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Generalized Reliability Centered Maintenance Modeling Through Modified Semi-Markov Chain in Power System

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Abstract - The purpose of power system maintenance is to prevent equipment failure. The maintenance strategy should be designed to balance costs and benefits because frequent maintenance increases cost while infrequent maintenance can also be costly due to electricity outages. This paper proposes maintenance modeling of a power distribution system using reliability centered maintenance (RCM). The proposed method includes comprehensive equipment modeling and impact analysis to evaluate the effect of equipment faults. The problem of finding the optimum maintenance strategy is formulated in terms of dynamic programming. The applied power system is based on the RBTS Bus 2 model, and the results demonstrate the potential for designing a maintenance strategy using the proposed model.

Keywords: Reliability centered maintenance (RCM), Power system equipment modeling, Modified semi-Markov chain, Impact analysis, Dynamic programming

1. Introduction

The main objective of maintenance is to prevent equipment failure or extend the mean time to the next failure. Maintenance activities can impact the frequency of failure by preventing the cause of failure. The frequency or duration of interruptions is related to the reliability of the distribution system.

One method for relating reliability to maintenance is reliability centered maintenance (RCM). The main feature of RCM is that it focuses on preserving the availability of the systems. The concept of RCM originated from the aircraft industry and was applied to other industries, such as nuclear power and offshore oil and gas, among others [1]. The application of RCM to transmission and distribution systems has also been studied [2-5].

In this paper, a comprehensive model for a power distribution system is developed. The model contains equipment state modeling using Markov chains and system impact analysis. It also considers systematic approaches for maintenance scheduling.

This paper is organized as follows. Section 2 reviews the RCM and RCM studies applied to power distribution systems. Section 3 explains the basic equipment modeling method. Section 4 is composed of three parts. The first part is the description of maintenance modeling for realizing the required specification. The second part is the impact analysis to evaluate the effect of equipment faults from a systematic point of view. The third part is the description of the dynamic programming formulation. Section 5 presents the case study and section 6 provides the conclusion.

2. Background

RCM is a preventive maintenance (PM) that maintains or improves the availability of the systems. RCM is designed to balance costs and benefits. Its main objective is to minimize cost by focusing on the essential functions of the system and avoiding unnecessary maintenance actions.

According to the Electric Power Research Institute (EPRI), RCM is a systematic consideration of system functions, the way functions can fail, and a priority-based consideration of safety and economics that identifies applicable and effective preventive tasks.

An RCM analysis mainly provides answers to the following seven questions [1]:

1. What are the functions and associated performance standards of the equipment in its present operating context?
2. How does it fail to fulfill its functions?
3. What is the cause of each type of functional failure?
4. What happens when each type of failure occurs?
5. How does each type of failure matters?
6. What can be done to prevent each type of failure?
7. What should be done if a suitable preventive task cannot be found?

RCM is a method for relating reliability to maintenance. Insufficient maintenance increases the outage cost and decreases the reliability level because of frequent failure. In

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contrast, excessive maintenance increases the cost of maintenance while decreasing equipment failure and outage costs.

The concept of RCM is described in many literature [1-5]. A number of papers focus on the relation between reliability and cost and on models for RCM using Markov chains [3-5]. The model in [3] determines a maintenance interval very similar to another maintenance method called time-based maintenance. The model in [4] determines the inspection interval; however, within the RCM framework, a varying failure rate is required for calculation on a yearly basis. The model in [5] includes various maintenance activities, but it decides on the maintenance method based only on the maintenance cost and associated probability.

In this paper, we proposed a comprehensive model for RCM that focuses on preserving system functions and system reliability. Using the proposed model, the optimal inspection interval and maintenance decisions can be determined simultaneously based on the impact of equipment maintenance to the system.

3. Basic Equipment Modeling

The state of equipment can be simply modeled as shown in Fig. 1: normal (N) state and failure (F) state. Events, for instance failure and repair, induce state transitions. Transition rates such as failure rate (λ) and repair rate (μ) are the reciprocals of the mean time to failure (MTTF) and mean time to repair (MTTR), respectively.

$$\lambda = \frac{1}{MTTF}, \qquad \mu = \frac{1}{MTTR} \tag{1}$$

The model in Fig. 1 can be expanded by considering deterioration and maintenance. The model of the equipment state including deterioration is shown in Fig. 2, where the state D is the deterioration state.

The transition matrix is as follows:

$$Q = \begin{bmatrix} -(\lambda_1+\lambda_3) & \lambda_1 & \lambda_3 \\ \mu_1 & -(\lambda_2+\mu_1) & \lambda_2 \\ \mu_3 & 0 & -\mu_3 \end{bmatrix} \tag{2}$$

The state transition probability is given by λ / Λ, where Λ is the total event rate. The transition probabilities of the model in Fig. 2 are given by the following:

$$P_{ND} = \frac{\lambda_1}{\lambda_1+\lambda_3}, P_{NF} = \frac{\lambda_3}{\lambda_1+\lambda_3}, P_{DF} = \frac{\lambda_2}{\lambda_2+\mu_1}, \\ P_{DN} = \frac{\mu_1}{\mu_1+\lambda_2}, P_{FN} = 1 \tag{3}$$

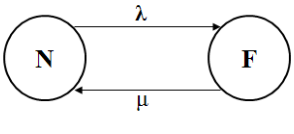

Fig. 1. Two-state equipment model.

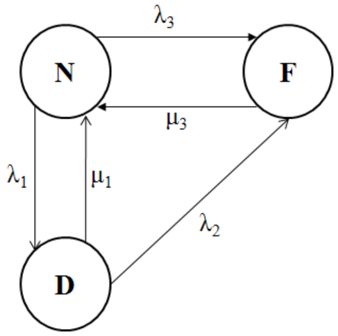

Fig. 2. Three-state equipment model.

Inspection is performed in order to ascertain the state of the equipment. Therefore, an equipment model, including inspection and maintenance, must be developed. The equipment model is suggested in the next section.

4. Comprehensive Model

4.1 Equipment Modeling

In this section, we propose a modified semi-Markov chain model for the equipment state. This process describes the deterioration of the equipment and the inspection and maintenance processes. Three types of equipment are chosen to illustrate the model in this paper. We propose the state model for these three types of equipment: overhead lines, cables, and circuit breakers. These equipment are installed in the distribution system and play very important roles in delivering electricity to end-use customers. The equipment may have different features and deterioration processes, thus the equipment model must be defined depending on the characteristics of the equipment. We define the deterioration state based on inspections used in the field.

4.1.1 Genetic Equipment Modeling

Without maintenance, the equipment ages as time advances and finally loses its functionalities. To decrease functional equipment failure and load outages, we need to inspect the equipment and decide whether to perform maintenance or not. These can be modeled using the Markov chain, as shown in Fig. 3 [6].

In Fig. 3, state N is the normal state, which indicates that the equipment is operating normally. The states D1 and D2 are the deterioration states, indicating that the equipment is aging as time advances; D2 is more significant than D1. The state F is the failure state, indicating that the equipment is not functioning adequately. The actions of inspection and maintenance are represented by “Ins” and “M”, respectively; these states are actions rather than equipment states. When an inspection is performed, the equipment is in the normal or deterioration state. If the equipment is in the normal state, hence no action is needed. On the other hand, if the equipment is in the deterioration state, then the

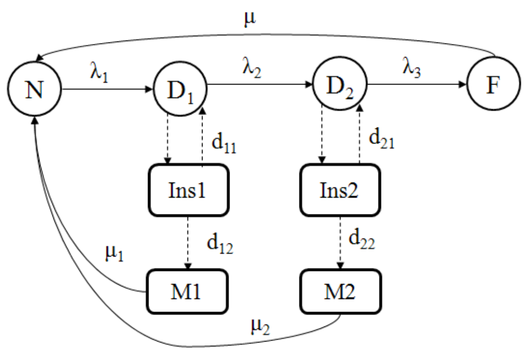

Fig. 3. Genetic equipment modelling.

state is "Ins". That is, the inspection state in Fig. 3 can only be activated at the inspection time. Therefore, inspection transitions are plotted as dashed lines.

After performing inspections at regular intervals, the inspector can decide whether the equipment needs maintenance or not. Decisions d_{11} and d_{21} refer to delaying equipment maintenance, while decisions d_{12} and d_{22} refer to performing equipment maintenance. We assume that the state reverts to normal once maintenance is performed. The decisions are aimed at minimizing the total expected cost, which is the sum of customer interruption cost, maintenance cost, and inspection cost. The equipment state and the impact of the equipment on the system must be considered when making maintenance decisions, which is a key point of this model.

Fig. 3 is a continuous-time Markov chain model. A Markov chain has the property of memorylessness, which has two aspects: one is that all past state information is irrelevant and the other is that inter-event times are exponentially distributed. A semi-Markov chain is an extension of a Markov chain where the second constraint is alleviated [6]. Because the inspection states are additionally considered and the maintenance decisions induce arbitrarily distributed inter-event times, this model is called a modified semi-Markov chain model.

In general, discrete-time Markov chain models are simpler to analyze [6]. The uniformization of a Markov chain is a means of transforming a continuous-time chain to a discrete-time Markov chain. The transition rates can be converted to probabilities through the uniformization of Markov chain. We can construct a stochastically equivalent uniformized discrete-time Markov chain by selecting a uniform transition rate γ. The uniform rate represents the actual total probability flow rate out of a state. In this model, the uniform rate is given by the following:

$$\gamma = \lambda_1 + \lambda_2 + \lambda_3 + \mu + \mu_1 + \mu_2 \tag{4}$$

All the transition probabilities are then obtained by dividing the original transition rates by γ and introducing self-loops. Fig. 4 shows the state transition diagram of the uniformized chain.

Note that the model allows for self-transitions where a state transitions back to itself, which is possible if the self-transition probability is nonzero. However, such self-transitions have no observable effects; because of the memoryless property of the exponential distribution, the remaining time until the next transition is the same [7].

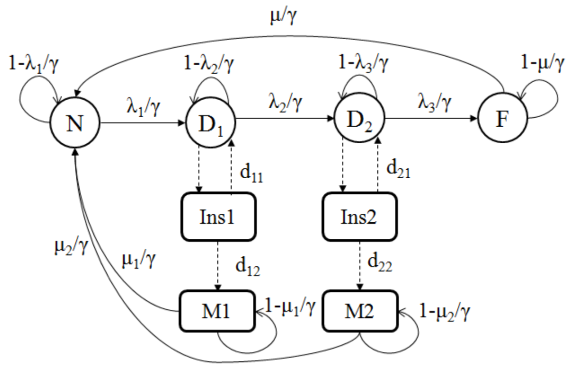

Fig. 4. State transition diagram of the uniformized chain.

4.1.2 Overhead Line

There are two important inspections for the overhead lines: the state of the protection cable and the overhead line erosion. State criteria for the overhead line depend on the erosion of the protection and overhead lines. If the inspection finds the protection cable and line erosion being in a normal condition, then the state of the overhead line can be defined as normal. If one of the protection cables and the line is eroded, the state of the overhead line can be defined as D1. If both are eroded, the state of the overhead line can be defined as D2. Table 1 shows the state criteria for overhead lines. An equipment state model of overhead line is the same as Fig. 3.

Table 1. State criteria of overhead lines

Protection cable	Line erosion	State
X	X	N
O	X	D1
X	O	
O	O	D2
Failure		F

4.1.3 Cable

To inspect a cable, isothermal relaxation current analysis is used to calculate the aging factors. It is a destruction-free method for determining the aging status of a dielectric. The insulation status can be determined by measuring the relaxation current in the time domain [8].

If a transient current or a recovery voltage across the insulation follows DC polarization of the cable insulation, we can predict the thermal release rate of charges from the traps in the aged samples. This polarization current is known as isothermal relaxation current. Isothermal relaxation current analysis is based on a relaxation model of the thermal release of carriers from the traps.

The aging factors are investigated using the depolarization currents measured with laboratory and field-aged cables. After the removal of the electric field, time-dependent reactions follow, by which the dipoles return to their random states within a few hundred seconds as a result of the thermal emission of electron. This depends on the aging status of the power cable insulation.

The states of a cable can be classified into four states according to the aging factors from the isothermal relaxation current analysis. Table 2 shows the aging factors and the state criteria of cables. The model of equipment state for cables is the same as Fig. 3.

Table 2. State criteria of cables

Aging factor	~1.85	1.85–2.60	2.60~	Failure
State	N	D1	D2	F

4.1.4 Circuit Breaker

The three inspections for the circuit breakers are the states of insulation, bushing, and adhesion. The equipment state is classified based on the results of these three inspections. If one result is unusual, the state of the circuit breaker can be defined as D1. If two results are unusual, the state can be defined as D2. Fig. 5 shows the modified semi-Markov chain modeling of circuit breakers, and Table 3 shows the state criteria for circuit breakers.

4.2 Impact Analysis

To analyze the impact of an equipment fault, there is a need to evaluate the system-wide effect in terms of three different aspects self-effect, downstream effect, and upstream effect [9].

First, the self-effect of the faulted section is considered. If an equipment fault occurs, all of the load points adjacent to the faulted section will not be supplied until the faulted section is repaired.

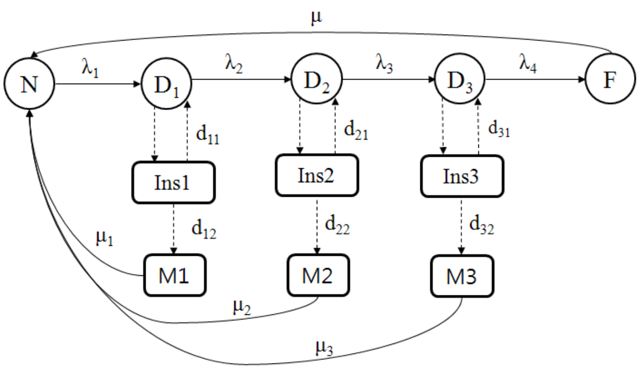

Fig. 5. Modified semi-Markov chain modeling for circuit breakers.

Table 3. State criteria of circuit breakers

Insulation	Bushing	Adhesion	State
O	O	O	N
O	O	X	D1
O	X	O	
X	O	O	
O	X	X	D2
X	O	X	
X	X	O	
X	X	X	D3
Failure			F

Secondly, the downstream effect of a faulted section is considered. If an equipment fault occurs, all the load points downstream from the faulted section will not be supplied until the faulted section is repaired. If the circuit breaker is installed, we should consider the switching effect in order to analyze the fault effect. The switching time is generally shorter than the repair time of the faulted section. If any isolating switch exists, partial load points between the faulted section and the section where any isolating switch exist closet downstream from the faulted section will not be supplied until the isolating switch is operating. After isolating the faulted section, the loads that would otherwise be left disconnected until repairs are completed can now be transferred to another part of the system. That is, the outage time of downstream loads is the switching time. This is the effect of transferring loads [10].

Lastly, the upstream effect of the faulted section is considered. If an equipment fault occurs, it can have an impact on the upstream load points from the faulted section. The upstream load points will experience outage during the switching time needed to isolate the faulted section.

The impact of an equipment fault can be evaluated in terms of the three aspects mentioned previously. The customer interruption cost can be calculated based on this impact analysis. In addition, the impact analysis is applied to make maintenance decisions.

4.3 Dynamic Programming Formulation

From the above equipment model and impact analysis, one of the objectives of the RCM method is to find the optimal inspection interval and the maintenance decision to minimize the total expected cost. The problem of finding the optimal inspection interval τ and the corresponding decisions can be formulated as a dynamic programming (DP) problem, including equipment states and control inputs (decisions), because it deals with cases of multi-stage decisions [11, 12]. Time is broken into a series of stages, with a decision made at each time stage of the inspection process. The equipment state can be expressed as the following equation:

$$x_{k+1} = f(x_k, u_k, w_k) \qquad (5)$$

Where $k = 0, 1, \ldots$ is the time stage index; x_k is the state at time stage k; u_k is the control input at time stage k; and w_k is a random disturbance. The control input u_k has to be in the set of admissible controls. The problem is to find the control policy that will minimize the total cost over the end of time stage N.

The algorithm for finding the optimum policy can be expressed by the following equations:

$$J_N(x_N) = g_N(x_N) \tag{6}$$

$$J_k(x_k) = \min_{u_k \in U}\ \underset{w_k}{E}\{g_k(x_k, u_k, w_k) + J_{k+1}(x_{k+1})\} \tag{7}$$

Where $g_k(x_k, u_k, w_k)$ is the cost; $g_N(x_N)$ is the terminal cost; and $J_k(x_k)$ is the optimal expected cost starting at time stage k. The DP algorithm starts by finding the optimal cost-to-go for the last stage and then iterates backward to calculate $J_k(x_k)$ from $J_{k+1}(x_{k+1})$, which has already been calculated. Iteration continues until the time stage reaches 0.

In this problem, iteration can be divided into two parts because decisions are made only when the time stage is in the inspection time. The calculation time step is one day. Thus, the calculation procedure can be expressed by the following equations:

(i) Time stage k is not a multiple of τ:

$$\begin{aligned} J_k(\tau, x_i) &= E[C_{i,j} + J_{k+1}(\tau, x_j)] \\ &= \sum_j p_{i,j}[C_{i,j} + J_{k+1}(\tau, x_j)] \end{aligned} \tag{8}$$

(ii) Time stage k is a multiple of τ:

$$J_{k^+}(\tau, x_i) = \sum_j p_{i,j}[C_{i,j} + J_{k+1}(\tau, x_j)] \tag{9}$$

$$J_k(\tau, x_i) = \min_u [C_{i,j}(x_j, u_j) + J_{k+1}(\tau, x_j)] \tag{10}$$

$$J_{k^-}(\tau, x_i) = J_k(\tau, x_i) + C_{ins} \tag{11}$$

Where τ is the inspection interval; x_i is the state of the equipment; $J_k(\tau, x_i)$ is the total expected cost; p_{ij} is the transition probability; C_{ij} is the transition cost; and C_{ins} is the inspection cost.

The above process is iterated for τ from N to 0. We then find the optimal inspection interval and corresponding maintenance decisions needed to minimize the total expected cost.

5. Case Study

The RBTS Bus 2 is used for the case study. RBTS is a distribution system that contains the main elements found in practical systems of a small enough size and all the basic data needed to perform analysis [13].

The proposed models are applied to the RBTS Bus 2. In RBTS, residential, commercial, and government/institution loads are metered on the low-voltage side. The feeders are operated as radial feeders but are connected as a mesh through the normally open sectionalizing points. The loading level of Bus 2 (20 MW) only justifies a single supply point. Each feeder and lateral is one of three types, where the lengths used are 0.6, 0.75, or 0.8 km. It is assumed that the feeders (1, 12, 16, and 26) connected to the bus are cables and that the others are overhead lines.

Fig. 6 shows the distribution system for the RBTS Bus 2. The required data for analysis are the feeder types and length, as well as customer data. Tables 4 and 5 present the data for the feeder and customer. We assume the transition rate, repair time, and cost, as shown in Tables 6 and 7. The time step used for the simulation is one day.

Applying equipment state modeling to the RBTS Bus 2, the optimum maintenance strategy can be determined. The maintenance strategy consists of the inspection interval and maintenance decisions. The optimum maintenance strategy minimizes the total expected cost. The results of each feeder are shown in Tables 8-11. For example, the optimal inspection interval for feeder 1 is 59.6 [months] and involves optimal decisions to perform maintenance at the D2 and D3 states for CB1.

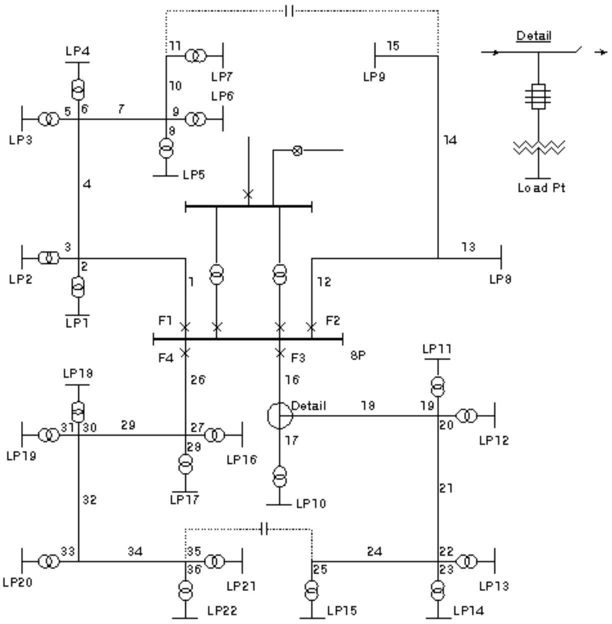

Fig. 6. Distribution system for RBTS Bus 2.

6. Conclusion

In this paper, we proposed a generalized reliability centered maintenance modeling through a modified semi-Markov chain for an overhead line, cable, and circuit breaker. The deterioration processes differ according to the equipment, and the deterioration states of the equipment are defined according to the inspection criteria used in the

Table 4. Feeder type and lengths

Type	Length (km)	Feeder section numbers
1	0.60	2, 6, 10, 14, 17, 21, 25, 28, 30, 34
2	0.75	1, 4, 7, 9, 12, 16, 19, 22, 24, 27, 29, 32, 35
3	0.80	3, 5, 8, 11, 13, 15, 18, 20, 23, 26, 31, 33, 36

Table 5. Customer data

Load points	Customer type	**Average load level per load point (MW)**	**Number of customers**
1–3, 10, 11	Residential	0.535	210
12, 17–19	Residential	0.450	200
8	Small user	1.00	1
9	Small user	1.15	1
4, 5, 13, 14, 20, 21	Govt./Inst.	0.566	1
6, 7, 15, 16, 22	Commercial	0.454	10
Totals		12.291	1,908

Table 6. Transition rate and repair time

	λ1 (f/yr)	λ2 (f/yr)	λ3 (f/yr)	λ4 (f/yr)	r (h/f)
Line	0.01	0.02	0.01	-	1
Cable	0.02	0.02	0.01	-	2
CB	0.024	0.024	0.024	0.036	1

Table 7. Cost data (1,000 KRW)

	Ins	Repair	M1	M2	M3
Line	1,000	6,768	2,256	6,768	-
Cable	1,000	28,377	9,450	28,377	-
CB	1,000	1,350	450	1,350	1,350

Table 8. Optimal maintenance strategy and cost for feeder 1

Optimal inspection interval	59.6 [months]		
Total expected cost [1,000 KRW/year]	11,282		
Maintenance cost [1,000 KRW/year]	4,215		
Component	Optimal decisions		
	D1	D2	D3
CB 1	D1	N	N
CB 2	D1	N	N
CB 3	D1	N	N
CB 4	N	N	N
Cable	N	N	-
Line 1	N	N	-
Line 2	N	N	-
Line 3	N	N	-

Table 9. Optimal maintenance strategy and cost for feeder 2

Optimal inspection interval	60.7 [months]		
Total expected cost [1,000 KRW/year]	2,722		
Maintenance cost [1,000KRW /year]	1,425		
Component	Optimal decisions		
	D1	D2	D3
CB 1	N	N	N
CB 2	D1	D2	N
Cable	D1	D2	-
Line	N	N	-

Table 10. Optimal maintenance strategy and cost for feeder 3

Optimal inspection interval	59.9 [months]		
Total expected cost [1,000 KRW/year]	7,171		
Maintenance cost [1,000 KRW /year]	2,501		
Component	Optimal decisions		
	D1	D2	D3
CB 1	D1	N	N
CB 2	N	N	N
CB 3	D1	D2	N
CB 4	D1	D2	N
Cable	D1	N	-
Line 1	N	N	-
Line 2	D1	N	-
Line 3	N	N	-

Table 11. Optimal maintenance strategy and cost for feeder 4

Optimal inspection interval	60.8 [months]		
Total expected cost [1,000 KRW/year]	8,434		
Maintenance cost [1,000 KRW/year]	2,493		
Component	Optimal decisions		
	D1	D2	D3
CB 1	N	N	N
CB 2	D1	N	N
CB 3	N	N	N
CB 4	N	N	N
Cable	N	N	-
Line 1	N	N	-
Line 2	N	N	-
Line 3	D1	N	-

field. From the proposed model, the optimal maintenance strategy consisting of the inspection interval τ and maintenance decisions can be determined. The optimal inspection interval τ and maintenance decisions minimize the total expected cost. The maintenance problem was formulated in terms of dynamic programming.

The proposed model was applied to the RBTS Bus 2, which enabled us to decide the optimal maintenance strategy that minimizes the total expected cost.

Acknowledgments

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