Degraded Performance Analysis of Phased Mission System

Manmohan Singh¹, M.D. Jaybhaye²*, S.K. Basu³

¹VRDE, Vahan Nagar, Ahmednagar (MS) 414006, manmohanjs@gmail.com
²Prod. Engg. Dept, College of Engineering, Pune-411005, mdj.prod@coep.ac.in
³Prod. Engg. Dept, College of Engineering, Pune-411005, basu_sk@yahoo.com

Abstract

In engineering applications many of the systems are working on the criteria of phased mission system. The success of such system is judged on the basis of its working at each phase of system and its functioning at each level. The total success of system depends on all success paths occurring in the system. While working with the system reliability if the system is in continuous working condition, the components in the system may get degraded due to wear and tear and thus causing the reduction in the successful working of the system. This dynamic change in the failure rates of components will lead to reduction in reliability value of the system. It is very essential to monitor the change in failure rate which lead to change in reliability and to be maintained so as to have the required successful life span of system working. In present paper an attempt is made to analyze the system with and without degrading factors and effect of degrading factor on reliability of system.

Keywords: Reliability, failure rate, degraded, phases

1 Introduction

A common scenario in engineering is that of a system which operates throughout several sequential and distinct periods of time during which the modes and consequences of failure differ from one another. This type of operation is known as a phased mission, and for the mission to be a success the system must successfully operate throughout all of the phases.

D R Prescott, R Remenyte, Prescott, J D Andres and C G Downes (2008) defined a “A Phased Mission is one in which a system is required to perform a number of consecutive and sequential phases & non overlapping time periods”. Leila Mashkat, et. al. (2003) described that Phased Mission System (PMS) are systems supporting missions consisting of multiple, consecutive and non-overlapping operational phases. Xinyu Zang, Hairong Sun and Kishore S. Trivedi (1999) presented a new algorithm for reliability analysis of Phased Mission System (PMS) based on Binary Decision Diagram. The Researcher used phase algorithm to deal with the dependence across the phases and a new BDD operation to incorporate the phase algorithm of PMS. The system may be subjected to different stresses as well as different requirements as it carries out its task(s) over the course of the mission, hence affecting the life of pump component as advised by Parker (2014). Hence, system configuration, success/failure, criteria and component failure parameters may change from phase to phase. S J Dunnett and J D Andrews (2006) mentioned that the methods used for phased mission analysis are dependent upon the reparability of the system during the phases. If the system is non-repairable, fault tree based method offer an efficient solution. For repairable systems Markov methods are used to calculate the mission failure probability. Y Ma and K S Trivedi (1999) developed an algorithm for reliability analysis of phased-mission systems. Liudong Xing and Joanne Bechta Dugan (2002) suggested Generalized Phased Mission System (GPMS) for reliability analysis of phased mission systems.

2 Case Study

The boring machine is mounted on a structural beam which is hinged on vehicle chassis at the rear. The beam along with drilling machine is made vertical within an positional accuracy of 90°±10 min. The articulation operation is carried out with a pair of hydraulic cylinders, which are operated through hydraulic power pack and control valves and “off line oil filtration system “ etc. There are three hydraulic pumps. Out of three pumps, two are operating through vehicle engine PTO and third one is operating through a motor driven system. However, only one pump is operating at a time and other are used as “cold standby”.

The operational sequence for the total system is briefly explained below:-

(i) Step I – Hydraulic Output -Before starting of pump, the hydraulic oil contamination level is to be checked. If contamination level is within acceptable limit i.e. less than NAS 8, then operate the hydraulic power pack. If oil contamination level is more than NAS 8 (for the present case), then operate the Off line Filtration System and check the contamination level, else check the off line filtration system i.e. filter clogging and motor operation etc.
Degraded Performance Analysis of Phased Mission System

(ii) Step II – Auto Leveling of Vehicle Platform - Once the hydraulic output is available from step I, than operate the Auto Leveling system and check the leveling of platform. If the platform level is within specified level limits i.e. ± 10 min then lock the outriggers movement by operating the outriggers sleeve. Else rectify the leveling system. Check again the platform leveling and go to Step III.

(iii) Step III – Articulation of Beam along with Boring Machine - Once the platform is made leveled and stabilized, then articulate the tilt beam along with drilling machine, through a pair of hydraulic cylinders and hydraulic power pack. Check the verticality of the tilt beam to the desired accuracy i.e. ± 10 min, else rectify the system.

The study considered is for Vertical Borer Machine having following three phases for final operation.

(i) Phase I: Hydraulic output - Here the pumps (P_A, P_B, P_C) are operating in parallel.

(ii) Phase II: Auto leveling system - Here, in addition to hydraulic pumps (3 Nos.) outrigger cylinders (OC) and Outrigger cylinder direction control valves (CVO) are also operating.

Phase III: Articulation operation - Here, in addition to hydraulic pumps (3 Nos.), tilt Cylinders (TC) and tilt Cylinder direction control valves (CVT) are also operating. The Reliability Block Diagram for three phases of the system is shown in Fig. 1(a) and the Boring Machine is shown in Fig. 1(b).

![Reliability Block Diagram](image1)

![Boring Machine](image2)

Figures 1(a) Reliability Block Diagram Fig. 1(b) Boring Machine

![Fault Tree Diagram](image3)

Figure 2 Fault Tree Diagram for Phased Mission System
3 Reliability Analysis of Fault Tree Diagram with conventional method

From the reliability block diagram shown in Fig. 1 the “fault tree diagram” (FTA) is constructed using the “event” and “gates” as shown in Fig. 2. The detailed calculations for above along with FTA diagram are given below:-

Probability of Failure for major component

i. Hydraulic Pump: Failure Rate \( \lambda = 10 \times 10^{-6} \) /hr ,
Reliability (R) = e\(^{-\lambda t}\), Considering time (t) for 100 hrs
\[ R = e^{-10 \times 10^{-6} \times 100} = 0.9999004999 \]
Q = Failure probability (Unreliability) = \(1 - R\) = 0.9999999

ii. Outrigger Cylinder (OC): Failure rate = \(1 \times 10^{-6}\) /hr

iii. Similarly, Outrigger cylinder valve : \( \lambda = 1 \times 10^{-6} \) /hr,
\[ Q_{CVO} = 10^{-6} \]

iv. Tilt Cylinder (TC): \( \lambda = 0.5 \times 10^{-6} \) /hr (Being multistage), \( Q_{TC} = 10^{-6} \)

v. Tilt Cylinder Valve (CVT): \( \lambda = 1 \times 10^{-6} \), \( Q_{CVT} = 1 \times 10^{-4} \)

4 Reliability Analysis of FTA under study using Phased Mission Technique

The conventional method for calculating the reliability which is obtained by the multiplication of the reliabilities of each of the individual phases cannot be used for the Phased Mission System since in the conventional system reliability analysis involves the false assumption that the phases are independent and all components are in the working system at the beginning of each phase and so results obtained give an appreciable over prediction of system reliability.

R A La Band and J D Andrews (2004) mentioned that for phased mission system the component failure event in each phase of the fault tree are to be replaced by an OR combination of the failure events that end all preceding phases. For example the pump A in phase II would be represented by the OR of failure of component in phase I \( A_1 \) and in phase II, \( A_2 \) since the component are not repairable. Similarly in phase III the \( P_A \) is having OR gate with three event of failures i.e \( A_3 \). The same method is applied for other two pumps also. This transforms the original multi phase mission into an equivalent single phase mission as shown in Fig. 3.

The overall mission failure in phased mission of FTA is calculated as follows :-

(i) Probability of Pumps failure in Phase Mission for Phase II=\( P_{A1} \times P_{A2} \) x \( P_{B1} \times P_{B2} \) x \( P_{C1} \times P_{C2} \)
Here, \( P_{A1} \times P_{A2} = P_{A1} \times P_{A2} - P_{A1} \times P_{A2} \) Considering same value of failure rate initially,
\[ P_{A1} = P_{A2} = 10^{-3} \]
\[ P_{A1} \times P_{A2} = 10^{-3} \times 10^{-3} \]
\[ = 10^{-6} \]
\[ P_{A1} \times P_{A2} = 1.999 \times 10^{-3} \]
Similarly, \( P_{B1} \times P_{B2} = P_{C1} \times P_{C2} = 1.999 \times 10^{-3} \)

Overall probability of Pumps Failure \( Q_2 \)
\[ Q_2 = 1.999 \times 10^{-3} \times 1.999 \times 10^{-3} \times 1.999 \times 10^{-3} \]
\[ Q_2 = 7.988 \times 10^{-9} \]

(ii) Probability of Pumps failure in Phased Mission \( Q_3 \) for Phase III
Overall probability of Pumps failure \( Q_3 = P_{A1} \times P_{A2} \times P_{A3} \)
\[ Q_3 = P_{A1} \times P_{A2} \times P_{A3} \times P_{A1} \times P_{A2} \times P_{A3} \]

Considering - \( P_{A1} = P_{A2} = P_{A3} = 10^{-3} \)
\[ Q_3 = 2.996999 \times 10^{-3} \]

Similarly, \( P_{B1} \times P_{B2} \times P_{B3} = P_{C1} \times P_{C2} \times P_{C3} = 2.996999 \times 10^{-3} \)
\[ Q_3 = 2.691 \times 10^{-8} \]

Overall Mission Failure of Phased Mission
\[ Q_{Mission} = P(Q_{PhII} \times Q_{PhIII}) \]
\[ P(Q_{PhII}) = (1 - Q_{PhII}) \times (1 - Q_{PhIII}) \]
Where \( Q_{PhII} = 1.999 \times 10^{-9} \)
\[ Q_{Mission} = 3.589 \times 10^{-8} \]

5 Reliability Analysis using Phased Mission Techniques and considering derating of pumps

In this section efforts are made to demonstrate, how the reliability is reduced due to derating of major components in the system here, an example of a hydraulic pump is considered.

The hydraulic pump is selected based on pressure, flow rate and environmental conditions etc. However, the life of the pump, hence reliability of the pump, is effected with duty cycle and many other parameters like fluid conditions, temperature and pressure peaks etc. “Parker” (2014) who is a leading manufacturer of the pump has given the details of pump life in various ranges (4).

Following details are given:–

(i) As the operating pressure is increased the pump life is decreased.
(ii) An average displacement reduction of 15% increase the bearing life by approximately 50%
(iii) As the operating rpm is increased the pump life is decreased.

In the present case study, following derating of pumps have been considered, based on hydraulic loading of pumps in phase II (Auto Leveling) and phase III (Articulation operation). Derating of pump is summarized as follows :-

Phase I - No derating since hydraulic output is at no load
Phase II -10% ( Failure rate is 110% )
Reliability of pumps failure \( Q_2 \):

Probability of Pumps failure (\( Q_2 \)) for Phase II - With De-rating of 10% 
Considering \( \lambda = 1.1 \times 10^{-6} \) (failure rate of each pump), \( \lambda = 1.1 \times 10^{-3} \)
Reliability of pump failure for 100 bar mission time 
\[ P = e^{-1.1 \times 10^{-5} \times 10^{100}} = 0.998900604 \]
\( QP_{A} = 1 - 0.998900604 \)
\( QP_{A1} = 1.0993 \times 10^{-3} \approx 1.1 \times 10^{-3} \)
\( QP_{A2} = 1.1 \times 10^{-3} \)
\( P_{A1} U P_{A2} = QP_{A1} + QP_{A2} - QP_{A1} x QP_{A2} \)
\( P_{A1} U P_{A2} = 3.2963 \times 10^{-3} \times 1.1 \times 10^{-3} \)
\( QP_{A1} U P_{A2} = 2.0989 \times 10^{-3} \)
Overall probability of Pumps failure
\[ Q_2' = 2.0989 x 10^{-3} x 2.0989 x 10^{-3} x 2.0989 x 10^{-3} \]
\[ Q_2' = 9.246 x 10^{-9} \]

Probability of pump failure in Phase III

Probability of Pumps Failure Q3' in Phase Mission Phase III
\( \lambda = 1.2 \times 10^{-4} = 1.2 \times 10^{-5} \)
\( R = e^{-1.2 \times 10^{-5} x 10^{100}} \)
\( R = 0.998800719 \)
\( QP_{A1} = 1 - 0.998800719 \)
\( QP_{A1} = 1.19928 x 10^{-3} \approx 1.2 x 10^{-3} \)
Considering De-rating of Pumps

\( >10\% \) in Phase II
\( >20\% \) in Phase III
\( P_{A2} = 110\% \approx 1.1 \times 10^{-3} \)
\( P_{A3} = 120\% \approx 1.2 \times 10^{-3} \)
Overall probability of Pumps failure Q3',
\( QP_{A} = QP_{A1} + QP_{A2} + QP_{A3} - QP_{A1} x QP_{A2} - QP_{A1} x QP_{A3} - QP_{A2} x QP_{A3} \)
Here, \( QP_{A1} = 10^{-3} \)
\( QP_{A2} = 10^{-3} + 1.1 \times 10^{-3} + 1.2 \times 10^{-3} - \left( 10^{-3} \times 1.1 \times 10^{-3} \right) - \left( 10^{-3} \times 1.2 \times 10^{-3} \right) - \left( 10^{-3} \times 1.1 \times 10^{-3} \times 1.2 \times 10^{-3} \right) \)
\( QP_{A3} = 3.2963 \times 10^{-3} \)
\( Q_3' = QP_{A} x QP_{B} = 3.2963 \times 10^{-3} \times 3.2963 \times 10^{-4} \)
\( Q_3' = 3.5806 \times 10^{-9} \)

A computer program has been prepared to demonstrate relationship between pump derating and failure probability/reliability. The details of program in Excel are given below:

Considering the derating of the pumps varying from 5% to 40% in different phases following formulae are used in Excel sheet for preparation of final result & graph
\( P_A = \text{Derating \% of Pump A in Phase I & Phase II (from 5\% to 40\%)} \)
\( P_{A1} = 0.00100 \)
\( P_{A2} = P_{A1} + (\text{Value of derating \% of pump / 100}) x P_{A1} \)
\( P_{A3} = P_{A1} + (\text{Value of derating \% of pump / 100}) x P_{A1} \)
\( P_{A3} = P_{A1} + P_{A2} + P_{A3} - (P_{A1} x P_{A2}) - (P_{A1} x P_{A3}) - (P_{A2} x P_{A3}) \)

\( P_B = \text{Derating \% of Pump B in Phase I & Phase II (from 5\% to 40\%)} \)
\( P_{B1} = 0.00100 \)
\( P_{B2} = P_{B1} + (\text{Value of derating \% of pump / 100}) x P_{B1} \)
\( P_{B3} = P_{B1} + (\text{Value of derating \% of pump / 100}) x P_{B1} \)
\( P_B = (P_{B1} + P_{B2} + P_{B3}) - (P_{B1} x P_{B2}) - (P_{B1} x P_{B3}) - (P_{B2} x P_{B3}) \)
\( P_C = \text{Derating \% of Pump C in Phase I & Phase II (from 5\% to 40\%)} \)
\( P_{C1} = 0.00100 \)
\( P_{C2} = P_{C1} + (\text{Value of derating \% of pump / 100}) x P_{C1} \)
\( P_{C3} = P_{C1} + (\text{Value of derating \% of pump / 100}) x P_{C1} \)
\( P_C = (P_{C1} + P_{C2} + P_{C3}) - (P_{C1} x P_{C2}) - (P_{C1} x P_{C3}) - (P_{C2} x P_{C3}) \)
\( Q_3' = (P_A x P_B x P_C) \)
\( R = 1 - Q_3' \)

Considering the derating of the pumps varying from 10% to 40% in different phases the corresponding failure probability is shown in Table 1. The corresponding graph is shown in Fig. 4. It is seen probability is increasing and hence, the reliability is decreasing as the derating of pump is increased.

### 6 Comparison of Failure probability Values

The failure probability values based on Conventional Technique of FTA, Phased Mission Technique & Phased Mission with derating of hydraulic pump as discussed and obtained from section 3, 4 & 5 have been summarized and presented in Table 2.

<table>
<thead>
<tr>
<th>Sr No</th>
<th>Simple FTA Technique</th>
<th>FTA with Phased Mission Technique without pump derating</th>
<th>FTA with Phased Mission and pump derating into consideration</th>
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<tbody>
<tr>
<td>1</td>
<td>2.0199 x 10^4</td>
<td>3.589 x 10^4</td>
<td>4.6051 x 10^4</td>
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</table>
Table 1 The details of Pumps derating Vs Failure Probability & Reliability

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PA1</th>
<th>PA2</th>
<th>PA3</th>
<th>PB1</th>
<th>PB2</th>
<th>PB3</th>
<th>PC1</th>
<th>PC2</th>
<th>PC3</th>
<th>PA</th>
<th>PB</th>
<th>PC</th>
<th>Q3</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Derating</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.002997</td>
<td>0.002997</td>
<td>0.002997</td>
<td>2.69E-08</td>
<td>0.9999999973</td>
</tr>
<tr>
<td>Derating 5% PH1 10% PH2</td>
<td>0.001</td>
<td>0.00105</td>
<td>0.0011</td>
<td>0.001</td>
<td>0.00105</td>
<td>0.0011</td>
<td>0.001</td>
<td>0.00105</td>
<td>0.0011</td>
<td>0.003147</td>
<td>0.003147</td>
<td>0.003147</td>
<td>3.12E-08</td>
<td>0.9999999969</td>
</tr>
<tr>
<td>Derating 10% PH1 15% PH2</td>
<td>0.001</td>
<td>0.0011</td>
<td>0.00115</td>
<td>0.001</td>
<td>0.0011</td>
<td>0.00115</td>
<td>0.001</td>
<td>0.0011</td>
<td>0.00115</td>
<td>0.003246</td>
<td>0.003246</td>
<td>0.003246</td>
<td>3.42E-08</td>
<td>0.9999999966</td>
</tr>
<tr>
<td>Derating 15% PH1 20% PH2</td>
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<td>0.00115</td>
<td>0.0012</td>
<td>0.001</td>
<td>0.00115</td>
<td>0.0012</td>
<td>0.001</td>
<td>0.00115</td>
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<tr>
<td>Derating 20% PH1 25% PH2</td>
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<td>0.0012</td>
<td>0.00125</td>
<td>0.001</td>
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<td>0.0013</td>
<td>0.001</td>
<td>0.00125</td>
<td>0.0013</td>
<td>0.001</td>
<td>0.00125</td>
<td>0.0013</td>
<td>0.003546</td>
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<tr>
<td>Derating 30% PH1 35% PH2</td>
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<td>0.0013</td>
<td>0.00135</td>
<td>0.001</td>
<td>0.0013</td>
<td>0.00135</td>
<td>0.001</td>
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<td>0.0014</td>
<td>0.001</td>
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<td>0.0014</td>
<td>0.001</td>
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<td>0.9999999947</td>
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</tbody>
</table>

Figure 3 Equivalent Single Phase Mission Fault Tree Diagram

Figure 4 Derating of Pumps Vs failure probability & reliability
7 Conclusions
In this work an attempt is made to analyze the system using three methods and results are discussed.
(i) In the conventional fault tree method, the probability of the system failure is observed overestimated as $2.0199 \times 10^{-4}$ and found very high. This may be referred for safe design without interdependency of functioning.
(ii) After modification of conventional fault tree with phased mission technique the assessment is more realistic and hence probability of failure is comparatively low, i.e., $3.589 \times 10^{-8}$.
(iii) Further, with incorporation of “derating concept” the probability of the system failure is observed little high (28.3%).

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