SCHEDULING OF PREVENTIVE MAINTENANCE FOR GENERATING UNIT CONSIDERING COST

Dong Jin KIM* Jun Seok SHIN* Jin O KIM* Hyung Chul KIM**

e-mail: jokim@hanyang.ac.kr

**Dept. of Electrical Engineering, Hanyang Univ., Seoul, Korea*

***Korea Railroad Research Institute*

Key words: *Markov Process, RCM, Preventive Maintenance, Gamma Distribution*

ABSTRACT

Traditional maintenance planning is based on a constant maintenance interval for equipment life. In order to consider economic aspect for time based preventive maintenance, preventive maintenance is desirable to be scheduled by RCM(Reliability-Centered Maintenance) evaluation. So, Markov state model is utilized considering a stochastic state in RCM. In this paper, the Markov state model which can be used for scheduling and optimization of maintenance is presented. The deterioration process of system condition is modeled by the stepwise Markov state model in detail. Also, because the system is not continuously monitored, the inspection is considered. In case study, simulation results about RCM will be shown using the real historical data of combustion turbine generating unit in Korean power systems.

I. INTRODUCTION

Power systems are the important to consumers for the stable supply of electric power. There are a lot of conditions for the stable supply. Specially, the maintenance of facilities is important. In the case of maintenance for Korean power systems, Time-based preventive maintenance is applied these days. However, it costs a lot excessively for the maintenance because it is applied without considering life cycle of system. Therefore, Reliability Centered Maintenance (RCM) is the optimal maintenance plan with the probability theory of the reliability considering life-cycle and the cost. The main objective of RCM is to reduce the maintenance cost, by focusing on the most important functions of the system and avoiding or removing maintenance actions that are not strictly necessary [1]. The RCM plan is important to decide the time for PM(*Preventive Maintenance*) in scheduling RCM. If can not continuously monitor about the condition of the system, it is important to decide the time of inspection interval for checking system's condition. If PM cycle and inspection cycle are short, the probability of system failure can be reduced but it costs more in operating system. From this point, the cost should be considered in deciding PM cycle and inspection cycle.

This paper proposed PM plan by using the stepwise Markov state model considering the stochastic state in RCM. To apply the Markov state model, the probability criterion is needed for recognizing each state of deteriorating performance. Therefore, this paper utilized the criterion of Norwegian Electricity Industry Association for diving system's state [2]. Each state from the criterion was represented by the gamma distribution and the exponential distribution. The transition rate between each state was calculated. Also, the cost for operating system (*PM* , *CM and Inspection cost*) was calculated using steady state probability and visit frequency of each state[3, 4]. The maintenance plan was proposed for the minimum cost in operating system. In case study, the Markov state model was applied to combustion turbine generating unit in Korean power systems.

II. DIVISION OF SYSTEM'S STATE

The criterion of probability state for applying the Markov state model is the same as Table 1.

Table 1 Main state condition in EBL, Norway

State	Description
1	No indication of degradation.
2	Some indication of degradation. The condition is noticeably worse than "as good as new".
3	Serious degradation. The condition is considerably worse than "as good as new".
4	The condition is critical.

The Markov state model was applied to 4 system states with failure state as the 5th state in Table 1. The 5th state is the failure state by no application of PM even though the system reaches the dangerous state of the 4th or it is the state by unexpected failure.

III. MAIN STATE AND SUB STATE MODELING

The state of system was described in Figure 1, to utilize the Markov state model by applying Table 1. 5 states were defined as main state and the main state m means the m^{st} main state. T_m indicates duration of the main state m in Fig 1, has the uncertainty and should be represented by the probability distribution. Therefore, the main state m is represented by a gamma distribution. Each state has the expectation and the variance.

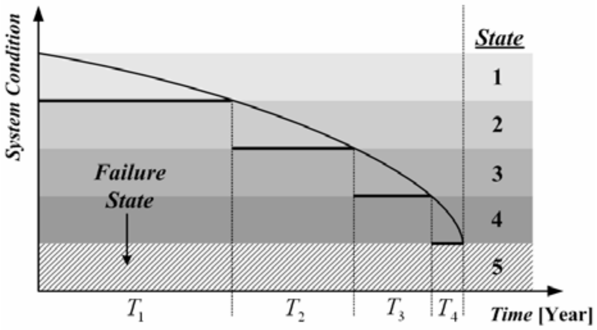

Fig. 1 Technical levels for main condition and life curve

Equation (1) is the failure density function of the gamma distribution in the main state m.

$$f(t) = \frac{1}{\alpha_m{}^{\beta_m}\Gamma(\beta_m)} \cdot t^{\beta_m - 1} \cdot e^{-\frac{t}{\alpha_m}} \quad (1)$$

where α_m indicates a scale parameter and β_m indicates a shape parameter. The relation between α_m and β_m is the same as the equation (2) and (3).

$$\beta_m = \frac{E(T_m)^2}{Var(T_m)} \quad (2)$$

$$E(T_m) = \alpha_m \beta_m \quad (3)$$

where $E(T_m)$ and $Var(T_m)$ indicate the expectation and the variance of the gamma distribution each. The main state m in the gamma distribution represents S_m in the exponential distribution to express the state of system in detail. S_m is the number of exponential distribution within main state m and all numbers of exponential distribution are represented as $s = 1, 2, \Lambda\ S_m$. In addition, the exponential distribution within the main state is defined as sub state. The gamma distribution is represented by the sum of each exponential distribution so that the relation between β_m and S_m of the gamma distribution in the main state m is the same as equation (4).

$$S_m \geq \beta_m \qquad S_m \in \{1, 2, 3, \mathrm{K}\} \quad (4)$$

The relation between expectation and variance of the exponential distribution is

$$Var(T_{m,s}) = E(T_{m,s})^2 \quad (5)$$

where $E(T_{m,s})$ and $Var(T_{m,s})$ represent the expectation and the variance of the S^{st} sub state in the main state m.

If all sub states in exponential distribution are independent in probability, $E(T_{m,s})$ and $Var(T_{m,s})$ are represented as (6) and (7).

$$E(T_m) = \sum_{s=1}^{S_m} E(T_{m,s}) \quad (6)$$

$$Var(T_m) = \sum_{s=1}^{S_m} Var(T_{m,s}) \quad (7)$$

The condition of system becomes worse rapidly if the life of system comes to an end. In the case of considering this, the relation between expectations of random sub state and former sub state in exponential distribution is

$$E(T_{m,s}) = f_{red,m} \cdot E(T_{m,s-1}) \quad (8)$$

where $f_{red,m}$ is a reduction factor $(f_{red,m} < 1)$. If (8) is represented by using $E(T_{m,1})$ of 1st sub state, $E(T_{m,s})$ is

$$E(T_{m,s}) = E(T_{m,1}) \cdot (f_{red,m})^{(s-1)} \quad (9)$$

Also, if express $E(T_m)$ by using (9), it can be expressed as (10).

$$E(T_m) = E(T_{m,1}) \cdot \sum_{s=1}^{S_m} f_{red,m}{}^{(s-1)} \quad (10)$$

If use (7) and (10), the variance of T_m is

$$Var(T_m) = E(T_{m,s})^2 \cdot \sum_{s=1}^{S_m} \left[f_{red,m}{}^{(s-1)} \right]^2 \quad (11)$$

Therefore, the shape parameter β_m of the gamma distribution can be expressed with (2), (10), and (11) as.

$$\beta_m = \frac{\left[\sum_{s=1}^{S_m} f_{red,m}{}^{(s-1)} \right]^2}{\sum_{s=1}^{S_m} \left[f_{red,m}{}^{(s-1)} \right]^2} \quad (12)$$

where $E(T_{m,1})$ and $f_{red,m}$ can be computed by (10) and (12). Also, the failure state F can be represented as (13).

$$F = \sum_{m=1}^{4} S_m + 1 \tag{13}$$

IV. MODEL ASUMPTIONS

The system is analyzed that is maintained according to the following specifications.

A. The system is subjected to a deterioration process. The deterioration process of system condition is modeled by the stepwise Markov model in detail.
B. Each inspection reveals the system degradation state.
C. Inspection about system is carried out periodically, is perfect and does not affect in the state of system.
D. If the state of system is in main state 1, 2, and 3 after the inspection, PM is not carried out. In it is in main state 4, PM is carried out.
E. If the system is failed, CM (*Corrective Maintenance*) should be carried out.
F. After a maintenance action, either PM or CM, the system is replaced or repaired to an "as good as new" state.
G. The cost for executing CM is more expensive than PM and the cost for PM is more expensive than inspection.

V. STEPWISE MARKOV STATE MODEL

λ_i indicates transition rate from i state to $i+1$ state.

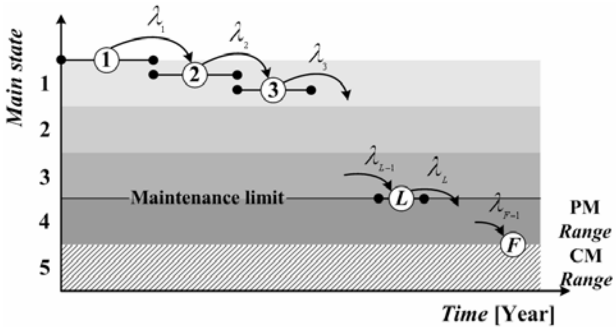

Fig. 2 Maintenance strategy in the Markov state model

Therefore, the expectation in state i is $E(T_i)$ and it can be represented as (14) and Figure 2.

$$E(T_i) = \frac{1}{\lambda_i} \tag{14}$$

If the maintenance limit that PM is carried out is represented as L, PM is carried out when the state of system is $L \le i < F$. CM is carried out when the system is failed. The Markov state model is the same as Figure 3 if it is represented by block diagram. The main state 1, 2, 3, and 4 includes each sub state in Figure 3. For example, if there is sub state by the number of S_2 in the main state 2, the main state 2 can be represented by the number of S_2 as Figure 3. Also, the state F indicates the failure of system and the state I indicates the inspection checking system. The state M indicates implementing PM after inspection in the main 4. The state of system becomes good as new after execution because PM and CM are perfect.

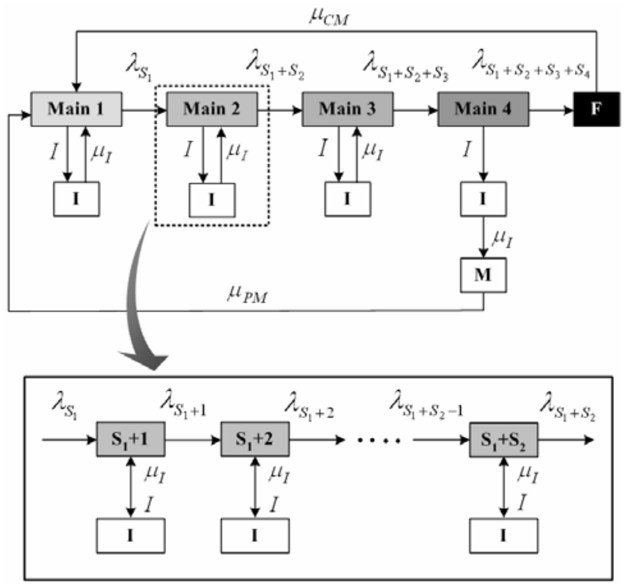

Fig. 3 Main state and Sub state in Markov state model

$1/I$, $1/\mu_I$, $1/\mu_{CM}$ and $1/\mu_{PM}$ are supposed as follows

$1/I$: mean uptime to the next inspection (inspection interval)
$1/\mu_I$: mean duration of inspection
$1/\mu_{CM}$: mean duration of corrective maintenance following a deterioration failure
$1/\mu_{PM}$: mean duration of preventive maintenance

VI. COSTS

If know the cost in operating system which is PM, CM, Inspection and total cost, the steady state probability and visit frequency of each state should be calculated [3, 4, 9]. The expected CM, PM, and inspection cost per year are

$$\begin{aligned} &PM\ cost = C_P \times frequency\ of\ maintenance \\ &CM\ cost = C_C \times frequency\ of\ failure \\ &Inspection\ cost = C_I \times frequency\ of\ inspection \end{aligned} \tag{15}$$

C_C is the repair cost after failure [won/time]. C_P is the maintenance cost [won/time] and C_I is the inspection cost [won/time].

Therefore, the expected total cost per year is

$$Total\ cost = CM\ cost + PM\ cost + Inspection\ cost \quad (16)$$

VII. CASE STUDY

RCM plan using the Markov state model in this study was applied to combustion turbine generating unit in Korean power systems. It needs the conformation about the functions of system or sub system for estimating RCM of system and the process of blocking by function after classifying the criterion of system or sub-system. Therefore, if apply the process that mentioned above to combustion turbine generating unit in case study, it is the same as Figure 4.

Case study was carried out to sub system of combustion turbine generating unit. However, it was difficult to get the data from 'Boiler/Turbine assistance device'. The Markov state model was applied to 4 installations such as 'Gas turbine equipment', 'Boiler equipment', 'Electrical device' and 'Control system / Computing equipment'.

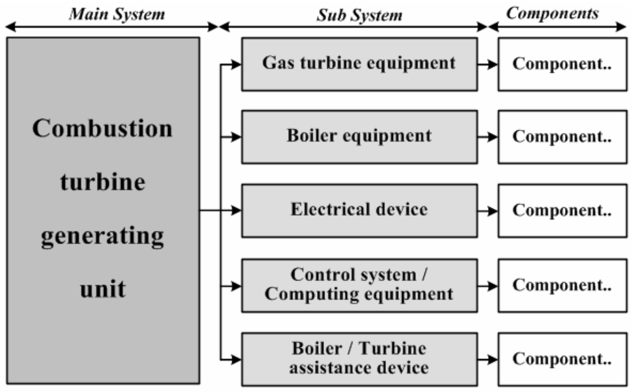

Fig. 4 Decomposition level of system of combustion turbine generator

The expectation and the standard deviation of each main state with considering the life of collected sub system are the same as Table 2.

Table 2 Main state modeling for each sub system in combustion turbine generator

Main State m		$E(T_m)$	$SD(T_m)$
Gas turbine equipment	1	4.793	1.567
	2	0.799	0.534
	3	0.559	0.324
	4	0.240	0.169
Boiler equipment	1	4.187	1.369
	2	0.698	0.467
	3	0.489	0.283
	4	0.209	0.148
Electrical device	1	5.330	1.743
	2	0.888	0.594
	3	0.622	0.361
	4	0.266	0.188
Control system / Computing equipment	1	1.549	0.507
	2	0.258	0.173
	3	0.181	0.105
	4	0.077	0.055

The Markov state model was applied to the expectation and the variance of each main state. α_m, β_m, $f_{red,m}$, and $E(T_{m,1})$ of all sub systems were calculated as Table 3

Table 3 Calculated α_m, β_m, $f_{red,m}$, and $E(T_{m,1})$ for main state of each sub system

Main State m		α_m	β_m	$f_{red,m}$	$E(T_{m,1})$
Gas turbine equipment	1	0.521	9.356	0.9121	0.7005
	2	0.357	2.239	0.4654	0.4750
	3	0.188	2.977	0.8978	0.2067
	4	0.119	2.017	0.3878	0.1560
Boiler equipment	1	0.448	9.354	0.9119	0.6122
	2	0.321	2.234	0.4636	0.4159
	3	0.164	2.986	0.9195	0.1769
	4	0.098	2.136	0.4289	0.1296
Electrical device	1	0.570	9.351	0.9117	0.7801
	2	0.397	2.235	0.4639	0.5288
	3	0.210	2.969	0.8822	0.2338
	4	0.133	2.002	0.3827	0.1740
Control system / Computing equipment	1	0.166	9.334	0.9105	0.2278
	2	0.110	2.224	0.4600	0.1543
	3	0.061	2.972	0.8877	0.0676
	4	0.039	1.960	0.7500	0.0440

The main state and the sub state of boiler equipment using Table 3 is the same as Figure 5. The main state 1 of boiler equipment among sub systems of combustion turbine generating unit has 10 sub states and the main state 2, 3, and 4 have 3 sub states each. It can be known if it is calculated by Table 3.

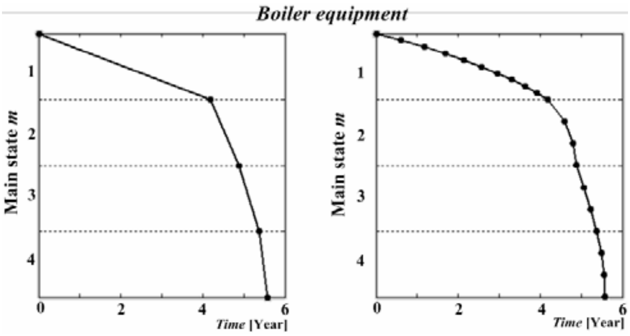

Fig. 5 Boiler equipment Life curve with main states and all sub states

The cost for operating electrical device was supposed as follows

$1/\mu_{CM}$ = 0.017 [Year]
$1/\mu_{PM}$ = 0.01 [Year]
$1/\mu_{I}$ = 0.003 [Year]
C_C = 600 [1,000,000 won/time]
C_P = 200 [1,000,000 won/time]
C_I = 10 [1,000,000 won/time]

PM, CM, inspection, and total cost were represented as Figure 6 by using (15) and (16).

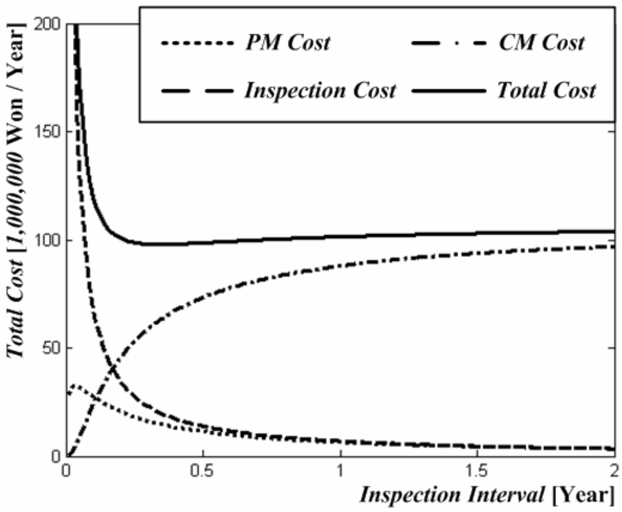

Fig. 6 PM , CM, Inspection and Total cost curve of the boiler equipment

Changes in CM cost, PM cost, inspection cost, and total cost of boiler equipment can be confirmed if change the mean uptime to the next inspection which is inspection interval as Figure 6. As the inspection interval becomes longer, the number of PM and inspection action are decreased. Therefore, PM cost and inspection cost are reduced. In contrary, the number of CM action is increased as inspection interval is extended so that CM cost is also increased. Therefore, the optimal inspection interval can be found that minimizes cost in curve of total cost.

Table 4 MTTF and optimal inspection interval of all sub systems [Year]

Sub System	MTTF without PM	MTTF with PM	Inspection interval
Gas turbine equipment	6.3910	8.84	0.41
Boiler equipment	5.5830	9.57	0.34
Electrical device	7.1060	11.67	0.47
Control system / Computing equipment	2.065	2.72	0.33

Table 4 represents the optimal inspection interval of each sub system. Also, Mean time to failure (*MTTF*) is represented with applying PM to system and without. In Table 4, it can be confirmed that MTTF of system is extended when PM plan is applied.

VII. CONCLUSION

This study suggested how to schedule RCM plan by using the Markov state model for optimal maintenance plan and applied the model to combustion turbine generating unit in Korean power systems. In this paper, time for practicing PM was decided for inspecting condition of system and the optimal inspection interval for the minimum cost was decided by calculating CM, PM, inspection and total cost.

As inspection interval is short as much as possible, MTTF of system can be extended and the number of CM action can be reduced but, PM and inspection cost is increased. Therefore the calculation of optimal inspection interval is useful.

However, this study did not examine imperfect PM and CM of Markov state model. Therefore, the future study about this point should be enforced afterward.

ACKNOWLEDGEMENTS

For the research presented in this paper the authors gratefully acknowledge the generous financial support provided by Korea Railroad Research Institute (*KRRI*)

REFERENCES

1. M. Rausand, "Reliability centered maintenance," *Reliability Engineering and System Safety*, vol. 60, pp. 121-132, 1998
2. Yhomas M. Welte, Jørn Vatn and Jørn Heggset, "Markov State Model for Optimization of Maintenance and Renewal of Hydro Power Components," *9th PMAPS KTH*, Stockholm, Sweden, 11-15 June, 2006
3. P. Jirutitijaroen and C. Singh, “The effect of transformer maintenance parameters on reliability and cost : a probabilistic model,” *Electric Power Systems Research*, pp. 213-224, 2004
4. George J. Anders and Armando M. Leite da Silva, “Cost Related Reliability Measures for Power System Equipment,” *IEEE Trans. Power System*, vol. 15, No. 2, May 2000
5. Wenjian Li and Hoang Pham, “An Inspection-Maintenance Model for Systems With Multiple Competing Processes,” *IEEE Trans. Reliability*, vol. 54, No. 2, June 2005
6. Suprasad V. Amari and Leland McLaughlin, “Optimal Design of a Condition-Based Maintenance Model,” *RAMS* 2004
7. R. Billinton and R. N. Allan, *Reliability Evaluating of Engineering System*, Plenum Press, 1992
8. J. Crowder, A. c. Kimber, R. L. Smith and T. J. Sweeting, *Statistical Analysis of Reliability Data*, Chapman and Hall, 1991
9. M. Rausand and A. Høyland, *System Reliability Theory*, Wiley-Interscience 2004