SUGGESTED PROCEDURE FOR OPTIMIZING MAINTENANCE SCHEDULES

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ABSTRACT

The problem of optimizing preventive maintenance schedules is discussed and resolved. A suggested procedure for that problem is presented. The main features of this procedure are: (i) The hazard function of the constituent components are not considered constant; (ii) The importance of the constituent components are evaluated to determine the precedence of components that will receive the maintenance action; and (iii) Cost and improvement in reliability are two competitive factors used to get the optimum policy. A case study is taken to apply the suggested procedure and the obtained results are presented and discussed.

1. INTRODUCTION

Maintenance is usually described by two major categories, corrective or preventive. Corrective maintenance is conducted when the system is failed while preventive maintenance (PM) periodically during the system operation to slow component degeneration and so the system life is extended. Following PM, the component hazard function, usually lies between "good as new" and "bad as old", hazard function will be improved by a factor called the improvement factor [1].

The importance of each constituent component in the system determines the precedence of components that will receive PM. It is often reasonable to use multiple independent criteria in determining an optimum maintenance policy. These criteria are [2]:

* minimum cost rate.
* maximum availability.
* lower-bound on mission reliability.

Starting from the component hazard function and ending with complete evaluation system failure pathways, the present work suggests a procedure for optimizing the maintenance schedules of engineering system.

2. THE SUGGESTED PROCEDURE

Step 1

Select an appropriate hazard function for each constituent component in the system and evaluate its characteristic parameters. The functions for probability density function, reliability, unreliability for each component can then be easily derived.

The exponential power model is recommended to be utilized [3] since it is practically convenient for the hazard to be continuously increasing with time. Exponential power model is expressed by:

$$h(t) = \alpha t^{\beta-1} \exp[\alpha t^{\beta}] \tag{1}$$

where α = scale parameter, β = shape parameter.

The hazard reaches a minimum value at a time t_c given by

$$t_c = \left(\frac{1-\beta}{\alpha\beta}\right)^{1/\beta} \tag{2}$$

The estimated hourly failure rate (λ) as extracted from actual operational experience over an operational period (t_f-t_c) can be considered as the average value of h (t) over that period. So, one can write.

$$\lambda = \frac{1}{t_f - t_c}\int_{t_c}^{t_f} h(t)\,dt$$

$$= \frac{1}{t_f - t_c}\left\{\exp[\alpha t_f^{\beta}] - \exp[\frac{1-\beta}{\beta}]\right\} \tag{3}$$

From equation (2), one can get

$$\alpha = \frac{1-\beta}{\beta t_c^{\beta}} \tag{4}$$

Substitution with equation (4) in (3) gives:

$$\lambda = \frac{1}{t_f - t_c}\left\{\exp\left[\left(\frac{1-\beta}{\beta t_c^{\beta}}\right)t_f^{\beta}\right] - \exp\left[\frac{1-\beta}{\beta}\right]\right\} \tag{5}$$

Equation (5) can be solved for β by a simple iterative procedure, then equation (4) is used to get α. In such case, the reliability and unreliability functions for the constituting component j can then be obtained from:

$$R_j(t) = \exp\{-[\exp(\alpha_j t^{\beta_j})-1]\},$$

$$Q_j(t) = 1-\{-[\exp(\alpha_j t^{\beta_j})-1]\} \tag{6}$$

Step 2:

Use appropriate quantification techniques to evaluate the hazard and reliability functions for the whole system. Parallel to that evaluation, importance of each component should be determined.

Fault tree and/ or event trees are very powerful techniques for conducting this step. Minimal cut sets algorithm (MCS) derived from the fault tree is very helpful in outlining the reliability block diagram (RBD) and evaluating the importance of each component at any given time.

The importance of component k at time t is denoted by $e_k(t)$ and can obtained from:

$$e_k(t) = \frac{\sum_{kei} Q_i(t)}{\sum_i Q_i(t)} \tag{7}$$

where

$\sum_{kei} Q_i(t)$ = Sum of unavailability of all MCS containing component k as one of its components.

$\sum Q_i$ = Q(t) = System unavailability
= Sum of all MCS unavailabilities.

Step 3

The optimum PM policy for the system can be postulated as follows:

(i) Do type 1P maintenance ($n^{\bullet}$-1) times on all components at times t_i, i=1,2,...,$n^{\bullet}$-1. At each time, the reliability of each component has to be improved by a value corresponds to a shrinkage in time equivalent to [5]:

$$t_i = t_1-(1-1/r)^{i-1}t_1, \quad i=2,3,...,n^{\bullet}-1 \tag{8}$$

where

t_1 = time to maintenance, is known.

$n^{\bullet}$-1 = an optimum number of type 1P maintenance actions before type 2P maintenance is obtained by minimizing the cost-rate when the failure times are exponential power distributed.

r = Improvement factor pertained to critical component. The inverse of improvement factor (1/r) can be evaluated from

$$1/r = \left(\frac{C_{1p} - C_{2P}}{C_{2P}}\right)^m + C.F, \; m = 2,4,6, \tag{9}$$

where

C = cost per maintenance action.

m = the shape parameter depending on importance of critical component.

C.F. = correction factor depending on a predetermined limiting value.

(ii) The degree of improvement in reliability function for the whole system after any time of 1P maintenance action must be at least 20%, So one can write.

% Improvement of the whole system reliability equals

$$= \frac{R(t_i) - R(t_1)}{R(t_1)} * 100\,\%, \quad i=2,3,...,n^{\bullet}-1 \tag{10}$$

3.CASE STUDY: PRESSURE TANK SYSTEM

3.1 System Definition and Reliability Data:

Figure (1) shows a schematic for a simple pressure tank system. The system includes a pressure tank, pump-motor device and its associated control system.

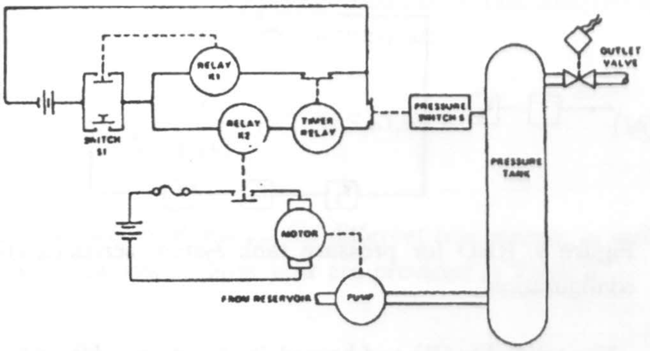

Figure 1. Pressure tank system [adapted from reference [4]].

The function of the control system is to regulate the operation of the pump. The latter pumps fluid from an infinitely large reservoir into the tank. We shall assume that it takes 60 second to pressurize the tank. The pressure switch has contacts which are closed when the tank is empty. When the threshold pressure has been reached, the pressure switch contacts open, de-energizing the coil of relay K2 so that relay K2 contacts open, removing power from the pump, causing the pump motor to case operation. The tank is fitted with an outlet valve, however, is not a pressure relief valve. When the tank is empty, the pressure switch contacts, close, and the cycle is repeated.

Initially the system is considered to be in its dormant mode:

Switch S1 contacts, open relay K1 contacts open, and relay K2 contacts open; i.e., the control system is de-energized. In this de-energized state the contacts of the timer relay are closed. We will also assume that the tank is empty and the pressure switch contacts are therefore closed.

System operation is started by momentarily depressing switch S1. This applies power to the coil of relay K2, whose contacts close to start up the pump motor.

The timer relay has been provided to allow emergency shut-down in the event that the pressure switch fails closed. Initially the timer relay contacts are closed and the timer relay coil is de-energized. Power is applied to the timer coil as soon as relay K1 contacts are closed. This starts a clock in the timer. If the clock registers 60 seconds of continuous power application to the timer relay coil, the timer relay contacts open (and latch in that position), breaking the circuit to the K1 relay coil (previously latched closed) and thus producing system shut-down. In normal operation, when the pressure switch contacts open (and consequently relay K2 contacts open), the timer resets to 0 seconds.

The failure probabilities of the constituent components are given in Table 1.

Table 1. Failure probabilities of the constituent components in the pressure tank system.

Component	Symbol	Failure Probability
Pressure Tank	T	5×10^{-6}
Relay K2	K2	3×10^{-5}
Pressure Switch	S	1×10^{-4}
Relay K1	K1	3×10^{-5}
Timer Relay	R	1×10^{-4}
Switch S1	S1	3×10^{-5}

3.2 Results

Step 1

For t_c = 0.5 year and t_f = 10 years, the scale and shape parameters for each component hazard function were evaluated and the results are presented in Table 2.

Table 2. Scale and shape parameters for the constituent components of the pressure tank system.

Component Number	Estimated Failure-rate	Scale Parameter	Shape Parameter
T	5×10^{-6}	3.8×10^{-6}	0.9976
K2, S1, K1	3×10^{-5}	1.9×10^{-5}	0.9560
S, R	1×10^{-4}	3.9×10^{-4}	0.7860

Step 2

Following a complete understanding of the design criteria of the pressure tank system and how it must function successfully, detailed fault tree can be constructed with the top event "Rupture of pressure tank after the start of pumping" [4]. Under some simplifications, the basic (reduced) fault tree shown in Figure (2) could be obtained.

The top and intermediate events are explained as follows:

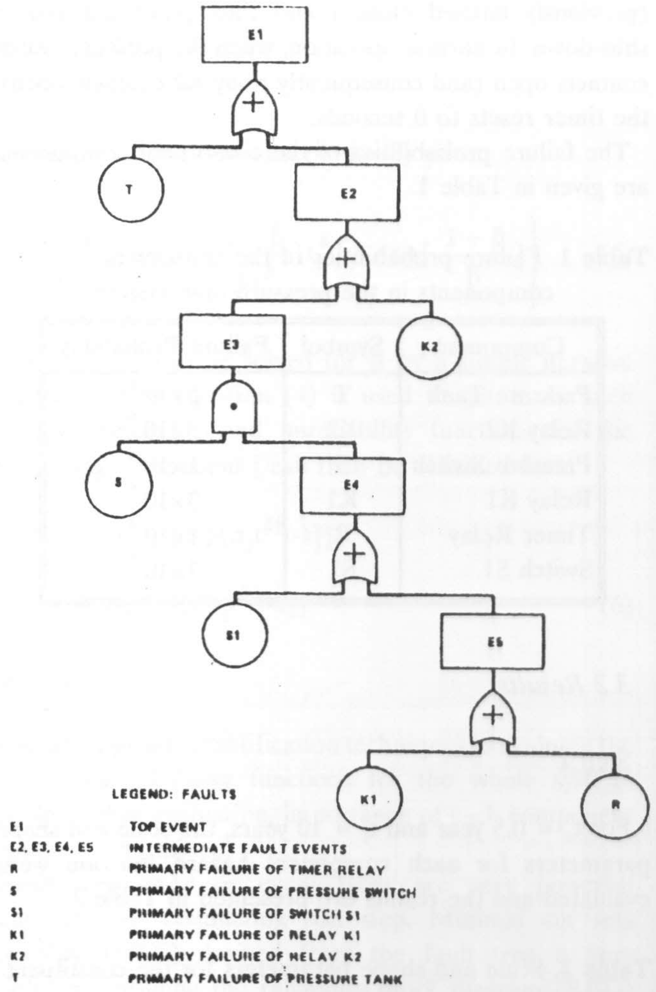

Figure 2. Basic (Reduced) fault tree for Pressure tank [adapted from reference [4]].

E1 = Pressure tank rupture (top event)

E2 = Pressure tank rupture due to internal overpressure from pump operation for t > 60 seconds which is equivalent to K2 relay contacts closed for t > 60 seconds.

E3 = EMF on K2 relay coil for t > 60 seconds.

E4 = EMF remains on pressure switch contacts when pressure switch contacts have closed for t > 60 seconds.

E5 = EMF through K1 relay contacts when pressure switch contacts have been closed for t > 60 seconds which is equivalent to timer relay contacts failing to open when pressure switch contacts.

The evaluation of the MCS algorithm shows that it can form a "series-parallel system" whose reliability block diagram appear in Figure (3).

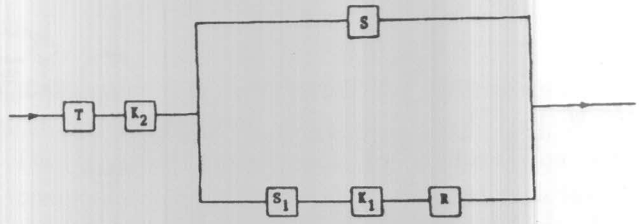

Figure 3. RBD for pressure tank system series-parallel configuration.

The reliability (R) and hazard (h) functions of the whole system can then be evaluated as:

$$R(t) = R_T(t)R_{K2}(t)[R_S(t) + R_{S1}(t)R_{K1}(t)R_R(t) - R_S(t)R_{S1}(t)R_{K1}(t)R_R(t)] \quad (11)$$

$$h(t) = \frac{1}{R(t)}\left[-\frac{d}{dt}R(t)\right] \quad (12)$$

Equation (6) is used for substituting the different component reliabilities in the right hand side of equation (11).

Referring to Figure (3), the number of minimal cut sets are live with the following unavailabilities:

$$Q_1(t) = Q_T(t),\ Q_2(t) = Q_{K2}(t),\ Q_3(t) = Q_S(t)Q_{S1}(t),$$
$$Q_4(t) = Q_S(t)Q_{K1}(t),\ Q_5(t) = Q_S(t)Q_R(t) \quad (13)$$

The system unavailability Q (t) can thus approximated as the sum of the minimal cut set unavailability Q_i (t):

$$Q(t) = \sum_{i=1}^{5} Q_i(t) \quad (14)$$

When applying equation (7), the importance of each component, the resulted importances are:

$$e_T(t) = \frac{Q_1(t)}{Q(t)},\ e_{K2}(t) = \frac{Q_2(t)}{Q(t)},\ e_S(t) = \frac{\sum_{i=3}^{5} Q_i(t)}{Q(t)},$$
$$e_{S1}(t) = \frac{Q_3(t)}{Q(t)},\ e_{K1}(t) = \frac{Q_4(t)}{Q(t)},\ e_R(t) = \frac{Q_5(t)}{Q(t)} \quad (15)$$

The relative quantitative importance of certain component (j) can be expressed quantitatively as:

$$e_{rj}(t) = \frac{e_j(t)}{\sum_j e_j(t)}, \; j=T,K2,S,S1,K1,R \qquad (16)$$

Values of h, R and e_{rj} for different components as well as for the system after year are provided in Table 3.

Step 3

Getting use of the data provided from Table 1, and taking the time t_o maintenance (t_1) = 1 year, the hazard and reliability function, importance of each constituent component in the system, and whole system are computed as shown in Table 3.

Table 3. Components, and system characteristic functions.

Component Number	$h(t_1)$	$R(t_1)$	Relative Quantitative Importance
T	3,8319 E-006	0.96743	2.1%
K2	1.3621 E-005	0.88861	7.3%
S	7.0595 E-005	0.53604	45.4%
S1	1.3621 E-005	0.88861	7.3%
K1	1.3621 E-005	0.88861	7.3%
R	7.0595 E-005	0.53604	30.6%
System	7.3485 E-005	0.62964	100%

Taking $1/r$ = 0.2, Table 4 illustrates how the reliability of the critical components as well as the reliability of the whole system are improved following type 1P maintenance. The optimum number is 5 after which 2P maintenance should be introduced.

Table 4. Reliability improvements following type 1P maintenance

Type 1P maintenance	% improvement in critical component reliability	% improvement in system reliability
1	62.18%	51.07%
2	47.17%	41.94%
3	36.40%	33.92
4	28.36%	27.23%
5	22.23%	21.79%
6	17.50%	17.40%

Since no improvement less than 20% is allowed, 1P maintenance ≠ 6 is rejected and the optimum number of 1P maintenance is 5.

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