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RELIABILITY ANALYSIS AND EVALUATION OF INDUSTRIAL TANK HEATING SYSTEM

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Abstract. The present paper describes the development and application of a methodology for reliability analysis and evaluation of a tank heating system. The reliability structure of the studied system is presented as a triple modular redundant system (TMR-system). A hybrid methodology composed of a Monte Carlo simulation and Markov state-space models is developed and applied for reliability evaluation of a TMR heating system. The so-developed simulations, models and structures are applied under real operating conditions in a tank heating system of a hot dip zinc galvanizing facility.

Keywords: reliability analysis and evaluation, Monte Carlo simulation, Markov models, industrial tank heating system

1. Introduction

The application of Lagrange approach to Markov models and Monte Carlo simulation has been proven to be very effective for reliability estimation of complex systems – [1, 4, 8]. However, the simulation of complex multi-component systems via Markov modelling and Monte Carlo methods is practically limited to systems that can be modelled via time-inhomogeneous Markov process [1, 2, 4]. Such types of models are capable to include and to utilize systems components dependencies as well as wear phenomena, represented by time dependent failure rates for systems reliability analysis [3, 4, 7, 8].

The application of Monte Carlo simulation for treating time-inhomogeneous Markov models allows to develop a replacement of the constant failure rates (accepted in various reliability analysis) with a more realistic "bathtub" curves, thus providing also the simulation of the wear in systems components, as well as their periodic maintenance – [1, 3, 4]. A further development of these methods allows also the application of the so-called "as good as new" *repair* (restoration) of the systems condition, or an eventual *renewal of the systems components* – an ability, which in fact *violates* the Markov properties of the time-inhomogeneous Markov process [1, 5, 6]. These events are illustrated by the representation of the failure rate curves, shown in Figure 1.

Curve 1 (see Figure 1) represents the failure rate during a preventive maintenance over the systems components, during time-inhomogeneous Markov calculations. Curve 1 is an adequate approximation to the "as-good-as-old" repair model, presented via curve 2, since the time intervals between failures and repairs, i.e., (T_R – T_F) is rather small. For the "as-good-as-new" repair model, the failure rate curves must be reinitialized at the point T_R. Therefore, if the age-replacement strategies (versus the batch replacement ones) must be developed and studied – then the time points at which the preventive replacement should be carried out also depend on the time point of the last components failure.

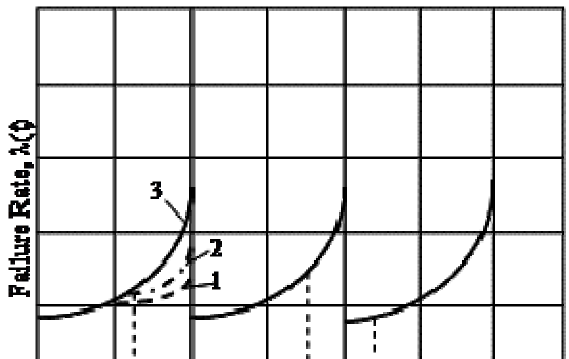

Figure 1. Failure rate curves, presenting three types of repair models: "as-good-as-new" (1) ; "as-good-as-old" (2); continuous aging (3).

Therefore, a Monte Carlo simulation, developed within the Markov framework [1, 4], could be generalized, to process also such kinds of non-Markovian repair models, which are needed to treat realistic industrial systems, via merely keeping track of the age of each replaceable component since its last renewal.

The present paper describes the development and application of a hybrid (a generalized) methodology for reliability analysis and evaluation of industrial tank heating system. The reliability structure of the studied system is presented as a triple modular redundant system (TMR-system). A hybrid methodology composed of a Monte Carlo simulation and Markov state-space models is developed and applied for reliability evaluation of a TMR heating system.

The so-developed simulations, models and structures are applied under real operating conditions in a tank heating system of a hot dip zinc galvanizing facility.

2. Development of a hybrid methodology composed of Monte Carlo simulation and non-Markovian repair model

The studied system consists of **n** components, which can respectively determine 2^n possible systems states, since the systems states are defined by combinations of operational and failed components [2]. The operation of the studied systems could then be described via time-inhomogeneous Markov process. If $P_K^S(t)$ is the probability for the system to be in state K at time moment t, then the differential equations, which simulate its behaviour are as follows,

$$\frac{dP_K^S(t)}{dt} = -\delta_K^S P_K^S + \sum_{i=1}^{K} P_C(K/K',t)\delta_K^S(t)P_K^S(t) \quad (1)$$

where, $K, K' = 0,1,2,\dots,2^n$

The transition rate δ_K^S out of the systems state "K" is determined by the relation,

$$\delta_K^S(t) = \sum_{j=1}^{R_{Sk}} \lambda_{jk}(t) + \sum_{j=1}^{F_{Sk}} \mu_{jk}(t) \quad (2)$$

where, $\lambda_{jk}(t)$ and $\mu_{jk}(t)$ are the failure and the repair rates of the systems component "j" respectively in the state "k";

R_{Sk} and F_{Sk} – represent the sets of operational and failed systems components.

P_C (K/K', t) - conditional probability, that expresses the transition from state K' to K, at time t, and be determined via the relation

$$P_C(K/K',t) = \delta_{KK'}^S(t)/\delta_K^S(t) \quad (3)$$

$$P_C(K/K',t) = \delta_{KK'}^S(t)/\delta_K^S(t) \quad (4)$$

where $\delta_{KK'}^S(t)$ represents the transition rate, corresponding to a transition from state K' to state K. It must be emphasized however, that an option for self transition (i.e., a transition from K to K and/or from K' to K') is not included in relations (2) and (3).

The Monte Carlo simulation comprises N number of random "paths", which follow the state transitions during some finite period of time T_M (i.e., the time period of a systems mission for the present case).

If there exists a necessary for processing also time-dependant failure rates, caused by wear and/or early failures, then the self-transition options should also be developed and included in the already developed relations (2) and (3). For providing options for self-transition a *self-transition rate* $\delta_{KK}^S(t)$ should be added to the left part of relation (2), and respectively determined as follows

$$\delta_{KK}^S(t) = \delta_K^C - \sum_{j=1}^{R_{Sk}} \lambda_{jK}(t) + \sum_{j=1}^{F_{Sk}} \mu_{jK}(t) \quad (5)$$

where, δ_K^C represents a superficial constant transition rate, which should be chosen in such a way, that $\delta_{KK'}^S(t) \geq 0$.

In order to determine whether a systems failure is caused via *state transition* a specific type of ***fault tree*** could be built. The so-developed fault tree can describe the interactions between the systems components (resulting in a failure generation), and could respectively be built via bottom-up evaluation of the systems interactions and/or via minimal cut sets techniques. The systems estimate for a failure event (i.e., for non-reliability) $Q^S(t)$ could be expressed by the following relation

$$Q^S(t) = \frac{1}{N}\sum_{t=t_i}^{T^{RS}} w_i \quad (6)$$

where, w_i is the stochastic weight of the i^{th} event at the time of the systems failure, if it occurs before the systems resource (i.e. the design life) – T^{RS}.

The renewal of every failed systems component could respectively be incorporated in the relation (2) by replacing the time moment "t" by a vector "T_{RC}", which contains the current resource (i.e., the age) of each replaceable component. As a consequence, the relation (3) representing the conditional probabilities for every transitions, can be modified as follows,

$$P_C(K/K',T_{RC}) = \delta_{KK'}^S(T_{RC})/\delta_{K'}^S(T_{RC}) \quad (7)$$

The ability for tracking the current resource (i.e., the age) of each systems component during the development of the random "paths" can thus be incorporated into the Monte Carlo simulation.

3. Development of triple modular redundant system (TMR-system) for a tank heating equipment

The tank heating system, which is the subject of the actual study, consists of 3 main burners (i.e., a so-called “hot sticks”), that must heat the process liquids from an ambient temperature up to 60-80 C° – please see Figure 2. A so-developed tank heating systems is utilized in the process technology of hot dip zinc galvanizing facility. The tanks are heated by immersion tube burners fabricated of schedule 40 steel pipes and fired with atmospheric type burners. The burners use a natural gas as fuel. In order to obtain a higher level of reliability of the heating systems – 2 spare burners are also included in the systems structure and provide redundancy during the heating processes.

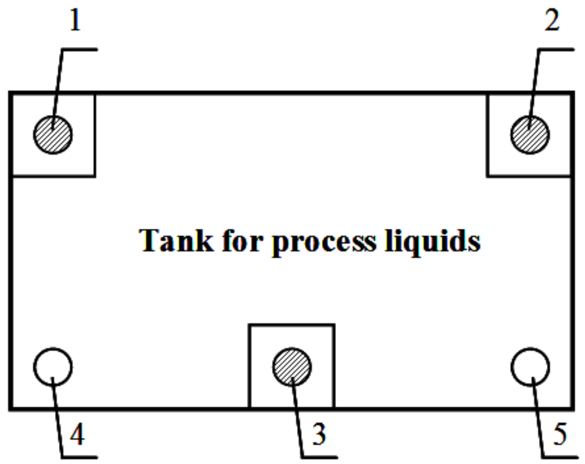

Figure 2. Tank heating system with 3 main and 2 spare burners of a “hot sticks” type.
1, 2 and 3 – main burners; 4 and 5 – spare burners

The structure of the tank heating system can be considered as a specific TMR-system. The reliability configuration of such a system is presented schematically in Figure 3. The TMR-system is essentially a 2 out of 3 (i.e., 2, 3) system, which is connected to a set of 2 spare units via switching device – a configuration that enhances systems reliability.

If one of the systems active components (A_1, A_2 or A_3), *fails*, the switching device replaces it by a spare one (S_1, …, S_K, where K = 1, 2 for the actual case). The active components are respectively the burners under operation, while the spare components are the supplementary burners, which provide the redundancy of the reliability configuration.

The switching process represents in fact *the reconfiguration* of the structure, which needs a finite period of time and is determined as submitted to an exponential distribution. The process is characterized by a reconfiguration (i.e., a repair) rate μ. In accordance with the relations, developed in the previous paragraph, as well as the structure, developed in Figure 3, the TMR heating system has $n = N + 3 = 5 + 3 = 8$ components. The number N_S of possible systems states can respectively be $N_S = 2^8$ possible systems states. It could be assumed however, that, the systems components are identical and as a consequence the number of possible systems states could be reduced to $N_S = 2N + 3$. It is assumed, that the switching device, the failure detector and the decision maker (D_M) practically do not fail (the failure rates of these systems elements can easily be incorporated into the Monte Carlo simulation. The structure of the developed state transition model for the TMR heating systems is presented in Figure 4.

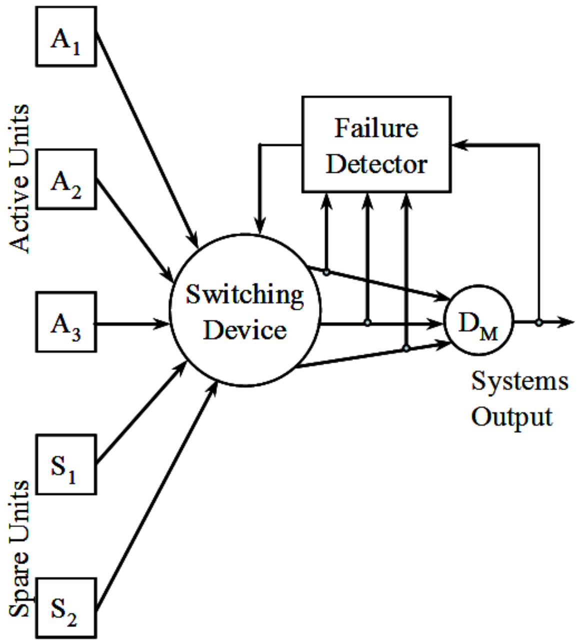

Figure 3. Reliability configuration of a TRM tank heating system

It must be noted, that, the systems state ($2N + 2$) represents a so-called “absorbing state”. This state does not allow outgoing transitions, and in fact corresponds to systems failure.

The TRM heating system can thus develop two types of failure modes – respectively *lack of cover and expiring of spares*. Lack of cover corresponds to a failure mode, in which a new failure event is generated (i.e., a failure of a second component) before the reconfiguration of a spare component is completed. The expiring of spares means, that no more spare components are available.

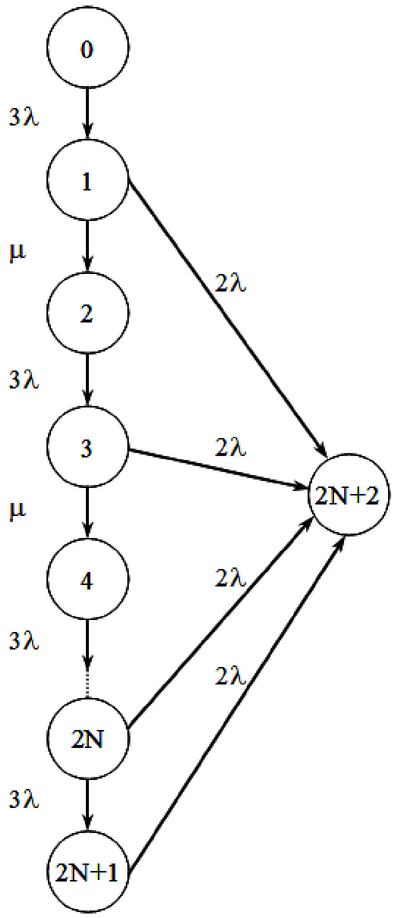

Figure 4. State transition model for TMR heating system

For the actual TRM heating system, the existence of cover is represented by the reconfiguration rate μ, and the components failure rate can be represented either by a constant failure rate λ_C, either by a function of time failure rate of the following type,

$$\lambda(t) = \lambda_C + \frac{\varphi}{\tau}\left(\frac{t}{\tau}\right)^{\varphi-1} \tag{7}$$

where, φ and τ are parameters, which describe the wearing effects over the active components (i.e., the operational systems burners for the present case). It is also assumed, that the spare components are in “stand – by” (or “cold” redundancy mode) and cannot fail during their non-operational time periods. The experimental results for the systems failure mode $Q^S(t)$, for constant and time-dependent failure rates and different values of N are presented respectively in Figure 5 and Figure 6.

The calculations were developed for a mission time of 120 hrs, and systems parameters $\lambda_C = 0{,}011 \cdot \mathrm{hr}^{-1}$; $\varphi = 2{,}8$; $\tau = 70$ hrs; $\mu = 80\ \mathrm{hr}^{-1}$. The results are presented for confidence limits of 75 %. Two specific cases must be considered during the analysis of the ratio μ/λ:

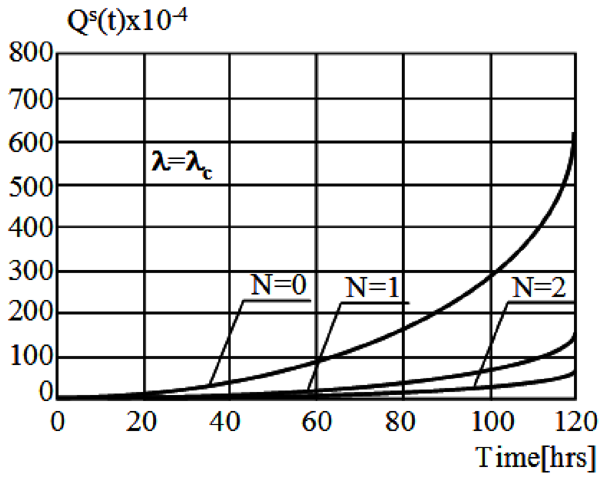

Figure 5. Failure modes for a TRM heating systems with constant failure rate

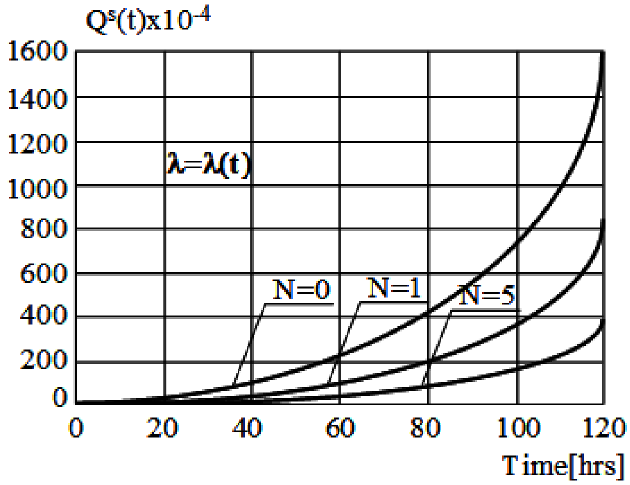

Figure 6. Failure modes for a TRM heating systems with time dependent failure rate

a) Case A: $\mu/\lambda = 0$ (or $\mu = 0$). This case is identical to the failure mode with $N = 0$, i.e., the system cannot be repaired.

b) Case B: $\mu/\lambda \neq 0$. If the value of the ratio increases, the probability of the system failure due to a lack of cover decreases. For the extreme case, when $\mu/\lambda \neq \infty$, the reconfiguration of the system is immediate and the only failure mode of the system is the expiring of the spares. For both cases the experimental results match with the analytical solutions. The developed experimental presentation allows the treatment of general components dependencies the modelling of the components wear and the analysis of variety repair models. The developed experiments are also capable to treat hybrid TRM heating systems (based on inhomogeneous Markov models and Monte Carlo simulation), which can fail in two different failure modes. It must be noted also, that even large ratios for μ/λ do not generate any difficulties.

4. Conclusions

A hybrid methodology composed of a Monte Carlo simulation and Markov state-space models is developed and applied for reliability evaluation of a triple modular redundant (i.e., TMR) heating system. The so-developed models, structures and experiments are applied under real operating conditions in a tank heating system of a hot dip zinc galvanizing facility.

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