Steady state behavior and maintenance planning of bleaching system in a paper plant

R. Khanduja*1; P. C. Tewari2; D. Kumar3

Assistant Professor, Department of Mechanical Engineering, JMIT, Radaur, Haryana, India
Assistant Professor, Department of Mechanical Engineering, NIT, Kurukshetra, Haryana, India
Professor, Department of Mechanical & Industrial Engineering, Indian Institute of Technology, Uttaranchal, India

Received: 17 March 2008; Revised: 2 September 2008; Accepted: 12 February 2009

Abstract: This paper presents the steady state behavior and maintenance planning of the bleaching system in a paper plant. The paper plant comprises of various systems including feeding, chipping, digesting, washing, bleaching, screening, stock preparation and paper making, etc. One of the most important functionaries of a paper plant, on which quality of paper depends, is the bleaching system, where removal of coloring constituents is done to obtain the desired degree of brightness. The bleaching system consists of two subsystems A and B arranged in series with two states; good and failed. The mathematical modeling is carried out on the basis of Markov birth-death process using a probabilistic approach. An expression for steady state availability is also developed. Based upon the maintenance data available from medium sized paper plant, the effect of each working unit on the system availability behavior has been explained. In this regard, the behavioral chart for bleaching system has been given. Besides, a maintenance schedule has also been suggested and utilized for the purpose of maintenance planning of the bleaching system in a paper plant. The findings of this paper have been discussed with the concerned plant personnel and found to be highly beneficial for enhancing the performance level of the plant concerned.

Keywords: Bleaching system; Steady state availability; Maintenance planning

1. Introduction

Nowadays, owing to automation, in the process industries maintenance is considered as an integral part of the production process. It is done by optimal utilization of maintenance resources and by ensuring high availability level. For increasing the productivity and availability of equipment, sub-systems and systems in operation must be maintained at the highest order. To achieve high production goals, the systems should remain operative (run failure free) for maximum possible time duration. But practically these systems are subject to random failures due to the poor design, wrong manufacturing techniques, lack of operative skills, poor maintenance, overload, delay in starting maintenance, human errors, etc. These causes lead to non-availability of an industrial system resulting into improper utilization of resources (man, machine, material, money, time, etc.). So, to achieve high production volumes / targets, there should be highest possible system availability (long-run system availability).

2. Literature Review

The available literature reflects that several approaches have been used to analyze the steady state behavior of various systems. The Markovian approach has been frequently used by Dhillon et al. (1981) for the availability analysis, using exponential distribution for failure and repair times. Kumar et al. (1988, 1989 and 1993) dealt with reliability, availability and operational behavior analysis for different systems in the paper plant. Kumar et al. (1988 and 1993) dealt with maintenance planning for the systems in fertilizer and thermal plants. Shooman (1996) suggested different methods for the reliability computations of systems with dependent failures. Sunand et al. (1999) dealt with maintenance management for Ammonia synthesis system in fertilizer plant. Tewari et al. (2003) dealt with the determination of availability for the systems with elements exhibiting independent failures and repairs or the operation with standby elements for sugar industry. They also dealt with mathematical modeling and behavioral analysis for a refining system of a sugar industry using Genetic Algorithm. Sunand et al. (2007) discussed simulated availability of CO2 cooling system in a fertilizer plant. Rajiv et al. (2008) have developed performance evaluation system for screening unit of paper plant. They also dealt with availability analysis of bleaching system of a paper plant.

*Corresponding Author Email: rajiv_khanduja@rediffmail.com
Tel.: +91 9896237144
3. Theory

A probabilistic analysis of the system under given operative conditions is helpful in the design modification for minimum failure run of the system and thus to optimize the system performance. The paper plants are complex and repairable engineering systems, comprising of various units namely chipping, cooking, washing, bleaching, screening, stock preparation, paper production etc.

These units are generally arranged in hybrid configuration. The important process of a paper industry, upon which the quality of paper depends, is bleaching process. In the process of paper formation, the chips from storage are fed in to a digester to form the pulp which is processed through subsystems called knotter, decker, opener, washers, etc. Then the washed pulp is kept in a chamber where chlorine at a controlled rate is pressed through the pulp for a few hours.

The pulp is passed over a filter and washer in four stages to get chlorine free white pulp. This pulp is again processed through screen and cleaner for final removal of chlorine, knots and other undesirable materials. The pulp so prepared is stored in a chamber.

3.1. System Description

The bleaching system comprises of two main subsystems, which are as follows:

(1) The filter ($A_i$) consists of four units to remove chlorine from the pulp received from the washing process. The failure of anyone causes the complete failure.

(2) The washer ($B_j$) consists of four units to wash the bleached pulp and open the fibers through combing action. The failure of anyone causes the complete failure.

4. Experiment

4.1. Assumptions and notations

The transition diagram (Figure 1) of bleaching system shows the two states, the system can acquire. Based on Markov process, a performance evaluating model has been developed. The assumptions and notations associated with the transition diagram of bleaching system are as follows:

4.1.1. Assumptions

(1) Failure/repair rates are constant over time and statistically independent.

(2) A repaired unit is good as new, performance wise for a specified duration.

(3) Sufficient repair facilities are available as and when required.

(4) Standby units are of the same nature as that of active units.

(5) System may work at a reduced capacity.

(6) Service includes repair and/or replacement.

(7) There are no simultaneous failures.

4.1.2. Notations

$A_i B_j$ Represent good working states of respective filter and washer,

$a_i b_j$ Represent failed states of respective filter and washer,

$\lambda_i, \mu_2$ Respective mean constant failure rates of $A_i B_j$,

$\mu_1, \mu_2$ Respective mean constant repair rates of $a_i b_j$,

$\frac{d}{dt}$ Represents derivative w.r.t ‘t’,

$P_i(t)$ State probability that the system is in $i^{th}$ state at time $t$,

4.2. Behavioral chart

The operating behavior of each subsystem depicted in table 1.

4.3. Mathematical modeling

The difference differential equations associated with the transition diagram (Figure 1) of the bleaching system are as follows:

$$(d/dt + 4 \sum_{j=1}^{2} \lambda_j) P_0(t) = \sum_{j=1}^{2} \mu_j P_j(t)$$

$$+ \sum_{j=1}^{2} \mu_j P_{j+2}(t) + \sum_{j=1}^{2} \mu_j P_{j+4}(t)$$

$$+ \sum_{j=1}^{2} \mu_j P_{j+6}(t)$$  \hspace{1cm} (1)
Steady state behavior and maintenance planning of ...

\[
(d/dt + \mu_i) P_i(t) = \lambda_i P_k(t)
\]

(2)

Where \( k = 0, i = 1,3,5,7 \)

\[
(d/dt + \mu_2) P_i(t) = \lambda_2 P_k(t)
\]

(3)

Where \( k = 0, i = 2,4,6,8 \)

With initial conditions at time \( t = 0 \),

\[
P_i(t) = \begin{cases} 
  1 & \text{for } i = 0 \\
  0 & \text{for } i \neq 0 
\end{cases}
\]

4.4. Steady state analysis

Since the paper plant is a process industry, its every system should be available for long period. Therefore, steady state behavior of the system can be analyzed by setting \( t \rightarrow \infty \) and \( d/dt \rightarrow 0 \). The limiting probabilities from Equations (1) to (3) are:

\[
\sum_{j=1}^{2} \lambda_j p_0 = \sum_{j=1}^{2} \mu_j p_j + \sum_{j=1}^{2} \mu_j p_{j+2}
\]

(4)

\[
\mu_i P_i = \lambda_i P_k
\]

(5)

Where \( k = 0, i = 1,3,5,7 \)

\[
\mu_2 P_i = \lambda_2 P_k
\]

(6)

Where \( k = 0, i = 2,4,6,8 \)

Solving these equations recursively, we get:

\[
P_1 = B_1 P_0 \quad P_2 = B_2 P_0 \quad P_3 = B_1 P_0 \\
P_4 = B_3 P_0 \quad P_5 = B_1 P_0 \quad P_6 = B_2 P_0 \\
P_7 = B_1 P_0 \quad P_8 = B_2 P_0
\]

Where \( B_i = \lambda_i / \mu_i \quad i = 1,2. \)

Use of Normalizing condition i.e. sum of all the state probabilities is equal to one

\[
\sum_{i=0}^{8} P_i = 1
\]

gives:

\[
P_0 = 1/(1 + 4B_1 + 4B_2)
\]

Now, the steady state availability (Av.) of the bleaching system is given by summation of all the full working and reduced capacity states probabilities.

\[
Av = 1/(1 + 4B_1 + 4B_2)
\]

4.5. Behavior analysis of bleaching system

By critically examining the process of bleaching system and taking the relevant values of the failure and repair rates of each subsystem, the effect of these parameters on the system availability has been shown in Tables 2 and 3.

5. Result and discussions

Table 2 reveals the effect of failure and repair rates of filter subsystem on the availability of the bleaching system of the paper plant concerned. It is observed that for some known values of failure rate \( \lambda_2 = 0.01 \) and repair rate \( \mu_2 = 0.25 \) of the washer subsystem, as failure rate of filter subsystem increases from 0.01 (once in 100 hrs) to 0.09 (once in 11.11 hrs), the system availability decreases sharply from 0.70093 to 0.28089 i.e. about 42%. Similarly as repair rate of filter subsystem increases from 0.15 (once in 6.66 hrs) to 0.55 (once in 1.81 hrs), the system availability increases from 0.70093 to 0.81120 i.e. about 11%. Table 3 shows the effect of failure and repair rates of washer subsystem on the availability of bleaching system. It is observed that for some known values of failure rate \( \lambda_1 = 0.01 \) and repair rate \( \mu_1 = 0.35 \) of filter subsystem, as failure rate of washer subsystem increases from 0.01 (once in 100 hrs) to 0.09 (once in 11.11 hrs), the system availability decreases drastically from 0.72413 to 0.28455 i.e. about 44%. Similarly as repair rate of washer subsystem increases from 0.15 (once in 6.66 hrs) to 0.55 (once in 1.81 hrs), the system availability increases considerably from 0.72413 to 0.84242 i.e. about 12%. From tables 2 and 3, it is observed that for any level of the system availability, various combination of failure and repair times are possible and we have to restrict these system parameters to practically feasible combinations. Besides, a proper maintenance schedule has also been prepared for the bleaching system of the paper plant concerned, which is given in table 4. This maintenance schedule might be helpful to determine the failure and repair behavior for various components and subsystems. On this basis, the effective maintenance planning of the bleaching system may be carried out in future.
Table 1: Nature and behavior of each subsystem.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Behavior</th>
<th>Effect/occurrence</th>
<th>Remedy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subsystem A</td>
<td>Major failure</td>
<td>Rare</td>
<td>By regular check of oil level in gear box</td>
</tr>
<tr>
<td></td>
<td>Minor failure</td>
<td>Often</td>
<td>Repaired by skilled worker</td>
</tr>
<tr>
<td></td>
<td>Performance Degradation</td>
<td>Yes</td>
<td>Skilled worker rectifies and repair</td>
</tr>
<tr>
<td></td>
<td>Inconvenience in operation</td>
<td>Yes</td>
<td>Maintain the vacuum</td>
</tr>
<tr>
<td>Subsystem B</td>
<td>Major failure</td>
<td>Very rare</td>
<td>Shut the system and repair</td>
</tr>
<tr>
<td></td>
<td>Minor failure</td>
<td>Rare</td>
<td>Easily repaired by skilled worker</td>
</tr>
<tr>
<td></td>
<td>Performance Degradation</td>
<td>Possible</td>
<td>Repair is the only solution</td>
</tr>
<tr>
<td></td>
<td>Inconvenience in operation</td>
<td>None</td>
<td>....</td>
</tr>
</tbody>
</table>

Table 2: Effect of failure and repair rates of the filter subsystem on bleaching system availability.

<table>
<thead>
<tr>
<th>( \lambda_1 )</th>
<th>( \mu_1 )</th>
<th>0.15</th>
<th>0.25</th>
<th>0.35</th>
<th>0.45</th>
<th>0.55</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>0.70093</td>
<td>0.75757</td>
<td>0.78475</td>
<td>0.80071</td>
<td>0.81120</td>
<td>( \lambda_2 = 0.01 )</td>
</tr>
<tr>
<td>0.03</td>
<td>0.51020</td>
<td>0.60975</td>
<td>0.66540</td>
<td>0.70093</td>
<td>0.72550</td>
<td>( \mu_2 = 0.25 )</td>
</tr>
<tr>
<td>0.05</td>
<td>0.40106</td>
<td>0.51020</td>
<td>0.57756</td>
<td>0.62326</td>
<td>0.65632</td>
<td></td>
</tr>
<tr>
<td>0.07</td>
<td>0.33039</td>
<td>0.43859</td>
<td>0.51020</td>
<td>0.56109</td>
<td>0.59912</td>
<td></td>
</tr>
<tr>
<td>0.09</td>
<td>0.28089</td>
<td>0.38461</td>
<td>0.45691</td>
<td>0.51020</td>
<td>0.55150</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Effect of failure and repair rates of the washer subsystem on bleaching system availability.

<table>
<thead>
<tr>
<th>( \lambda_2 )</th>
<th>( \mu_2 )</th>
<th>0.15</th>
<th>0.25</th>
<th>0.35</th>
<th>0.45</th>
<th>0.55</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>0.72413</td>
<td>0.78475</td>
<td>0.81395</td>
<td>0.83113</td>
<td>0.84242</td>
<td>( \lambda_2 = 0.01 )</td>
</tr>
<tr>
<td>0.03</td>
<td>0.52238</td>
<td>0.62724</td>
<td>0.66827</td>
<td>0.72413</td>
<td>0.75048</td>
<td>( \mu_2 = 0.35 )</td>
</tr>
<tr>
<td>0.05</td>
<td>0.40856</td>
<td>0.52238</td>
<td>0.59322</td>
<td>0.64154</td>
<td>0.67662</td>
<td></td>
</tr>
<tr>
<td>0.07</td>
<td>0.33546</td>
<td>0.44757</td>
<td>0.52238</td>
<td>0.57586</td>
<td>0.61600</td>
<td></td>
</tr>
<tr>
<td>0.09</td>
<td>0.28455</td>
<td>0.39149</td>
<td>0.46666</td>
<td>0.52238</td>
<td>0.56534</td>
<td></td>
</tr>
</tbody>
</table>
6. Conclusion

It can thus be concluded that the steady state behavior of bleaching system can be analyzed with the help of availability model developed. The behavior analysis has also been explained by means of availability Tables (2,3). These availability tables have shown the effect of failure and repair rates of various subsystems on the steady state availability of bleaching system. Besides, the maintenance planning has also been suggested with the help of maintenance schedule, given in Table 4, mainly to enhance the overall availability of bleaching system of the paper plant concerned. The results obtained from these tables also reveal that the repairs in the subsystems of bleaching system should be accorded in the order of preference as given in Table 5.

Table 4: Maintenance schedule.

<table>
<thead>
<tr>
<th>Schedule</th>
<th>Component</th>
<th>Check/Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily</td>
<td>All stationary &amp;</td>
<td>Regular checks by maintenance</td>
</tr>
<tr>
<td></td>
<td>rotary equipment, washer</td>
<td>department</td>
</tr>
<tr>
<td>Weekly</td>
<td>Pumps</td>
<td>Monitoring unbalance,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>misalignment, looseness</td>
</tr>
<tr>
<td></td>
<td>Bearings</td>
<td>Lubricate if required</td>
</tr>
<tr>
<td></td>
<td>Filter</td>
<td>Check the leakage</td>
</tr>
<tr>
<td></td>
<td>Gearbox</td>
<td>Check the oil level</td>
</tr>
<tr>
<td>Fortnightly</td>
<td>Pumps</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Check the vibration level</td>
</tr>
<tr>
<td></td>
<td>Bearings</td>
<td>Check the temperature</td>
</tr>
<tr>
<td>Quarterly</td>
<td>Pumps</td>
<td>Greasing, Sleeve and Coupling</td>
</tr>
<tr>
<td>Annual</td>
<td></td>
<td>inspection</td>
</tr>
<tr>
<td>(Two weeks shut down)</td>
<td></td>
<td>Overhauling of stationary &amp;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>rotary equipment through</td>
</tr>
<tr>
<td></td>
<td></td>
<td>planned maintenance schedule.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>By checking all the components</td>
</tr>
<tr>
<td></td>
<td></td>
<td>of each unit</td>
</tr>
</tbody>
</table>

Table 5: Repair priority of each subsystem.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Increase in failure rate</th>
<th>Decrease in availability</th>
<th>Increase in repair time</th>
<th>Increase in availability</th>
<th>Repair priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter</td>
<td>0.01-0.09</td>
<td>42%</td>
<td>0.15-0.55</td>
<td>11%</td>
<td>II</td>
</tr>
<tr>
<td>Washer</td>
<td>0.01-0.09</td>
<td>44%</td>
<td>0.15-0.55</td>
<td>12%</td>
<td>I</td>
</tr>
</tbody>
</table>


References


Tewari, P. C.; Kumar, D. and Mehta, N. P., (2003), Decision support system of refining system of sugar plant. Journal of Institution of Engineers (India), 84, 41-44.
