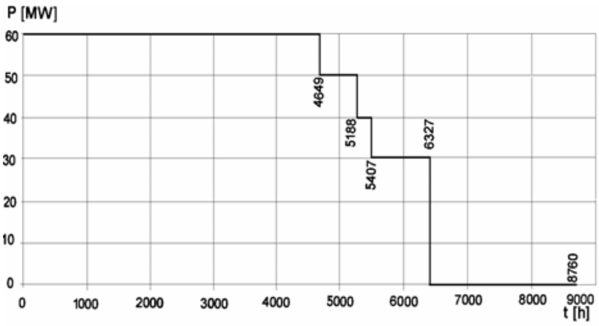


Fig.6 Power availability of turbogenerator obtain by the means of reliability block diagram

Applying the proposed method for availability assessment on the basis reliability block diagram may be identified, besides extreme states (operating at nominal capacity, respectively defect), and the states characterized by a partial availability. The method allows the evaluation of performance reliability and availability of the turbogenerator, based on which, finally can assess the safety indicators energy group. The benefits of applying this method are obvious relative to modelling by two states (operation / defect) when is only assessing safety indicators of time.

4. Simulation program via The Monte Carlo technique

Applying Monte-Carlo simulation to a complex system the following parameters are considered [6]:

$Y_i (i = 1, 2, ...m)$ output parameters with the inferior limits($Y_{ai}^{//}$) and superior limits ($Y_{ai}^{/}$)

$X_k (k = 1, 2, \cdots ...n)$ input parameters with the inferior limits ($X_{ak}^{//}$) and superior limits ($X_{ak}^{/}$)

The simulation supposes the following steps:

1. Writing the equations which describe the operating system:

$$Y_i = G_i (X_1, X_2, ...X_n), \quad i = 1, 2, ...m \tag{18}$$

2. The value x_k is assigned to each stochastic variable X_k. The assigned values are generated by an algorithm depending on distribution type (exponential, normal, Weibull), verifying if $x_k \in [X_{ak}^{//}, X_{ak}^{/}]$

3. The X_k values introduced in equation (18) calculate the Y_i of the output parameters

4. A quantitative criterion is formulated to determine the system reliability. Thus, system reliability in moment t can be defined and evaluate

the probability of output parameters to be in the interval $\left[Y_{ai}^{//}, Y_{ai}^{/}\right]$

$$R_S(t) = \Pr ob\left[Y_{ai}^{//} \le y_i(t) \le Y_{ai}^{/}\right], \text{ i=1, 2, ...m} \quad (19)$$

5. If, based on the x_k obtained by simulations is determined the probability density of the stochastic output parameters, then the system reliability can be calculated as follows:
- for a single output parameter:

$$R_S(t) = \Pr ob\left[Y_a^{//} \le Y(t) \le Y_a^{/}\right] = \int_{Y_a^{//}}^{Y_a^{/}} f(Y) \cdot dY \quad (20)$$

- for more independent output parameters:

$$R_S(t) = \Pr ob\left[Y_{ai}^{//} \le Y_i(t) \le Y_{ai}^{/}\right] = \prod_{i=1}^{m} \int_{Y_a^{//}}^{Y_a^{/}} f(Y) dY \quad (21)$$

Starting with distribution low, the N states of system are simulated, obtaining output parameters values, which can be used in further indices calculation.
For the turbogenerator group, Monte Carlo simulation generates an aleatory number in interval [0, 8760] and depending on this number and components availability is established availability for subsystem. Successively are calculated steam, mechanical power of turbine generator subsystem and the availability of connection bar between turbogenerator group and electrical power system. Procedure is repeated (103-104 simulations), each corresponding a certain group availability value. Sorting descending the simulation values for A_{steam}, A_{MP}, A_{GP}, A_P, are find availability in a year (analyzed time interval).
Given the strong drive to evaluate the impact of each system *i* on the group availability, we define the indices:
1. absolute availability decrease on subsystem *i* of turbogenerator group as

$$\begin{cases} \Delta A_{TK}(t) = 1 - A_{steam}(t) \\ \Delta A_T(t) = A_{steam}(t) - A_{MP}(t) \\ \Delta A_{GS}(t) = A_{MP}(t) - A_{GP}(t) \\ \Delta A_{EPES}(t) = A_{GP}(t) - A_B(t) \end{cases} \quad (22)$$

2. mean availability decrease of subsystem i from turbogenerator group:

$$\Delta A_{i\,m} = \frac{1}{T_A} \int_0^{T_A} \Delta A_i(t) \cdot dt \quad (23)$$

where $i = \{TK, T, SG, EPES\}$
The simulation program has the following steps:
1. Set the availability (A_k) of the aggregates and group subsystem for selected system, previously calculated using binomial, or Markov chains method;
2. For each subsystem is generated a random number in the interval [0, 8760]. In this purpose, in the first phase, the congruent method generates a pseudoaleatory number, uniform distributed on the interval [0, 1] which is multiplied by 8760;

$$\begin{cases} y_{k,i} = a \cdot y_{k,i-1} + c \\ x_{k,i} = 8760 \cdot y_k \end{cases} \quad (24)$$

where a, c, yk,i-1 are integer between 0 and (m-1);
m is set value for maximal repeating interval;
k is aggregate or subsystem of the group.
3. For each subsystem or aggregate, depending on value of random number ($x_{k,\ i}$) is set the value of availability A_k(xk, i) in concordance with before calculated values;
4. Using relations (17-20) are calculated subsystems availabilities: $A_{steam\,i}$, $A_{MP\,i}$, $A_{GP\,i}$, $A_{P\,i}$;
5. Pre-establish number iteration (N) ended, the obtain availability are sorted descending and graphical represented;
With eq. 6, 7 are calculated absolute availability decrease and mean availability decrease of subsystem i from turbogenerator group;
6. Having the descending values ($A_{P,i}$), are set the availability levels for (A_j) and the number of achievement of each availability level;
7. The probability of availability is written as:

$$prob\ j = \frac{n_j}{N} \quad (25)$$

The mean annual time occupation of a certain availability level (A_j) may be represented as follows:

$$\alpha(T_A) = \Pr ob_j \cdot T_A = \Pr ob_j \cdot 8760 \quad (26)$$

Group energy availability is calculated:

$$A_W = \frac{\sum_j A_j \cdot \alpha_j(T_A)}{T_A} \quad (27)$$

The graphical representation of availability of turbogenerator group is drawn. Power availability corresponding to each level is :

$$P_j = A_j \cdot P_n$$

where P_n is nominal power of the generator.

5 Case Study

To evaluate the availability in a tubogenerator group of a power plant, simulation program utilizes the success probability (100% availability) of the group, based on the operating values to appreciate the number of simulation necessary to the accuracy of results:

$$P_S = \prod_k P_{Sk} = 0,4267 \quad (28)$$

Used under the form of relative percentage error, this success probability is compared with Prob1 obtain by running the program:

$$\varepsilon_r^{\%} = \frac{|P_s - \mathrm{Pr}\,ob_1|}{P_s} \cdot 100 \quad (29)$$

For an increasing number of simulations is obtained the acceptable error value (table 3).
The decrease of errors number along with the increase of the number of simulations recommends as acceptable error (under 1%) after 5000 simulation.

Table 3 Influences of simulations number on the accuracy of computation

Number of simulations	Prob1	ε_r
1.000	0,434	1,7
5.000	0,4304	0,87
10.000	0,4261	0,14
20.000	0,4271	0,09

The steam availability (A_{steam}), mechanical power availability (A_{MP}) and electrical power availability at turbogenerator connection bar (A_{GP}) obtain by Monte Carlo simulation are presented in fig.7.

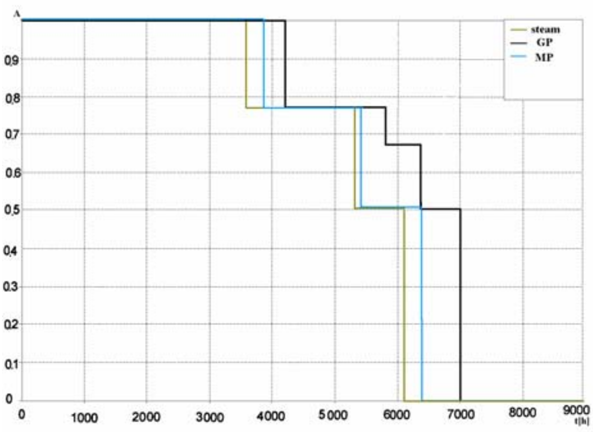


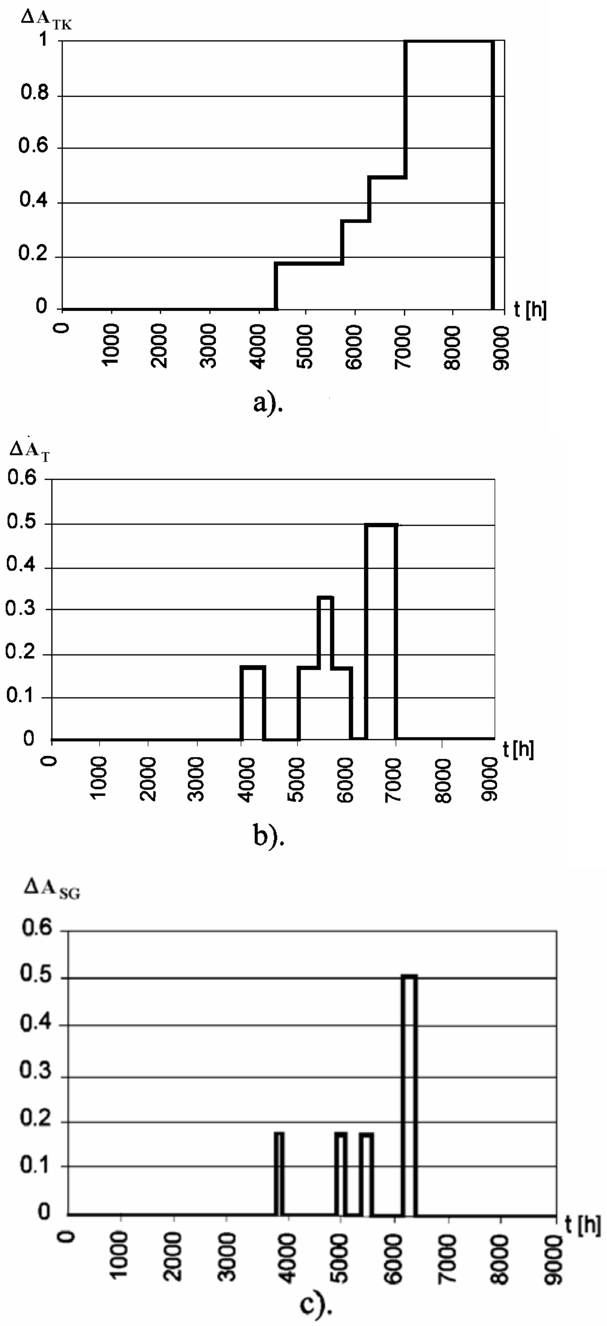
Fig. 7 Availability characteristics

The decrease of mean values of availability (ΔA_{imed}), power availability ($\Delta P_i[Mw]$) and undelivered electrical power {$\Delta W_i[MWh]$} due to subsystem unavailability are shown in table 4

Table 4 The availability diminution, power availability and undelivered electrical power due to subsystem unavailability

Subsystems	ΔA_{imed}	$\Delta P_i[Mw]$	$\Delta W_i[MWh]$
Tank	0289941	17.396	152.389
Turbine	0,068430	4.106	35.968
Generator	0,022841	1.307	12.001
Auxiliaries	0,002971	0,179	1.568
Group	0,384183	23.051	201.927

In figure 8 are shown the absolute availability decrease of subsystems and aggregates: tank, $\Delta A_{TK}(t)$, turbine, $\Delta A_T(t)$, generator, $\Delta A_{SG}(t)$, evacuation system $\Delta A_{EPES}(t)$.



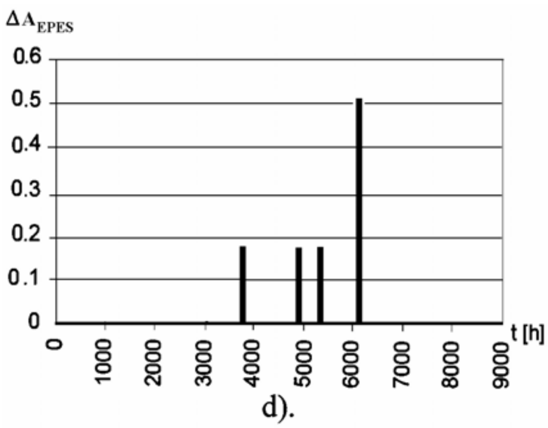


Fig.8 The absolute availability decrease of subsystems: tank (a), turbine (b), generator (c), evacuation system (d)

The reliability indices turbogenerator group the results obtain are presented in table 5.

Group power availability is calculated:

$$A_w = \frac{P_n(3742 + 0{,}83 \cdot 1169 + 0{,}67 \cdot 463 + 0{,}5 \cdot 744)}{8760}$$

$= 0{,}6158$

The mean availability decrease values of group ΔA_{Group} is distributed as follows: 75,5% for tank., 17.8% for turbine, 5,9% generator, 0,8% auxiliaries.

Table 5 Turbogenerator group reliability indices

State number	Availability level (A_j)	State probability ($Prob_j$)	Mean Time occupation α_j (T_A)
1	1	0,4271	3742
2	0,83	0,1334	1169
3	0,67	0,0528	463
4	0,5	0,0849	744
5	0	0,3018	2642

Power availability of turbogenerator group at the level of connection bar with electrical system is shown in figure 9, (nominal power of generator is 60 MW).

The probability of full availability calculated with block diagram reliability [10], [11] method is P(100%)=0,530712. The results obtain by Monte Carlo simulation: $Prob_i$=0,4271.

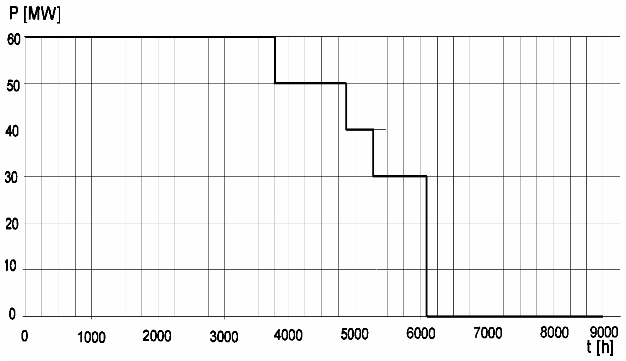


Fig. 9 Power availability of turbogenerator

The Monte Carlo simulation of availability of turbogenerator group has a good precision and accuracy is accessible, although requires a previous evaluation of the subsystem availability.

6 Conclusions

One of the purposes of system reliability and availability analysis is to identify the weakness in a system and to quantify the impact of component failures.

This analysis identified the critical and sensitive subsystems or components of the system that need more attention for improvement.

Values obtained for absolute availability decrease (ΔA_i) and mean availability decrease ($\Delta A_{i\,mean}$) of subsystem i of turbogenerator group, allowed to create a subsystems hierarchy from viewpoint of the impact on the power unavailability.

Starting with availability values, a strategy aimed to increase the availability of system is designed to improve the performances of the subsystem with greater impact on availability of the system.

Referances

[1] Barlow, R.E., Proschan, F., *Statistical Theory of Reliability and Life Testing: Probability Models,* New York: Rinehart and Winston1975.

[2] Blanchard, B.S., Fabrycky, W.J., *System Engineering and Analysis,* Prentice Hall, New Jersey1998.

[3] Ebeling, C.E., *An introduction to reliability and maintainability engineering,* McGraw-Hill, New York, 1997.

[4] Băjenescu T. I., *Fiabilitatea sistemelor tehnice,* Editura Matrix Rom, Bucureşti, 2003.

[5] Cătuneanu, V. M., Mihalache A., *Bazele teoretice ale fiabilității,* Editura Academiei, Bucureşti, 1983.

[6] Leemis, L.M., Reliability: *Probabilistic Models and Statistical Methods*, Englewood Cliffs, N.J.: Prentice Hall, Inc. 1995.).
[7] Wang, W., Loman, J., Vassiliou, P., *Reliability importance of components in a complex system*, Proceedings of the Annual Reliability and Maintainability Symposium, International Symposium on Product Quality and Integrity, 2001, pp. 6-11
[8] Charles, C., Kondo, A. *Availability allocation to repairable systems with genetic algorithms: a multi-objective formulation*, Reliability Engineering and System Safety, Vol. 82, No. 3, December 2003, pp. 319-330.
[9]. Richard Cassady, C., Pohl, E.A., *Managing availability improvement efforts with importance measures and optimization*, IMA Journal of Management Mathematics, Vol. 15, No. 2, 2004, pp. 161-174.
[10] Tonț G., Tonț D. G, A *Simulation Method for Risk Assessment*, Analele Universității din Oradea, EMES 2007, pp. 165-169.
[11] Tonț G., Tonț D. G, *Fault and Failure Detection in Nuclear Power Plants*, REV.ACTA ELECTROTEHNICA, Vol. 46, nr. 4, Cluj Napoca, 2005, pp. 173-178.
[12] Gertsbakh, I., Y Shpungin, *Network Reliability Importance Measures : Combinatorics and Monte Carlo based Computations*, 7th WSEAS International Conference on APPLIED COMPUTER SCIENCE, Venice, Italy, November 21-23, 2007, pp. 88 – 94.
[13] Maris, T.I., Sideris, K.M., Pappas, S.SP., Ekonomou L., *Distribution systems' reliability increase using a cost-benefit decision-making process* Proceedings of the 6th WSEAS/IASME Int. Conf. on Electric Power Systems, High Voltages, Electric Machines, Tenerife, Spain, December 16-18, 2006, pp 46-51.
[14] Fukutome, S., Yokoyama R., *Efficient Evaluation of Nodal Reliability Index based on AC-OPF by Fast Monte Carlo Method*, Proceedings of the 6th WSEAS International Conference on Power Systems, Lisbon, Portugal, September 22-24, 2006. pp. 220-225.
[15] Shubin Cai, Shixian Li, Zhong Ming, Sishan Gu, Xinhong Zeng, *Abstract Machine and Structural Availability,* WSEAS TRANSACTIONS on COMPUTERS Issue 5, Volume 5, May 2006, pp. 870-878.