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Ordinal Optimization을 이용한 배전계통에 RCM 적용기법에 관한 연구

A Study on Application of RCM Method to Power Distribution System using Ordinal Optimization

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Abstract - This paper proposes optimal maintenance strategies for power distribution systems that involve the use of the reliability-centered maintenance (RCM) method. We developed an improved decision model based on the Markov process. This model can obtain the optimal inspection interval and maintenance method based on the total expected cost. We used ordinal optimization for solving the optimal problem. Optimal maintenance strategies were presented by applying the developed method to the RBTS model. A B/C analysis proved that these strategies offer maximum benefit-to-cost.

Key Words : Reliability-centered maintenance, Power distribution system, Ordinal optimization

1 Introduction

The main objective of the preventive maintenance of power system equipment is to prevent the failure of the equipment and extend its lifetime or its time to failure (TTF), thus ultimately minimizing the operating cost of the power system.

The preventive maintenance of power distribution systems includes measures such as the maintenance or replacement of aging equipment and the quick detection and settlement of failed equipment. In order to achieve these objectives, maintenance work can be classified into periodic inspection and repair or maintenance of equipment.

In all, these maintenance activities can be divided into time-based maintenance (TBM) and condition-based maintenance (CBM) activities. Periodic inspection corresponds to TBM, while repair or maintenance of equipment corresponds to CBM. The TBM method is based on the lifetime of equipment, and it places more emphasis on safety than on cost. On the other hand, CBM is an improved maintenance method that is based on the condition of the equipment. However, neither of methods can guarantee the highest cost-effectiveness. Moreover maintenance strategies in Korea stress more on safety than cost because of the characteristics of public enterprises.

However, the power system industry will attempt to achieve the maximum benefit through minimum cost, and consequently, the maintenance cost will be curtailed as much as possible. Thus, power system companies will require a more efficient maintenance method to minimize maintenance cost, while retaining the specified reliability level.

The RCM method was applied to the many engineering fields requiring maintenance techniques, such as the military forces, the nuclear power industry, the offshore oil and gas industry, and so on [1]. Several studies on RCM have confirmed significant reductions in maintenance cost or even enhanced system availability. As regards the power system field, RCM application to transmission and distribution systems has been studied for a few years [2,3].

Based on the RCM model, the most important studies on RCM can be divided into three parts as follows.

First, many published studies have emplyed the Markov model to determine the optimal maintenance interval. These models are helpful in deciding the optimal maintenance interval. However, the abovementioned method is not really RCM but TBM.

The second model is identical to the first model with the exception that the failure rate is not constant [2]. This model also provides the optimal maintenance interval as in the first model. However, this model is considered to be an improvement over the first model because it estimates the total cost, including the maintenance and interruption costs.

The third model involves the identification of the most

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improved and realistic method of all the models involving RCM for various maintenance activities [3]. However, the weakness of this model lies in the fact that the decision regarding which maintenance method to adopt is taken solely on the basis of probability, which is not a realistic scenario.

Further, all models are applied to one component, which is very different from the systematic approach. Whenever maintenance methods are applied to large systems such as power distribution systems, each component acquires different values according to its installed position. Hence, this aspect requires additional research.

In this paper, we propose optimal maintenance strategies for power distribution system equipment using the RCM method. In order to achieve this final objective, we first developed an improved decision model based on the Markov process. This model consists of deterioration stages that represent component aging and uses constant failure rates. Further, it can determine the optimal inspection interval, and not the maintenance interval, according to the total expected cost. The inspection results decide whether or not each component requires maintenance on the basis of the total expected cost and component conditions. We used ordinal optimization which allows the determination of enabled us good enough solutions and decreases the calculating time considerably.

2. RCM model

2.1 Power distribution system maintenance

Time-based Maintenance(TBM) is one of the oldest and the simplest methods, and has been used most frequently until now. TBM is a maintenance method wherein the equipment is serviced or replaced per a fixed interval (e.g. 1 month, 1 year, or 5 years) independent of its condition (wear-out) at that time. Although it is evident that TBM is the simplest maintenance method, it is not an optimal maintenance method when the benefit-to-cost is considered.

Condition-based Maintenance (CBM) is a maintenance method for fixing or replacing a equipment based on its condition at random intervals. It is relatively reasonable to replace large equipment if some defects have been discovered after the large equipment are inspected, and evaluated measured with respect to some set standards. Nevertheless, CBM has a limit that should be applied to large equipment, because the inspection and evaluation of the condition of the equipment is an expensive procedure.

Reliability-centered Maintenance (RCM) is a method for establishing a preventive maintenance program that will efficiently and effectively allow the achievement of the required safety and availability levels of equipment and structures, which is intended to result in improved overall safety, availability and economy of operation [4].

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 maintenance (PM) tasks.

In other words, RCM can determine the most cost-effective maintenance interval and methods based on the failure rate, the upfront maintenance cost, and the potential customer interruption cost of losing loads, etc, by maintaining the desired reliability level.

2.2 Proposed RCM model

In this paragraph, we describe the proposed new RCM model called “Decision Model” and the solution techniques as dynamic programming.

1) Model & Objective Function

The proposed decision model is shown in Fig. 1.

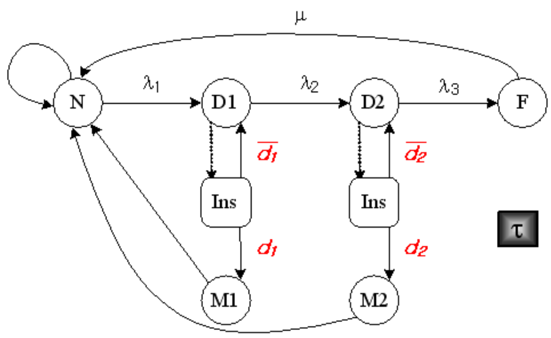

Fig. 1 Proposed decision model

where “N” is the normal state; “D1” and “D2” the deterioration states; and “F” the failure state. Also “Ins” represents the inspection state, and “M1” and “M2” are the minor and major maintenances, respectively. When we inspect the equipment every τ weeks, the equipment can be at any state, N, D1, D2, or F, and it is decided by the probability of the failure and the repair rate.

When the component is in state D1 or D2, we have to decide whether to undertake equipment maintenance (d_1, d_2) or do nothing ($\overline{d_1}, \overline{d_2}$) at the inspection state. The decision is based on the total expected cost. This is the main idea of this model.

The objective function is represented by the total expected cost, J. The total expected cost involves two costs represented by C_{ins} and $C_{i,j}$. C_{ins} is the inspection cost incurred by every τ intervals. $C_{i,j}$ includes four costs such as minor/major maintenance cost, replacement cost, repair cost, and customer interruption cost; These costs are selected by the values of i and j.

In order to express the objective function mathematically, some assumptions must be made as follows.

- The configuration of the Power distribution system does not vary until next inspection time
- An average load is used instead of the real time load
- The conditions of all components are known. This is reasonable because if the current maintenance method is used, the condition of the components can be estimated.

Thus, the objective function of this model can be represented mathematically by equation (1).

$$\min_{\tau, x_i} J_0(\tau, x_i) \tag{1}$$

(1) Reliability constraints
; SAIFI(τ, x_i) < SAIFI*, SAIDI(τ, x_i) < SAIDI*

(2) Cost constraint ; $0 < J_0(\tau, x_i) \leq C_{max}$

This function is divided to two parts according to k as following.

(1) Probability part (k is not a multiple of τ)

$$J_k(\tau, x_i) = \sum_{j \in i} p_{i,j}\left[C_{i,j} + J_{k+1}(\tau, x_j)\right] = p_{i,i}\left[C_{i,i} + J_{k+1}(\tau, x_i)\right] + \sum_{m=1}^{N_E} p_{i,j}\left[C_{i,j} + J_{k+1}(\tau, x_j)\right] \tag{2}$$

where if $4^m \times s < (i + 4^{m-1}) \leqq 4^m \times s + 4^{m-1}$, j is $[(i+4^{m-1}) - 4^m]$, otherwise j is $(i + 4^{m-1})$, $m = 1, 2, \cdots, N_E$, $s = 1, 2, \cdots, 4^{N_E - m}$, $0 \leqq k \leqq N$, and $\tau = 1, 2, \cdots$, N.

(2) Decision part (k is a multiple of τ)

1) $J_{k^+}(\tau, x_i) = \sum_{j \in i} p_{i,j}\left[C_{i,j} + J_{k+1}(\tau, x_j)\right]$ (3a)

2) $J_k(\tau, x_i) = \min_{j \in i}\left[C_{i,j} + J_{k^+}(\tau, x_j)\right]$ (3b)

3) $J_{k^-}(\tau, x_i) = J_k(\tau, x_i) + C_{INS}$ (3c)

where

$J_k^\tau(x_i)$: Total expected cost at node (state) i accumulated from time N to k

x_i, x_j : Each node (state)

N_E : The number of equipment

$p_{i,j}$: Transitional (branch) probability from node (state) i to j

$C_{i,j}$: Transitional cost from state i to j

N : Total operating time [hour]

τ : Inspection time [hour], 1, 2, ..., N

$j \in i$: means the all nodes (state) j connected to node (state) i

The known good technique for decision problems as equation (1) is dynamic programming (DP). Fig. 2 shows the DP diagram for 1 component when τ is 5. If k is not equal to a multiple of τ, the state of the equipment changes according to the failure rates and repair rate. If k is equal to a multiple of τ and the state of equipment is on D1 or D2, we have to decide whether to undertake maintenance or do nothing, which depends on the total expected cost, J.

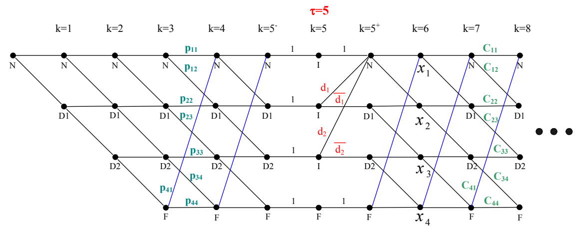

Fig. 2 DP diagram of 1 component

DP can provide the best solution. However, as the number of equipments increases, the number of nodes increases exponentially. For example, if the number of equipments is 10, the number of nodes increases to 4^{10}. This indicates that DP requires a very large calculation time, although it can provide the best solution.

Radial power distribution systems can be converted to a series Markov model. A power distribution system has a number of series-connected components and each component should be converted to the Markov model to evaluate the reliability and to apply various maintenance methods. However, the changed Markov model has 4^{N_E} nodes to apply DP to the model as described in this paper. This implies that as the number of components increases, the number of nodes grows infinitely. Further, the failure rates and customer interruption costs are uncertain. These values represent the means of probability or subjective values and not the exact values. Thus it is reasonable to use ordinal optimization while providing good enough solutions with a high probability although it may not provide the best solution.

3. Application of ordinal optimization to power distribution system maintenance

3.1 Ordinal optimization

Ordinal optimization is an approach for determining a solution to an optimization problem in which a large number of possible policies have to be considered. In ordinal optimization, the objective is not to determine the one best policy but rather to select a policy which, due to its significantly high probability, is has the highest percentile of ranking among all possible policies [5,6].

Ordinal optimization has three basic steps. First, the size of the good enough solution (g) is selected. Second, a subset of the N policy samples (s) is chosen. The size of this subset (s) should be sufficiently large to enable at least one "good enough" solution to be included in g with high probability. Finally, the policy choices in the selected subset can be provided with a more thorough evaluation and the best policy among these is chosen.

3.2 Power distribution system model for case studies

The distribution system model used in this paper is shown in Fig. 3; This is called Roy Billinton Test System (RBTS) bus 2 model [8].

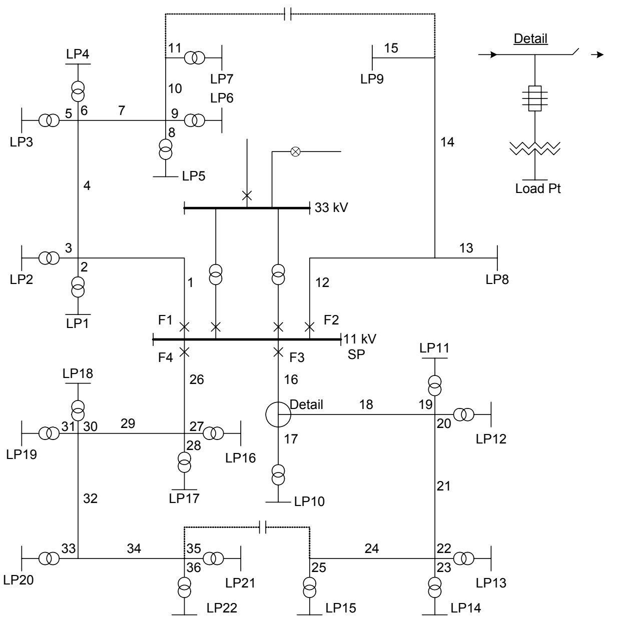

Fig. 3 RBTS bus 2 model

The model system has a 100% reliable substation (33kV/11kV) and 4 feeders with failure rates. We assumed that the first sections of all feeders are cable lines and the others are overhead lines. The data related to this model are represented in Table 1~3 and reference [8]. The switching time for all cases is assumed to be 1 [h].

Table 1 Failure and repair rate of equipments

Equipment	λ [f/yr]	r [hr/f]
Transformer	0.0005	2
COS	0.002	3

Table 2 Failure and repair rate of equipments for RCM

Equipment	λ_1 [f/yr]	λ_2 [f/yr]	λ_3 [f/yr]	r [hr/f]
Overhead line [/km]	0.1	0.2	0.1	1
Cable [/km]	0.2	0.2	0.1	2
Breaker	0.036	0.018	0.012	3

Table 3 Customer interruption cost surveyed from Canada (1000₩/kW)

Customer types	Duration of interruption				
	1 [min]	20 [min]	1 [hr]	4 [hr]	8 [hr]
Residential	0.021	0.093	0.482	4.914	15.69
Commercial	0.881	2.969	8.552	31.32	83.01
Office building	4.778	9.878	21.06	68.83	119.2
Industrial	1.625	3.868	9.085	25.16	55.81

3.3 Applying ordinal optimization to the model system

Ordinal optimization is applied to RBTS in order to obtain the optimal maintenance strategies. Firstly, the failure modes are analyzed and the effected load points are searched for the model. Next, ordinal optimization is applied. The procedure of ordinal optimization is as follows; problem formulation, setting search space, procuring sample ordered performance curves, performing Monte Carlo simulation, and obtaining the optimal strategies. Finally, optimal strategies and the related reliability indices are analyzed

3.3.1 Failure mode & effect analysis (FMEA)

FMEA results for feeder 2 are shown in Table 4. Where T_r and T_s are the repair time and switching time required to separate the faulted section, respectively.

Table 4 FMEA of feeder 2

Series/ Parallel	Component		Effected LP	Outage time
	Name	No.		
Series components	CB1	5	All (1~22)	Tr
	CB2	6	8,9	Tr
	Cable	12	8	Tr
			9	min(Ts,Tr)
	Line1	14	9	Tr
			8	min(Ts,Tr)
Parallel components	Line1	13	8	Tr
			9	min(Ts,Tr)
	Line2	15	9	Tr
			8	min(Ts,Tr)

3.3.2 Ordinal optimization

Step 1) Problem formulation

$$\min_{\theta\in\Theta} J^{x_1}(\theta) = E\left[L(\theta)\right] \tag{5}$$

where L is a sample performance; Θ, search space; and θ, the design parameter vector. In other words, the problem is finding the optimal θ in the full search space Θ to minimize the performance (total expected cost).

Step 2) Setting search space

θ is $[(N_E+1)\times 2]$ vector. For a 3-component system, If θ is [100 0 ; 1 1 ; 0 1; 0 0], this implies that the inspection interval is 100 days and the decision for the component 1 is D1 to N and D2 to N, the decision for the component 2 is D1 to D1 and D2 to N, and the decision for the component 3 is D1 to D1 and D2 to D2.

The full search space is calculated by multiplying τ with the decision cases. That is, τ is from 1 to 365×30 days, and there are 4 decision cases when the number of components is 1 and 65,536 decision cases when the number of components is 8. Thus the full search space equals $\Theta = 365 \times 30 \times 65{,}536 = 717{,}619{,}200$ if the life time of the equipment is 30 years. As the number of components increases, the decision cases increase infinitely. Therefore, we reduced the search space. The basic concepts are as follows;

1) In a real problem, it is assumed that the value of τ is 5 years or less.

2) For series-connected systems, it is impossible that a component at an important position is left as it is while a component at a less important position is maintained simultaneously. Therefore, if the component at the more important position is in state D1 and the decision is D1, the decision of the component at the less important position should be D1 when the component is in state D1. Similarly, if the component at the more important position is in state D2 and the decision is D2, the decision of the component at the less important position should be D2 when the component is in state D2.

3) For a component, it is impossible that the component in state D1 is maintained, while and the one in state D2 is left as it is.

Thus, the reduced full search space is calculated as follows.

Reduced full search space

- 3 cases for each component
- 3^8=6,561 decision cases for 8 components
- 6561 × (365×5) = 1,705,860 cases which are 0.237 [%] of the original full search space size

Step 3) Simulating the sample ordered performance curve

If the search space is set, the design parameter θ is selected randomly, and the sample ordered performance curve (OPC) is found by calculating the sample performance using the Monte Carlo Method. If about 1,000 performances are calculated, the sample OPC can be plotted as shown in Fig. 4. This OPC represents many good designs, which proves that ordinal optimization is suitable for the RCM problem.

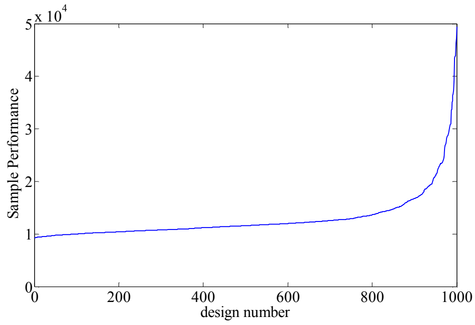

Fig. 4 Sample ordered performance for RCM

Step 4) Selecting the number of designs

Once the sample OPC is calculated, we have to decide the number of designs that will be selected. However the subset size selection is related to the size of the good enough solution. In step 3, because the RCM problem has many good solutions, we can select a large number of good enough solutions (g). 3,000 designs are selected in RCM problems. In this case, although the good enough solution is top-1 [%], probability that 1 sample among 3,000 belongs to the good enough solution is 99.82 [%].

Step 5) Performing simulation and selecting the good enough design

5-1) Randomly selecting the design parameters

The design parameter θ (τ and decision) is randomly selected in a reduced full search space.

5-2) Performing Monte Carlo simulation

If the design parameter is selected, it is not necessary to select the decision problem. Therefore, we calculate the total expected cost and the reliability indices using the Monte Carlo simulation method

5-3) Calculating the sample performance, J_i

The sample performance for one design parameter is calculated through step 5-2.

5-4) Repeating steps 5-1) ~ 5-3)

The sample performances for all chosen design parameters are calculated through step 5-1 to 5-3.

5-5) Selecting the design having minimal J

The design having minimal J is selected from the sample performances calculated in Step 5-4 and the design parameter that causes J to be minimal is selected for the good enough solution.

The flowchart of ordinal optimization applied to RBTS is shown in Fig. 5.

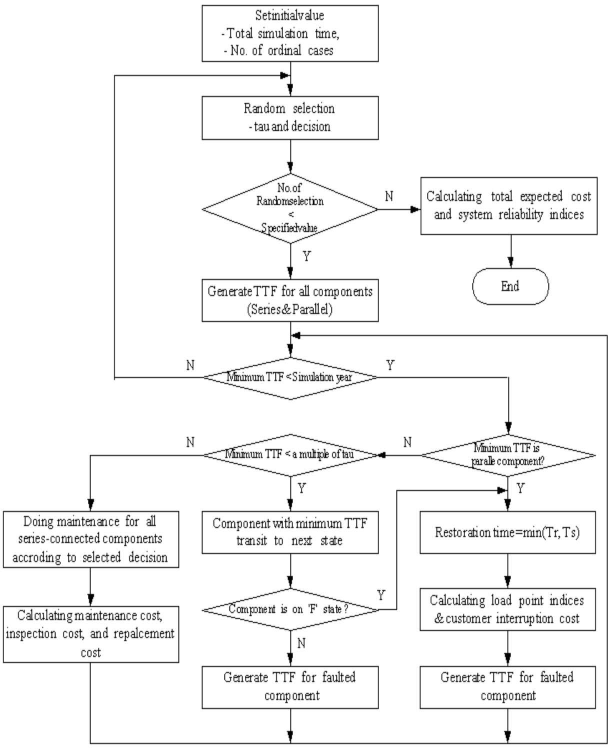

Fig. 5 Flowchart of ordinal optimization

The 3,000 random designs are selected for all feeders. The results of the application of ordinal optimization to RBTS are as follows; Table 5 lists the results of the optimal maintenance interval, total expected cost, and inspection and PM cost. Tables 6 and 7 give the results of the strategies with minimal total expected value and reliability indices, respectively.

For example, in Table 6, the optimal decision for CB2 of feeder 1 is that it should be maintained in state D2, while nothing should be done in state D1.

Table 5 Results of cost and optimal inspection interval

Feeder	Optimal inspection interval (τ) [week]	Total expected cost (J) [1000₩/year]	Inspection and PM cost [1000₩/year]
F1	236	8,983	2,498
F2	118	4,989	1,199
F3	241	8,436	2,507
F4	222	9,112	2,732

Table 6 Results of optimal maintenance strategies

Feeder	Component	Optimal decisions	
		D1	D2
F1	CB1	N	N
	CB2	D1	N
	CB3	N	N
	CB4	N	N
	Cable	N	N
	Line 1	N	N
	Line 2	N	N
	Line 3	N	N
F2	CB1	N	N
	CB2	D1	N
	Cable	N	N
	Line 1	D1	N
F3	CB1	N	N
	CB2	N	N
	CB3	N	N
	CB4	N	N
	Cable	N	N
	Line 1	N	N
	Line 2	N	N
	Line 3	N	N
F4	CB1	N	N
	CB2	D1	N
	CB3	N	N
	CB4	N	N
	Cable	N	N
	Line 1	N	N
	Line 2	N	N
	Line 3	N	N

Table 7 Results of reliability indices

Feeder	SAIFI [f/cus.year]	SAIDI [hr/cus.year]
F1	0.2156	0.1647
F2	0.0643	0.1975
F3	0.1845	0.1430
F4	0.2116	0.1625

4. Conclusions

Preventive maintenance has been used to extend the lifetime of components, prevent outages in systems, and consequently, reduce the maintenance cost in the power system industry. Thus far, the conventional maintenance methods mainly consisted of TBM and CBM. These methods have merits as well as demerits. However, these conventional methods are certainly not the most cost-effective ones.

In this paper, we have presented the most cost-effective maintenance strategies for power distribution systems by using the RCM method. The conventional RCM was transformed into a new concept in order to apply it to such systems.

The new RCM method was formulated by combining TBM and CBM. This decision model was developed in order to apply RCM to power distribution systems; the model can represent the failure process of components and decide the maintenance method based on the total expected cost. Moreover, it would be possible to use the developed model in various fields. The optimal maintenance strategies are presented by combining the concept of interval from TBM and that of condition from CBM. Further, the conventional RCM method can only be applied to a component. Hence, it conventional method is not suitable for large systems such as power systems. Thus the concept of the conventional RCM was extended in this paper in such a manner that it could be applied to power distribution systems. Moreover, the CIC was used to evaluate the total expected cost. The cost that was incurred as a result of component outage included not only the replacement/ maintenance cost but also the CIC.

We applied ordinal optimization to the RCM problem and presented optimal maintenance strategies by applying the developed method to the RBTS model. These strategies provide maximum benefit-to-cost.

The proposed RCM method accounts for realistic problems such as “maintenance” or “doing nothing.” Moreover, it can reduce the computation time when applied to large power distribution systems.

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