Performance and Reliability Analysis of a Single Unit Power Cable with Inspection Policy in Metro Railways

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Abstract: Metro railways become an essential part of everyone's life. Various power cables of different capacities are used for supplying power (energy) to the metro system. The current study of the metro network system discusses the reliability modelling and profit analysis of this failure resistant network through power cables. These cables are used for supplying power to substations from each station. The study is concentrated taking single unit cable of 33 KV with no standby unit. If it fails then immediately inspection is carried out at each failure to check whether the system is in repairable or irreparable condition. The calculations to measure System Effectiveness and Profit Analysis are completed using "Semi-Markov Processes" and "Regenerative Point Technique". Various results have been analysed and represented graphically using software MATLAB.

Keywords: ***Metro-Railways, Power Cables, System Effectiveness, Profit Analysis, "Semi-Markov Processes", "Regenerative Point Technique".***

I. INTRODUCTION

Scientists have been intensely concerned with work on reliability, availability and profit analysis on the system without and with distinct standby redundant systems. Researchers [1] modelled and studied gain margin of a one server system subject to inspection. References [2] analysed one unit reliability system affected by random shocks with no preventive maintenance. Other researchers such as [3], [4] and [5] analyzed the availability and profit analysis of the PLC system by considering single unit, hot standby system with two types of repair and optimization of single unit PLC respectively based upon real data collected from industry. Reference [6] obtained the profit of a single unit reliability model for different failure models. Scholars [7], [8] studied the reliability and availability analysis of a single unit cable manufacturing process wherein a rod of Copper (Cu) or Aluminium (Al) of 10mm is transformed into a wire of 2mm with scheduled maintenance and demand variations. References [9], [10] applied inspection policy in the study of a single unit model with controlled, uncontrolled demand factor and feasibility of repair not under warranty respectively. Few researchers [11] analysed the cable plant system with priority to repair over preventive maintenance. References [12] studied a system of ID fans in a thermal power plant wherein different conditions making the system work at full/reduced capacity were discussed. References [13] approached a system of power cables of two unit cold standby systems in Metro Railways based upon real data collected. Electricity is heart-throb of modern day human life. The flow of Electrical Energy takes place through medium namely metal conductors. Cables are insulation covered conductors, thus, become energy transportation nerves and to allow the system to work effectively and efficiently, it becomes imperative that the failure whether due to cable manufacturing defects or some system malfunctioning, gets reduced to lowest level [14]. However, to assess and predict the failure or breakdown, mathematical modelling tools come handy. The probability analysis is thought of for critically delving into the problem of "FAILURE" and achieving near reality solution. The reduction in break-downs to a minimum level contributes to higher availability of the Electrical System in considered Metro trains, and their transportation became smooth and public at large gets relief and motivated with better confidence.

In a metro network system, power cables ranging 220, 132, 66, 33, 25 KV capacities have been deployed for energising the system and its proper and flawless operation. The system functioning failure data of eight years have been collected for the power cable with the capacity of 33KV. These cables are laid in loops for feeding supply to the substation at each station. So in order to overcome the damage of 33 KV power cables due to numerous factors that include manufacturing defects, external defects etc.. The regular schedule of inspection and maintenance of these power cables is of prime concern as it has a direct impact on the functioning of the metro

 DOI : 10.18231/2454-9150.2018.1196

ISSN : 2454-9150 Vol-04, Issue-09, Dec 2018

railways system. The study aims to analyse the reliability by considering an inspection in two units hot standby identical parallel power cable of 33KV capacity. The following measures of the system effectiveness are analysed by making use of "**Semi-Markov Processes**" and "**Regenerative Point Technique**":

- Mean Time to System Failure
- The steady-state Availability Analysis
- A busy period of the maintenance person for Inspection, repair and replacements of the power cable at $t=0$
- Maintenance person expected number of visits at $t=0$
- Expected number of replacements
- Expected profit gained to the system

II. SYMBOLS AND NOTATIONS

O	Power cable in an operative state
λ	The failure rate of the operative power cable
p	The probability of failure (repairable) of the unit
q	The probability of replacement (irreparable) of the unit
r	The probability of the unit found Ok
F_{ui}	The unit is under inspection in case of failure
F_r	The unit is under repair
F_{rp}	The unit is under replacement
γ	Constant rate of inspection
α	Constant rate of repairable failure
β	Constant rate of replacement failure
$g(t), G(t)$	The p.d.f and c.d.f of repair-time of the failed unit
$h(t), H(t)$	The p.d.f. and c.d.f. of replacement-time of the failed unit
$h_1(t), H_1(t)$	The p.d.f. and c.d.f. of inspection-time of the failed unit
$q_{ij}(t), Q_{ij}(t)$	The p.d.f. and c.d.f. of first transit time from a regenerative-state "i" to "j" or to a failed state "j" without visiting any other regenerative-state in $(0,t]$
p_{ij}	Transition probability from regenerative-state "i" to regenerative-state "j"
$M_i(t)$	The probability that system up initially in regenerative-state "i" is up at the time "t" without passing through any other regenerative-state
m_{ij}	Contribution to mean sojourn-time in regenerative-state "i" before transiting to regenerative-state "j" without visiting any other state
$\mu_i(t)$	Mean sojourn-time in regenerative-state before transiting to any other state
©, ⊗	Symbols for 'Laplace' and 'Laplace-Stieltje's' convolution
*, **	Symbols for 'Laplace' and 'Laplace-Stieltje's' transforms
C_0	Revenue per unit up-time
C_1	Represent cost per unit up-time for which the maintenance person is busy with repair
C_2	Cost per unit up-time for the maintenance person busy in replacement
C_3	Represent cost per unit up-time for the maintenance person busy in the inspection
C_4	Cost per visit of the maintenance person
C_5	Cost per unit replacement
A_0	Steady-state availability of the system
B_0	The busy period of the maintenance person for repair at $t=0$
BR_0	The busy period of the maintenance person for replacement at $t=0$
BR_{i0}	The busy period of the maintenance person for inspection at $t=0$
V_0	Maintenance person expected number of visits at $t=0$
R_0	Expected number of replacements

III. DATA SUMMARY

The following values have been obtained from the collected data:

- The estimated value of failure rate (λ)=.000015 per hour
- The estimated value of repair rate (α)=.067per hour

DOI : 10.18231/2454-9150.2018.1196

International Journal for Research in Engineering Application & Management (IJREAM)
ISSN : 2454-9150 Vol-04, Issue-09, Dec 2018

- The estimated value of replacement rate (β) =.002 per hour
- The estimated value of inspection rate (γ) =1 per hour
- The probability of repairable failure (p) =.69
- The probability of replaceable failure (q) =.16
- The probability of unit found ok (r) =.15
- The expected cost of Revenue up time (C_0) = 30000
- The expected cost of maintenance person during repair (C_1) = 3000
- The expected cost of maintenance person during replacement (C_2) = 250
- The expected cost of maintenance person per visit during inspection (C_3) = 600 per hour
- The expected cost of maintenance person per visit (C_4) = 500 per hour
- The expected cost of cable replacement (C_5) = 150000

(All costs are in INR)

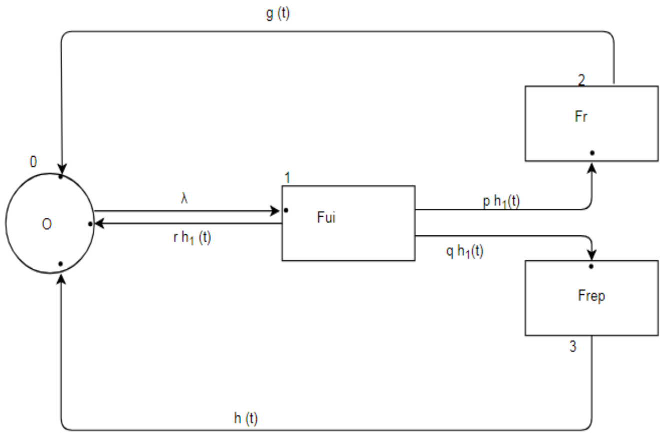
IV. SYSTEM MODEL ASSUMPTIONS AND DESCRIPTIONS

The probabilistic model uses the following assumptions:

1) Initially, the system is operative at full capacity with single power cable.
2) As the unit fails, it is undertaken for inspection.
3) Failure, repair and inspection times are assumed to follow an exponential and general time distribution respectively.
4) The maintenance person is available for inspection and is common for repair as well as for replacement.
5) The repaired unit works as good as a new one.
6) The system will be in the failed state when the unit is not working.
7) All the random variables are independent.
8) The system history prior to the time point is irrelevant to the system condition.

V. TRANSITION DIAGRAM

All the possible states from a given state transition diagram have been considered as shown in the Fig.1. The times of entry into states 0, 1, 2, 3 are regeneration points, and thus these are called regenerative states. The state 0 is up state whereas 1, 2, 3 are failed states. Power cable is operative (functional) at 0 state and if the cable failed then it is taken for repair at 1 state from this expert (repairman) decide whether to repair state 2 or replacement state 3.



- Regeneration Point

System in Operative State

System in Failed State

Figure1: State Transition Diagram

VI. TRANSITION-PROBABILITIES AND MEAN SOJOURN TIMES

The steady-state transition probabilities are

$$dQ_{01}(t) = \lambda e^{-\lambda t}dt,$$
$$dQ_{12}(t) = ph_1(t)dt,$$
$$dQ_{10}(t) = rh_1(t)dt,$$
$$dQ_{13}(t) = qh_1(t)dt,$$
$$dQ_{20}(t) = g(t)dt,$$
$$dQ_{30}(t) = \mathrm{h}(t)dt,$$

(1)

The non-zero elements $p_{ij} = \lim_{s\to 0} q_{ij}^{*}(s)$ can be obtained as

$$p_{01} = 1,$$
$$p_{12} = p,$$
$$p_{13} = q,$$
$$p_{10} = r,$$
$$p_{20} = 1,$$
$$p_{30} = 1.$$

(2)

 DOI : 10.18231/2454-9150.2018.1196

From the above steady-state transition probabilities, it can be verified that

$$p_{01} = p_{20} = p_{30} = 1,$$
$$p_{10} + p_{12} + p_{13} = 1,$$

(3)

The mean sojourn time (μ_i) in the regenerative state "i" is

$$\mu_0 = \frac{1}{\lambda},$$
$$\mu_1 = \int_0^\infty t h_1(t)dt,$$
$$\mu_2 = \int_0^\infty t g(t)dt,$$
$$\mu_3 = \int_0^\infty t h(t)dt,$$

(4)

For the system to transit for any regenerative state "j" when it is counted from the time of entrance into state "i", the unconditional mean time is mathematically stated as

$$m_{ij} = \int_0^\infty t dQ_{ij}(t) = -q_{ij}^{*'}(0).$$

(5)

Thus,

$$m_{01} = \mu_0,$$
$$m_{20} = \mu_2,$$
$$m_{30} = \mu_3,$$
$$m_{12} + m_{13} + m_{10} = \mu_1.$$

(6)

where,

$$\mu_1 = \int_0^\infty \bar{H}_1(t)dt = \int_0^\infty t h_1(t)dt,$$
$$\mu_2 = \int_0^\infty \bar{G}(t)dt = \int_0^\infty t g(t)dt,$$
$$\mu_3 = \int_0^\infty \bar{H}(t)dt = \int_0^\infty t h(t)dt.$$

VII. MEASURES OF SYSTEM EFFECTIVENESS

A. Mean Time to System Failure (MTSF). Taking the failed state of the system as absorbing state, Let $\phi_i(t)$, be the cumulative distribution function of first passage time from i^{th} state to a failed state where i =0,1,2,3,4,5,6,7,8. MTSF of the system can be determined by the following recursive relations for $\phi_i(t)$

$$\phi_0(t) = Q_{01}(t).$$

(7) Taking Laplace-Stieltjes Transform (L.S.T.) of the above relations given by (7) on both the sides and solving them for $\phi_0^{**}(s)$, we obtain

$\phi_0^{**}(s) = \dfrac{N_0(s)}{D_0(s)}$, $\phi_0^{**}(s)$ represents the Laplace-Stieltjes Transform of $\phi_0(s)$.

The MTSF for the present system starts from the state "0" is

$$MTSF = \lim_{s \to 0} \frac{1-\phi_0^{**}(s)}{s} = \frac{D_0'(0) - N_0'(0)}{D_0(0)} = \frac{N}{D} = \mu_0.$$

(8)

B. Availability Analysis

Let $A_i(t)$ be the probability that the system is working at the instant time "t", given that the system entered regenerative state "i" at $t = 0$.

Then,

$$A_0(t) = M_0(t) + q_{01}(t) © A_1(t),$$
$$A_1(t) = q_{10}(t) © A_0(t) + q_{12}(t) © A_2(t) + q_{13}(t) © A_3(t),$$
$$A_2(t) = q_{20}(t) © A_0(t),$$
$$A_3(t) = q_{30}(t) © A_0(t), \quad (9)$$

Where,

$$M_0(t) = e^{-\lambda t}.$$

Taking Laplace transforms of above equations and solving them for $A_0^*(s)$, we get

$$A_0^*(s) = \frac{N_1(s)}{D_1(s)},$$

The availability A_0 in steady-state of the present system is defined as

$$A_0 = \lim_{s \to 0} s.\frac{N_1(s)}{D_1(s)} = \frac{N_1(0)}{D_1'(0)} = \frac{N_1}{D_1},$$

Where,

$$N_1 = \mu_0,$$
$$D_1 = \mu_0 + \mu_1 + p\mu_2 + q\mu_3.$$

(10)

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C. Busy Period Analysis of Maintenance person (Repair only)

The total time $B_0^*(s)$ of the system under repair by the maintenance person is calculated by the following recursive relation

$$B_0(t) = q_{01}(t) \copyright B_1(t),$$

$$B_1(t) = q_{10}(t) \copyright B_0(t) + q_{12}(t) \copyright B_2(t) + q_{13}(t) \copyright B_3(t)$$

$$B_2(t) = W_2(t) + q_{20}(t) \copyright B_0(t),$$

$$B_3(t) = q_{30}(t) \copyright B_0(t),$$

(11)

Where,

$$W_2(t) = \bar{G}(t).$$

Taking Laplace transforms of above equations and solving them for $B_0^*(s)$, we get

$$B_0^*(s) = \frac{N_2(s)}{D_1(s)},$$

In steady-state, the busy period of the maintenance person is given by,

$$B_0 = \lim_{s \to 0} s.B_0^*(s) = \frac{N_2}{D_1},$$

Where,

$$N_2 = p\mu_2.$$

(12)

And $D_1(s)$ is already calculated.

D. Busy Period Analysis of Maintenance person (Replacement only)

$$BR_0(t) = q_{01}(t) \copyright BR_1(t),$$

$$BR_1(t) = q_{10}(t) \copyright BR_0(t) + q_{12}(t) \copyright BR_2(t) + q_{13}(t) \copyright BR_3(t)$$

$$BR_2(t) = q_{20}(t) \copyright BR_0(t),$$

$$BR_3(t) = W_3(t) + q_{30}(t) \copyright BR_0(t),$$

(13)

Where,

$$W_3(t) = \bar{H}(t).$$

Taking Laplace transforms of above equations and solving them for $BR_0^*(s)$, we get

$$BR_0^*(s) = \frac{N_3(s)}{D_1(s)},$$

In steady-state, the busy period of the maintenance person is given by,

$$BR_0 = \lim_{s \to 0} s.BR_0^*(s) = \frac{N_3}{D_1},$$

Where,

$$N_3 = q\mu_3,$$

(14)

And $D_1(s)$ is already specified.

D. Busy Period Analysis of Maintenance person (Inspection time only)

$$BR_{i0}(t) = q_{01}(t) \copyright BR_{i1}(t),$$

$$BR_{i1}(t) = W_1(t) + q_{10}(t) \copyright BR_{i0}(t) + q_{12}(t) \copyright BR_{i2}(t) + q_{13}(t) \copyright BR_{i3}(t),$$

$$BR_{i2}(t) = q_{20}(t) \copyright BR_{i0}(t),$$

$$BR_{i4}(t) = q_{30}(t) \copyright BR_{i0}(t).$$

(15)

Where,

$$W_2(t) = \bar{H}_1(t).$$

Taking Laplace transforms of above equations and solving them for $BR_0^*(s)$, we get

$$BR_{i0}^*(s) = \frac{N_4(s)}{D_1(s)},$$

In steady-state, the busy period of the maintenance person is given by,

$$BR_{i0} = \lim_{s \to 0} s.BR_{i0}^*(s) = \frac{N_4}{D_1},$$

Where,

$$N_4 = \mu_1,$$

(16)

And $D_1(s)$ is already specified.

E. Expected Number of Visits by the Maintenance person

$$V_0(t) = Q_{01}(t) \otimes [1 + V_1(t)],$$

$$V_1(t) = Q_{10}(t) \otimes V_0(t) + Q_{12}(t) \otimes V_2(t) + Q_{13}(t) \otimes V_3(t),$$

$$V_2(t) = Q_{20}(t) \otimes V_0(t),$$

$$V_3(t) = Q_{30}(t) \otimes V_0(t),$$

(17)

Taking Laplace-Stieltjes Transforms (L.S.T.) of above equations on both the sides and solving them for $V_0^{**}(s)$, we get

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$$V_0^{**}(s) = \frac{N_5(s)}{D_1(s)},$$

In steady-state, the expected number of visits per unit time by the maintenance person is given by,

$$V_0 = \lim_{s\to 0} s.V_0^{**}(s) = \frac{N_5}{D_1},$$

Where,

$$N_5 = 1.$$

and $D_1(s)$ is already specified.

(18)

F. Expected Number of Replacements.

$$R_0(t) = Q_{01}(t) \otimes R_1(t),$$

$$R_1(t) = Q_{10}(t) \otimes \mathrm{R}_0(t) + Q_{12}(t) \otimes R_2(t) + Q_{13}(t) \otimes [1 + R_3(t)],$$

$$R_2(t) = Q_{20}(t) \otimes R_0(t),$$

$$R_3(t) = Q_{30}(t) \otimes R_0(t), \quad (19)$$

Taking Laplace-Stieltjes Transforms (L.S.T.) of above equations on both the sides and solving them for $R_0^{**}(s)$, we get

$$R_0^{**}(s) = \frac{N_6(s)}{D_1(s)},$$

In steady-state, the expected number of replacements is given by,

$$R_0 = \lim_{s\to 0} s.R_0^{**}(s) = \frac{N_6}{D_1},$$

Where,

$$N_6 = p_{01}p_{13}. \quad (20)$$

And $D_1(s)$ is already specified.

VIII. PROFIT ANALYSIS

The total expected profit P of the system at steady state could be calculated by expected total revenue in $(0,t]$ minus expected total costs of repair, replacement and inspection in $(0,t]$ minus expected cost of visits by maintenance person in $(0,t]$minus the cost of many replacements in $(0,t]$. Hence, the overall profit in $(0,t]$ is given by

$$P = C_0A_0 - C_1B_0 - C_2BR_0 - C_3BR_{i0} - C_4V_0 - C_5R_0$$

,)

PARTICULAR CASE

For the particular case, the inspection, repair and replacement rate are assumed to be exponentially distributed, let us take

$$g(t) = \alpha e^{-\alpha t};\, h(t) = \beta e^{-\beta t};\, h_1(t) = \gamma e^{-\gamma t}$$

Using the values, as estimated in section 3, of various probabilities and repairable/replaceable/inspection rates the following measures of system effectiveness are obtained as:

Mean Time to System Failure: 66666.6666667 hrs

Availability of the system A_0 : 0.9986324

The expected busy period of the maintenance person for repairable failure B_0 : 0.0001543

The expected busy period of the maintenance person for replaceable failure BR_0 : 0.0011984

The expected busy period of the maintenance person for inspection of a failure BR_{i0} : 0.000016

Expected number of visits by the maintenance person V_0 : 0.0000151

Expected number of replacement R_0 : 0.0000024

GRAPHICAL INTERPRETATIONS

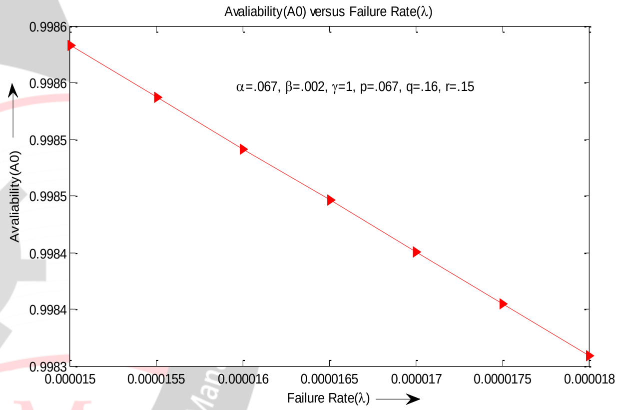

Figure2. Availability versus Failure Rate

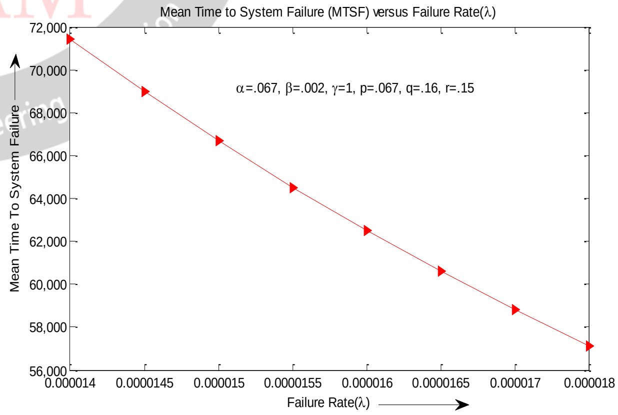

Figure3. MTSF versus Failure Rate

 DOI : 10.18231/2454-9150.2018.1196

ISSN : 2454-9150 Vol-04, Issue-09, Dec 2018

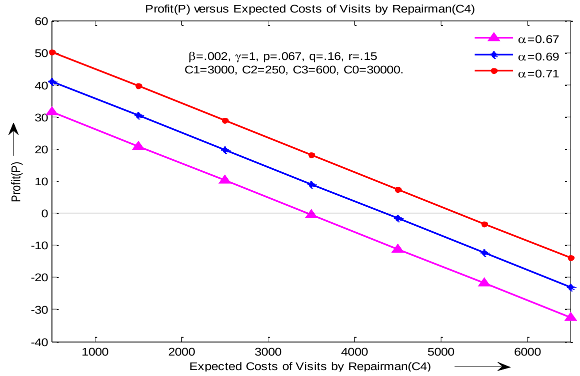

Figure4. Profit (P) versus Expected costs of visits by Maintenance person (C4) for different values of repair rate.

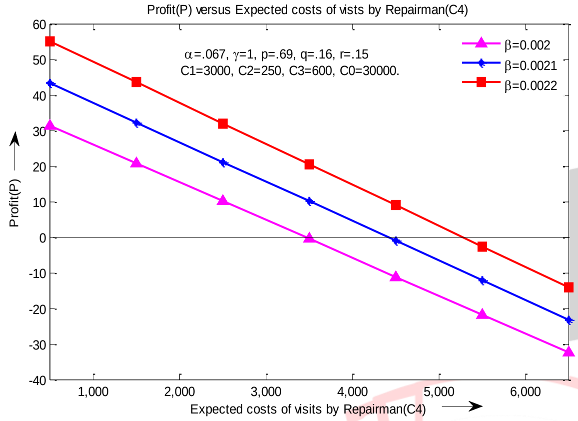

Figure5. Profit (P) versus Expected costs of visits by Maintenance person (C4) for different values of replacement rate.

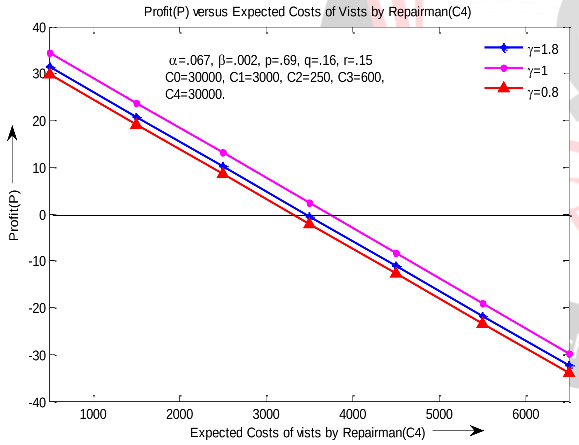

Figure6. Profit (P) versus Expected costs of visits by Maintenance person (C4) for different values of inspection rate.

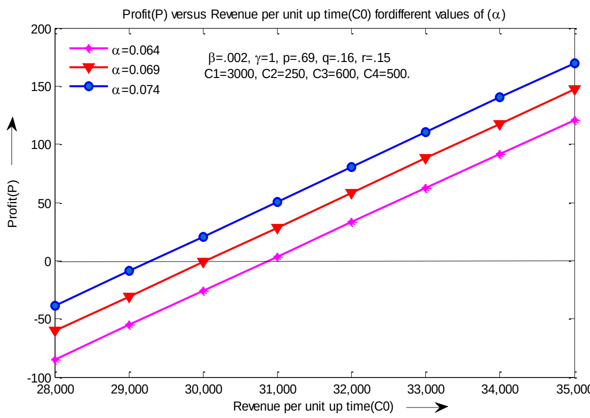

Figure7. The Profit (P) Revenue per unit up time (C0) for different values of repair rate

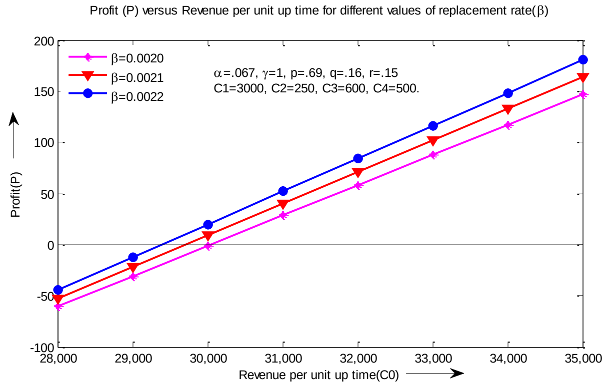

Figure8. Profit (P) vs Revenue per unit up time (C0) for different values of replacement rate.

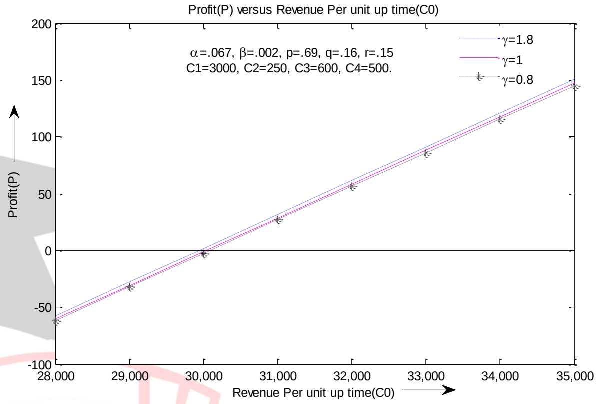

Figure9. Profit (P) vs Revenue per unit up time (C0) for different values of inspection rate.

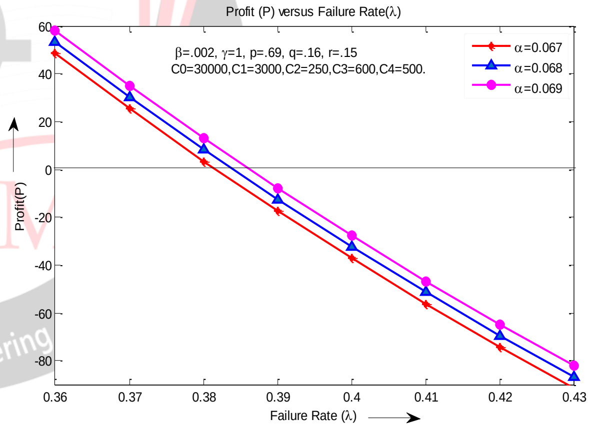

Figure10. Profit (P) vs Failure rate for different values of repair rate.

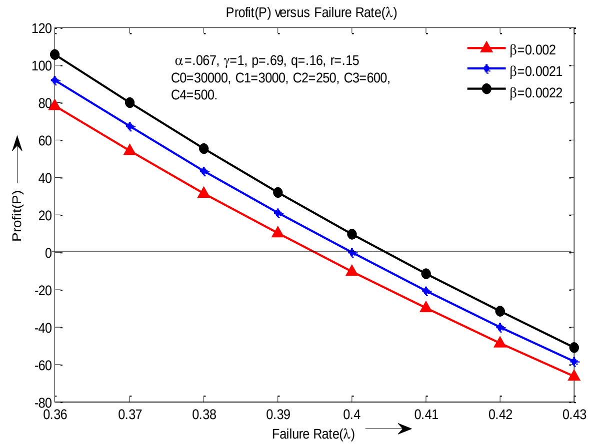

Figure11. Profit (P) vs Failure Rate for different values of replacement rate.

 DOI : 10.18231/2454-9150.2018.1196

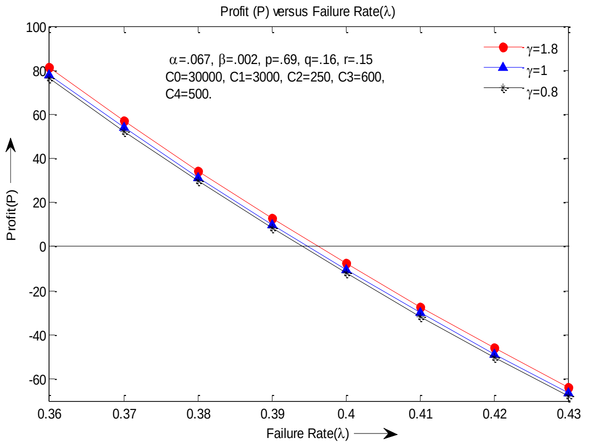

Figure12. Profit (P) vs Failure Rate for different values of inspection rate.

i. Figure 2 and 3 shows the decrease in Availability and MTSF of the system with an increase in the failure rate λ.

ii. Figure 4 analysis shows that the profit decreases with an increase in the expected costs of visits by a maintenance person (C_4) for different values of repair rate (α). It is concluded that if C_4 =3300 then P >or=or<0 accordingly as C_4 < or=or>3300. So, for the system to be beneficial for α =.067, C_4 should be less than .3300. Similarly, for α =.069 and .071, the values of expected costs of visits by maintenance person (C_4) should be less than 4300 and 5200 respectively.

iii. Figure 5 analysis shows that the profit decreases with an increase in the expected costs of visits by a maintenance person (C_4) for different values of replacement rate (β). It is concluded that if C_4 =3400 then P >or=or<0 accordingly as C_4 < or=or>3400. So, for the system to be beneficial for β =.002, C_4 should be less than 3400. Similarly, for β =.0021 and .0022 the values of expected costs of visits by maintenance person (C_4) should be less than 4400 and 5300 respectively.

iv. Figure 6 analysis shows that the profit decreases with an increase in the expected costs of visits by a maintenance person (C_4) for different values of inspection rate (γ). It is concluded that if C_4 =3800 then P >or=or<0 accordingly as C_4 < or=or>3800. So, for the system to be beneficial for γ =.8, C_4 should be less than 3800. Similarly, for γ =1 and 1.8 the values of expected costs of visits by maintenance person (C_4) should be less than 3500 and 3200 respectively.

v. Figure 7 analysis shows that the profit increases with an increase in the revenue costs per unit up time (C_0) for different values of repair rate (α). It is concluded that if C_0 =30900 then P >or=or<0 accordingly as C_0 > or=or<30900. So, for the system to be beneficial for α =.064, C_0 should be greater than 30900. Similarly, for α =.069 and .074, the values of revenue costs per unit uptime C_0 should be greater than 30000 and 29300 respectively.

vi. Figure 8 analysis shows that the profit increases with an increase in the revenue costs per unit up time (C_0) for different values of replacement rate (β). It is concluded that if C_0 =30000 then P >or=or<0 accordingly as C_0 > or=or<30000. So, for the system to be beneficial for β =.0020, C_0 should be greater than 30000. Similarly, for β =.0021 and .0022 the values of revenue costs per unit uptime C_0 should be greater than 29750 and 29300 respectively.

vii. Figure 9 analysis shows that the profit increases with an increase in the revenue costs per unit up time (C_0) for different values of inspection rate (γ). It is concluded that if C_0 =30000 then P >or=or<0 accordingly as C_0 > or=or<30000. So, for the system to be beneficial for γ =.8, C_0 should be greater than 30000. Similarly, for γ =1 and 1.8 the values of revenue costs per unit uptime C_0 should be greater than 29950 and 29850 respectively.

viii. Figure 10 shows that the profit decreases with an increase in the failure rate λ for different values of replacement rate α if repair rate α =.067 then P >or=or<0 accordingly as failure rate λ <or=or>.3833. For the system benefit, failure rate λ must be less than .3833 similarly, if repair rate α =.068 and .069 the cut-off points of failure rate λ must be less than .3845 and .3874 respectively.

ix. Figure 11 shows that the profit decreases with an increase in the failure rate λ for different values of replacement rate β if replacement rate β =.002 then P >or=or<0 accordingly as failure rate λ <or=or>.3943. For the system benefit, failure rate λ must be less than .3943 similarly, if replacement rate

 DOI : 10.18231/2454-9150.2018.1196

β =.0021 and .0022 the cut-off points of failure rate λ must be less than .3990 and .4050 respectively.

x. Figure 12 shows that the profit decreases with an increase in the failure rate λ for different values of inspection rate γ if inspection rate γ =1.8 then P >or=or<0 accordingly as failure rate λ <or=or>.3975. For the system benefit, failure rate λ must be less than .3975 similarly, if inspection rate γ =1 and .8 the cut-off points of failure rate λ must be less than .3956 and .3935 respectively.

CONCLUSION

Power cable of 33 KV used in metro railway stations utilize in lighting up of metro stations, control room, passenger information (power control room and communication control room) and signal to metro railways. Thus, failure of 33 KV power cable will leads to failure in conveying signal to direct metros which result in failure of a system. Present paper deals in considering a particular metro station with one power cable (33KV) for supplying energy to the respective purpose. It is therefore, to analyze the reliability and profitability of a single unit power cable used in metro railways system, various measures like "Mean Time to System Effectiveness (MTSF), Availability Analysis, Busy period analysis of maintenance person during inspections, repairs, replacements, Expected numbers of visits by maintenance person and Expected number of Replacements" have been calculated in order to get the clear picture of the present system of a particular metro railway station. With this study of a single unit, various observations have been drawn about the profit of an existing system in line with the cut-off points duly marked in the graph analysis. Keeping this model as a base, there is a full-fledged scope of proposing other models having redundancy for obtaining more substantial profit and availability of the considered system.

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 DOI : 10.18231/2454-9150.2018.1196