Chapter 2

Risk assessment of a hydroelectric dam with parallel redundant turbine
2.1 INTRODUCTION
This chapter deals with the risk assessment of a hydroelectric dam. Hydroelectric dam produces electric power with the help of water collected in a pond. The whole system consists of five major parts and these are named here as:

(i) Subsystem A : Reservoir, intake gate
(ii) Subsystem B : Penstock
(iii) Subsystem C : Turbine
(iv) Subsystem D : Generator
(v) Subsystem E : Power house.

The system has been shown in fig -1(a). The subsystem A takes the water and sends it to subsystem B (Penstock). By the movement of this water, we rotate the turbine and by rotation of turbine, generator produces electricity. The so produced electric power can be stored at power house and also can further distribute to various territories. Here, in this model, the author has been taken one extra parallel redundant turbine to improve system’s overall performance. On failure of any one turbine, the whole system works in reduced efficiency state. The whole system can fail due to failure of any of its subsystems. All failures follow exponential time distribution whereas all repairs follow general time distribution.

Since, the system under consideration in Non-Markovian, the author has used supplementary variables to formulate mathematical model of the system. This model has been solved further by taking help of Laplace transform. In order to risk assessment of the system, we have obtained reliability function, M.T.T.F. and availability function for considered system. A particular case, when all repairs follow exponential time distribution, and long-run behaviour of system have also been computed to improve practical utility of the model. Graphical illustration followed by a numerical computation has also been appended at the end to highlight important results of present study.

2.2 ASSUMPTIONS
This model is based on following assumptions:

(1) Initially the whole system is good and operable.
(2) After failure, repair facilities can be provided immediately.
(3) All failures follow exponential time distribution and are S-independent.
(4) All repairs follow general time distribution and are perfect.
(5) Nothing can fail from a failed state.
(6) On failure of any one turbine (subsystem C), the whole system works in reduced efficiency.

Fig-1(a): System Configuration
Fig-1(b): Transition-state diagram

States:  
- Good  
- Degraded  
- Failed
2.3 LIST OF NOTATIONS

\[ \alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5 \] : Failure rates of subsystems A, B, C, D and E respectively.

\[ \psi_1(x) \Delta \text{ etc.} \] : First order probability that subsystem A can be repaired in the time interval \((x, x+\Delta)\), conditioned that it was not repaired upto time \(x\).

\[ \psi_{3,3}(u) \Delta \] : First order probability that both the units of subsystem C can be repaired in the time interval \((u, u+\Delta)\), conditioned that they were not repaired upto time \(u\).

\[ P_0(t) \] : \(\text{Pr}\{\text{at time } t, \text{ whole system is operable}\}\).

\[ P_1(x,t) \Delta \text{ etc} \] : \(\text{Pr}\{\text{at time } t, \text{ system is failed due to failure of subsystem A}\}.\) Elapsed repair time lies within \((x, x+\Delta)\).

\[ P_3(z,t) \Delta \] : \(\text{Pr}\{\text{at time } t, \text{ system is degraded due to failure of any one component of subsystem C}\}. \text{ Elapsed repair time lies within } (z, z+\Delta)\).

\[ P_{3,1}(x,t) \Delta \text{ etc} \] : \(\text{Pr}\{\text{at time } t, \text{ system is failed due to failure of subsystem A while one component of subsystem C has already failed}\}. \text{ Elapsed repair time of subsystem A lies within } (x, x+\Delta)\).

\[ \overline{P}(s) \] : Laplace transform (L.T.) of function \(P(t)\).

M.T.T.F. : Mean time to failure.

\[ S_i(j) \] : \(\psi_i(j) \exp\{\int_{-\infty}^{j} \psi_i(j) \, dj\}, \forall i \text{ and } j.\)

\[ D_i(j) \] : \([1 - S_i(j)]^j, \forall i \text{ and } j.\)

2.4 FORMULATION OF MATHEMATICAL MODEL

Using continuity argument and limiting procedure, we obtain the following set of difference-differential equations, governing the behaviour of considered system, discrete in space and continuous in time:

\[
\left[ \frac{d}{dt} + \sum_{i=1}^{5} \alpha_i + h_i \right] P_0(t) = \int_0^x P_1(x,t) \psi_1(x) \, dx + \int_0^y P_2(y,t) \psi_2(y) \, dy + \int_0^z P_3(z,t) \psi_3(z) \, dz \\
+ \int_0^m P_4(m,t) \psi_4(m) \, dm + \int_0^n P_5(n,t) \psi_5(n) \, dn + \int_0^k P_6(k,t) \psi_6(k) \, dk \\
+ \int_0^u P_{3,1}(u,t) \psi_{3,1}(u) \, du
\]  

...(1)
\[
\left[ \frac{\partial}{\partial j} + \frac{\partial}{\partial t} + \psi_j(j) \right] P_i(j,t) = 0 \\
i = 1,2,4,5 \text{ and } j = x, y, m, n \text{ respectively.}
\]

\[
\left[ \frac{\partial}{\partial z} + \frac{\partial}{\partial t} + \sum_{i=1}^{5} \alpha_i + h_i + \psi_j(z) \right] P_z(z,t) = 0 \\
\]

\[
\left[ \frac{\partial}{\partial j} + \frac{\partial}{\partial t} + \psi_j(j) \right] P_{3,j}(j,t) = 0
\]

\[
i = 1,2,4,5 \text{ and } j = x, y, m, n \text{ respectively.}
\]

\[
\left[ \frac{\partial}{\partial u} + \frac{\partial}{\partial t} + \psi_{3,3}(u) \right] P_{3,3}(u,t) = 0 \\
\]

\[
\left[ \frac{\partial}{\partial k} + \frac{\partial}{\partial t} + \psi_{k}(k) \right] P_k(k,t) = 0
\]

**Boundary conditions are:**

\[
P_i(0,t) = \alpha_i P_0(t) \quad , \ i = 1, 2, 4 \text{ and } 5 \\
\]

\[
P_i(0,t) = \alpha_i P_0(t) + \int_0^\infty P_{3,j}(x,t)\psi_{1}(x)dx + \int_0^\infty P_{3,2}(y,t)\psi_{2}(y)dy
\]

\[
+ \int_0^\infty P_{3,4}(m,t)\psi_{4}(m)dm + \int_0^\infty P_{3,5}(n,t)\psi_{5}(n)dn \\
\]

\[
P_{3,i}(0,t) = \alpha_i P_3(t) \quad , \ i = 1, 2, 4 \text{ and } 5 \\
\]

\[
P_{3,3}(0,t) = \alpha_3 P_3(t) \\
\]

\[
P_h(0,t) = h_i P_0(t) + h_i P_i(t) \\
\]

**Initial conditions are:**

\[
P_0(0) = 1, \text{ otherwise zero.} \\
\]

**2.5 SOLUTION OF THE MODEL**

Taking Laplace transforms of equations (1) through (11) subjected to initial conditions (12), we have:

\[
\left[ s + \sum_{i=1}^{5} \alpha_i + h_i \right] \bar{P}_0(s) = 1 + \int_0^\infty \bar{P}_1(x,s)\psi_1(x)dx + \int_0^\infty \bar{P}_2(y,s)\psi_2(y)dy + \int_0^\infty \bar{P}_3(z,s)\psi_3(z)dz
\]

\[
+ \int_0^\infty \bar{P}_4(m,s)\psi_4(m)dm + \int_0^\infty \bar{P}_5(n,s)\psi_5(n)dn + \int_0^\infty \bar{P}_6(k,s)\psi_6(k)dk
\]
\[ + \int_0^\infty \bar{P}_{3,3}(u, s)\psi_{3,3}(u)du \]  

\[ \left[ \frac{\partial}{\partial j} + s + \psi_j(j) \right] \bar{P}_i(j, s) = 0 \]  

\[ i = 1, 2, 4, 5 \text{ and } j = x, y, m, n \text{ respectively.} \]  

\[ \left[ \frac{\partial}{\partial \zeta} + s + \sum_{i=1}^5 \alpha_i + h_2 + \psi_3(\zeta) \right] \bar{P}_3(\zeta, s) = 0 \]  

\[ \left[ \frac{\partial}{\partial j} + s + \psi_j(j) \right] \bar{P}_{3,i}(j, s) = 0 \]  

\[ i = 1, 2, 4, 5 \text{ and } j = x, y, m, n \text{ respectively.} \]  

\[ \left[ \frac{\partial}{\partial u} + s + \psi_{3,3}(u) \right] \bar{P}_{3,3}(u, s) = 0 \]  

\[ \left[ \frac{\partial}{\partial k} + s + \psi_k(k) \right] \bar{P}_h(k, s) = 0 \]  

\[ \bar{P}_i(0, s) = \alpha_i \bar{P}_0(s) \text{, } i = 1, 2, 4 \text{ and } 5 \]  

\[ \bar{P}_3(0, s) = \alpha_3 \bar{P}_0(s) + \int_0^\infty \bar{P}_{3,3}(x, s)\psi_1(x)dx + \int_0^\infty \bar{P}_{3,2}(y, s)\psi_2(y)dy \]  

\[ + \int_0^\infty \bar{P}_{3,4}(m, s)\psi_4(m)dm + \int_0^\infty \bar{P}_{3,5}(n, s)\psi_5(n)dn \]  

\[ \bar{P}_{3,i}(0, s) = \alpha_i \bar{P}_3(s) \text{, } i = 1, 2, 4 \text{ and } 5 \]  

\[ \bar{P}_{3,3}(0, s) = \alpha_3 \bar{P}_3(s) \]  

\[ \bar{P}_h(0, s) = h_1 \bar{P}_0(s) + h_2 \bar{P}_3(s) \]  

Now solving equation (14), by using boundary condition (19), we obtain
\[ \bar{P}_i(j, s) = \alpha_i \bar{P}_0(s) \exp\left[ -s j - \int \psi_j(j) dj \right] \]
integrating this again w.r.t. \( j \) from 0 to \( \infty \), we get
\[ \bar{P}_i(s) = \alpha_i \bar{P}_0(s) \frac{1 - S_i(s)}{s} \]
or \[ \bar{P}_i(s) = \alpha_i \bar{P}_0(s) D_i(s) \]  

where \( i = 1, 2, 4 \text{ and } 5 \)

Similarly, solving equation (18) subjected to (23), we have
\[ \overline{P}_n(k, s) = \overline{P}_n(0, s) \exp \left\{ -sk - \int \psi_n'(k) \, dk \right\} \]

\[ \Rightarrow \overline{P}_n(s) = \left[ h_1 \overline{P}_0(s) + h_2 \overline{P}_3(s) \right] D_n(s) \]  

...(25)

Now solving differential equation (16) subjected to boundary condition (21), we obtain

\[ \overline{P}_{3,i}(j, s) = \alpha_i \overline{P}_3(s) \exp \left\{ -sj - \int \psi_i'(j) \, dj \right\} \]

\[ \Rightarrow \overline{P}_{3,i}(s) = \alpha_i \overline{P}_3(s) D_i(s) \]  

...(26)

where, \( i = 1, 2, 4 \) and 5

Integrating (17) together with boundary condition (22), we get

\[ \overline{P}_{3,3}(u, s) = \alpha_3 \overline{P}_3(s) \exp \left\{ -su - \int \psi_{3,3}(u) \, du \right\} \]

\[ \Rightarrow \overline{P}_{3,3}(s) = \alpha_3 \overline{P}_3(s) D_{3,3}(s) \]  

...(27)

Simplifying (20) with the help of relevant relations, we have

\[ \overline{P}_3(0, s) = \alpha_3 \overline{P}_0(s) + \overline{P}_3(s) \left[ \alpha_1 \overline{S}_1(s) + \alpha_2 \overline{S}_2(s) + \alpha_4 \overline{S}_4(s) + \alpha_5 \overline{S}_5(s) \right] \]

...(28)

Now solving (15) together with (28), we obtain

\[ \overline{P}_3(z, s) = \overline{P}_3(0, s) \exp \left\{ -\left( s + \sum_{i=1}^{5} \alpha_i + h_2 \right) z - \int \psi_3(z) \, dz \right\} \]

\[ \Rightarrow \overline{P}_3(s) = \overline{P}_3(0, s) D_3 \left( s + \sum_{i=1}^{5} \alpha_i + h_2 \right) \]

or, \[ \overline{P}_3(s) = \frac{\alpha_3 \overline{P}_0(s) D_3 \left( s + \sum_{i=1}^{5} \alpha_i + h_2 \right)}{1 - \sum_{i=1}^{5} \alpha_i \overline{S}_i(s) - \alpha_3 \overline{S}_3(s) \left[ s + \sum_{i=1}^{5} \alpha_i + h_2 \right]} \]

...(29)

or, \[ \overline{P}_3(s) = A(s) \overline{P}_0(s) \]

Finally, simplifying (13) subjected to related expressions, we obtain

\[ \overline{P}_0(s) = \frac{1}{B(s)} \]

Thus, we obtain the following L.T. of probabilities of various states of fig- 1(b), in terms of \( B(s) \):

\[ \overline{P}_0(s) = \frac{1}{B(s)} \]  

...(30)

\[ \overline{P}_i(s) = \frac{\alpha_i D_i(s)}{B(s)} \]  

for \( i = 1, 2, 4 \) and 5  

...(31)
\[ P_3(s) = \frac{A(s)}{B(s)} \]  \hspace{1cm} \text{...(32)}

\[ P_{3,i}(s) = \frac{\alpha_i A(s) D_i(s)}{B(s)} ; \quad \text{for } i = 1, 2, 4 \text{ and } 5 \]  \hspace{1cm} \text{...(33)}

\[ P_{3,3}(s) = \frac{\alpha_3 A(s) D_{3,3}(s)}{B(s)} \]  \hspace{1cm} \text{...(34)}

\[ P_h(s) = \frac{1}{B(s)} [h_i + h_2 A(s)] D_h(s) \]  \hspace{1cm} \text{...(35)}

\[ \alpha_3 D_3 \left( s + \sum_{i=1}^{5} \alpha_i + h_2 \right) \]

where,  \[ A(s) = \frac{1}{1 - \left[ \sum_{i=1}^{5} \alpha_i S_i(s) - \alpha_3 S_3(s) \right] D_3 \left( s + \sum_{i=1}^{5} \alpha_i + h_2 \right)} \]  \hspace{1cm} \text{...(36)}

and  \[ B(s) = \frac{s[1 + \alpha_1 D_1(s) + \alpha_2 D_2(s) + \alpha_4 D_4(s) + \alpha_5 D_5(s)] + \alpha_3 + h_1}{- \left[ h_i + h_2 A(s) \right] S_h(s) - \alpha_3 A(s) S_{3,3}(s)} - \left[ \alpha_3 + A(s) \left( \alpha_1 S_1(s) + \alpha_2 S_2(s) + \alpha_4 S_4(s) + \alpha_5 S_5(s) \right) \right] S_3 \left( s + \sum_{i=1}^{5} \alpha_i + h_2 \right) \]  \hspace{1cm} \text{...(37)}

It is worth noticing that

Sum of equations (30) through (35) = \[ \frac{1}{s} \]  \hspace{1cm} \text{...(38)}

**2.6 LONG-RUN BEHAVIOUR OF CONSIDERED SYSTEM**

Using final value theorem of Laplace transform, viz., \( \text{Lim } P(t) = \text{Lim } t \to \infty \) \( \frac{1}{s} P(s) = P \) (say),

provided limit on left exists, we obtain the following long-run behaviour of considered system from equations (30) through (35):

\[ P_0 = \frac{1}{B'(0)} \]  \hspace{1cm} \text{...(39)}

\[ P_i = \frac{\alpha_i M_i}{B'(0)} ; \quad \text{for } i = 1, 2, 4 \text{ and } 5 \]  \hspace{1cm} \text{...(40)}

\[ P_3 = \frac{A(0)}{B'(0)} \]  \hspace{1cm} \text{...(41)}

\[ P_{3,i} = \frac{\alpha_i A(0) M_i}{B'(0)} ; \quad \text{for } i = 1, 2, 4 \text{ and } 5 \]  \hspace{1cm} \text{...(42)}

\[ P_{3,3} = \frac{\alpha_3 A(0) M_{3,3}}{B'(0)} \]  \hspace{1cm} \text{...(43)}
\[ P_h = \frac{1}{B'(0)} [h_1 + h_2 A(0)] M_h \] \hspace{1cm} \ldots(44)

where, \( A(0) = \frac{\alpha_3 \left[ 1 - \overline{S}_1 \left( \sum_{i=1}^5 \alpha_i + h_2 \right) \right]}{\alpha_3 + h_2 + \left( \sum_{i=1}^5 \alpha_i - \alpha_3 \right) \overline{S}_1 \left( \sum_{i=1}^5 \alpha_i + h_2 \right) } \) \hspace{1cm} \ldots(45)

\[ B'(0) = \left[ \frac{d}{ds} B(s) \right]_{s=0} \] \hspace{1cm} \ldots(46)

and \( M_i = -\overline{S}_i'(0) \) = Mean time to repair \( i^{th} \) failure. \hspace{1cm} \ldots(47)

### 2.7 PARTICULAR CASE

**When all repairs follow exponential time distribution**

In this case, setting \( \overline{S}_i(j) = \psi_i/j + \psi_i \) for all \( i \) and \( j \), in equations (30) through (35), we obtain the following L.T. of different state probabilities of fig-1(b):

\[ \overline{P}_0(s) = \frac{1}{E(s)} \] \hspace{1cm} \ldots(48)

\[ \overline{P}_i(s) = \frac{\alpha_i}{E(s)(s + \psi_i)} ; \quad \text{For} \ i = 1, 2, 4 \text{ and } 5 \] \hspace{1cm} \ldots(49)

\[ \overline{P}_3(s) = \frac{F(s)}{E(s)} \] \hspace{1cm} \ldots(50)

\[ \overline{P}_{3,i}(s) = \frac{\alpha_i F(s)}{E(s)(s + \psi_i)} ; \quad \text{For} \ i = 1, 2, 4 \text{ and } 5 \] \hspace{1cm} \ldots(51)

\[ \overline{P}_{3,3}(s) = \frac{\alpha_3 F(s)}{E(s)(s + \psi_{3,3})} \] \hspace{1cm} \ldots(52)

and \( \overline{P}_h(s) = \frac{1}{E(s)} \left[ h_1 + h_2 F(s) \right] \frac{1}{(s + \psi_h)} \) \hspace{1cm} \ldots(53)

where, \( F(s) = \frac{\alpha_3}{\left[ s + \sum_{i=1}^5 \alpha_i + h_2 + \psi_3 \right] - \frac{\sum_{i=1}^5 \alpha_i \psi_i}{s + \psi_i} - \frac{\alpha_3 \psi_3}{s + \psi_3} } \) \hspace{1cm} \ldots(54)
and \[ E(s) = s \left[ 1 + \frac{\alpha_1}{s + \psi_1} + \frac{\alpha_2}{s + \psi_2} + \frac{\alpha_4}{s + \psi_4} + \frac{\alpha_5}{s + \psi_5} \right] + \alpha_3 + h_1 \quad \ldots(55) \]

\[ - \left[ h_1 + h_2 F(s) \right] \frac{\psi_h}{s + \psi_h} - \frac{\alpha_3 F(s)\psi_{3,3}}{s + \psi_{3,3}} \]

\[ - \left[ \alpha_3 + F(s) \left( \frac{\alpha_1 \psi_1}{s + \psi_1} + \frac{\alpha_2 \psi_2}{s + \psi_2} + \frac{\alpha_4 \psi_4}{s + \psi_4} + \frac{\alpha_5 \psi_5}{s + \psi_5} \right) \right] \frac{\psi_3}{s + \sum_{i=1}^{5} \alpha_i + h_2 + \psi_3} \]

### 2.8 Reliability and M.T.T.F. Evaluation

Form equation (30), we obtain the L.T. of reliability function

\[ \bar{R}(s) = \left( s + \sum_{i=1}^{5} \alpha_i + h_2 \right)^{-1} \]

Taking inverse Laplace transform, we get

\[ R(t) = \exp \left\{ - \left( \sum_{i=1}^{5} \alpha_i + h_1 \right) t \right\} \quad \ldots(56) \]

Also, \[ M.T.T.F. = \int_{0}^{\infty} R(t) dt \]

\[ = \frac{1}{\sum_{i=1}^{5} \alpha_i + h_1} \quad \ldots(57) \]

### 2.9 Availability of Considered System

Availability of considered system can be obtained from equations (30) and (32) as:

\[ \bar{P}_{up}(s) = \frac{1}{s + \sum_{i=1}^{5} \alpha_i + h_1} \left[ 1 + \frac{\alpha_3}{s + \sum_{i=1}^{5} \alpha_i + h_2} \right] \]

Taking inverse Laplace transform, we obtain

\[ P_{up}(t) = \left[ 1 + \frac{\alpha_3}{h_2 - h_1} \right] \exp \left\{ - \left( \sum_{i=1}^{5} \alpha_i + h_1 \right) t \right\} - \frac{\alpha_3}{h_2 - h_1} \exp \left\{ - \left( \sum_{i=1}^{5} \alpha_i + h_2 \right) t \right\} \quad \ldots(58) \]

Also,

\[ P_{down}(t) = 1 - P_{up}(t) \quad \ldots(59) \]
2.10 NUMERICAL ILLUSTRATION

For a numerical illustration we consider the values:

\[ \alpha_1 = 0.002, \; \alpha_2 = 0.001, \; \alpha_3 = 0.06, \; \alpha_4 = 0.08, \; \alpha_5 = 0.15, \; h_1 = 0.008, \; h_2 = 0.009 \] and \[ t = 0,1,2,-,-10. \]

Using these values in equations (56), (57) and (58), we compute the table-1, 2 and 3 respectively. The corresponding graphs have been drawn in fig-2, 3 and 4 respectively.
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<th>t</th>
<th>R(t)</th>
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<tr>
<td>10</td>
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**Table-1**

**Reliability Vs Time**

**Fig-2**
### Table-2

<table>
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<th>$h_1$</th>
<th>M.T.T.F.</th>
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<tbody>
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</tr>
</tbody>
</table>

### Fig-3

**M.T.T.F. Vs Human error**

![Graph showing the relationship between M.T.T.F. and human error](image)
<table>
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<tr>
<th>t</th>
<th>$P_{up}(t)$</th>
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</table>

**Table-3**

**Fig-4**
2.11 RESULTS AND DISCUSSION
A critical examination of graphs, shown in fig-2, 3 and 4, yields that reliability and availability of considered system decreases smoothly with the increase in values of time $t$. It should be noted that there are no sudden jumps in the values of $R(t)$ and $P_{up}(t)$. Also M.T.T.F. of considered system decreases catastrophically in the beginning but thereafter it decreases approximately in constant manner.