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Optimization of Asset Management and Power System Operation Based on Equipment Performance

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***Abstract*-- odern T&D system has the issues about economical aspects, aged equipment, reliability etc. To solve these issues, equipment should be maintained optimally and the T&D system should be operated based on the present performance of equipment. For realization of these purposes, Intelligent Grid Management System (IGMS) was proposed and its basic functions are being investigated.**

In this paper, failure modes of a T&D system were chronologically simulated using Monte Carlo method, and all events occurred by failures in a T&D system were evaluated as cost with nonlinear programming. The expected T&D cost was calculated by repeating these procedure many times. By minimizing the expected T&D cost, the most optimum maintenance strategies of circuit breakers and transformers were derived quantitatively.

***Index Terms*—reliability, economy, maintenance, diagnosis, electric power system, circuit breaker, transformer**

I. Introduction

THE T&D system is composed of much different equipment. Many of them were installed several decades ago, and have essentially deteriorated. Their further deterioration is unavoidable in the near future. So, equipment performance will be lowered and the equipment failure rate will increase. Such a situation will not meet the requirements of high power quality and high reliability of the power system in modern society. Today, the main topics relating to this issue are how and when to do maintenance, refurbish and replacement of equipment, how to operate equipment until they expire and how to minimize costs due to failure.

In order to solve these issues, the operation and maintenance planning of the T&D system based on the present performance, reliability and residual lifetime estimated by the monitoring and diagnosis of equipment is absolutely essential. For their realization, we have proposed "Intelligent Grid Management System (IGMS)" [1, 2].

This paper describes the concept of IGMS and demonstrates its effectiveness. Optimization of the T&D route, minimization of the total expected cost and the optimum maintenance strategies of circuit breakers and transformers are simulated and discussed.

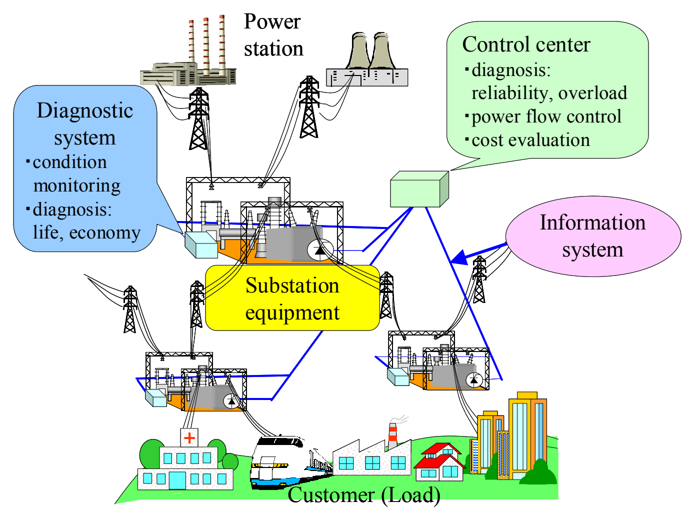

Fig. 1 Concept of Intelligent Grid Management System (IGMS)

II. Concept of IGMS

A. Basic concept

The reliability of the T&D system normally increases with the maintenance cost. On the other hand, the damage cost due to system failures decreases as the level of reliability increases. Moreover, the power delivery cost increases when electric power flows through low efficiency equipment and long distance transmission lines. The total T&D cost becomes a minimum at which an optimum on target reliability level is achieved and an optimum T&D route is selected. So, the cost and reliability must be evaluated as the whole T&D system but not as each individual equipment.

To optimize the total T&D cost and the system reliability, it is necessary to understand and evaluate the present performance of all equipment in the T&D system through its diagnoses and to operate the T&D system. IGMS makes these functions possible. Figure 1 shows the IGMS concept. The present performance and the equipment history of operation and maintenance are acquired by diagnostic systems and information systems. All data are collected at the control

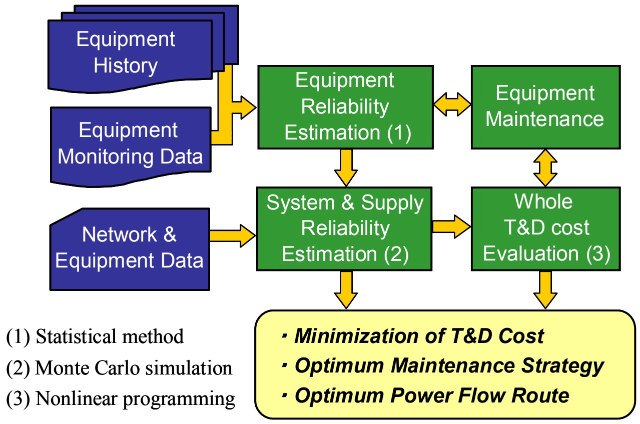

Fig. 2 Algorithm for cost and reliability evaluation in IGMS.

center. The T&D system is comprehensively evaluated there in terms of the T&D loss, T&D system reliability, overload operation, total cost, etc. Based on the evaluation, the T&D system is operated optimally. Moreover, the maintenance method and schedule of equipment are evaluated and the optimum maintenance strategy can be proposed.

B. Simulation procedure

Figure 2 shows the algorithm for minimization of the total T&D cost, the optimization of maintenance strategy and the optimization of power flow routes.

Equipment reliability is estimated first based on its present performance and history. Statistical methods such as Bayesian estimation and hidden Markov Model are applicable in this step. For a macroscopic understanding of the algorithm of IGMS in Fig. 2, the relation between the average failure rate and operation year was applied in chapter III.

Next, based on equipment reliability and the T&D system data, failure patterns and duration of all equipment in the T&D system are calculated chronologically with the sequential Monte Carlo simulation [3]. The duration of a component residing in its present state is assumed to disperse exponentially. And it is estimated by generating uniform random number. Sequential Monte Carlo simulation is repeated for all equipment in the T&D system, and the chronological failure patterns of the whole T&D system are derived.

Based on the derived failure patterns, the total T&D cost z and the optimum power flow route are calculated using nonlinear programming. The objective function is given by

$$\min z = \sum_{(i,j)\in Line} a_{ij}(X_{ij})X_{ij} + \sum_{(i,j)\in OLine} b_{ij}(X_{ij})X_{ij} + \sum_{k\in Equip} c_k + \sum_{k\in Equip} d_k \tag{1}$$

The first term on the right side represents the T&D cost of the normal system operation. And the second term represents the cost when the T&D system fails. This term includes the cost of overload, customer outage and owner outage. The cost concerning shortening of the equipment life due to overload is also included in the second term. The third term denotes the maintenance cost, and the fourth term denotes the repair cost of faulted equipment and possible damages to further components. a_{ij} and b_{ij} are the power-cost conversion coefficients when electric power X_{ij} is transmitted from substation i (SS$_i$) to j (SS$_j$). c_k is the maintenance cost of equipment k, d_k is the repair cost or damages of equipment k, Line is the set of transmission lines, OLine is the set of overload and failure transmission lines, Equip is the set of equipment in the T&D system.

To enhance the accuracy of the simulation, calculations were repeated about 50,000 times in this paper.

Aged equipment needs maintenance to keep its performance. Maintenance affects the equipment reliability and the total T&D cost. Therefore, it is necessary to recalculate both the chronological failure patterns of the T&D system and the objective function (1) of every maintenance.

The total T&D cost of all maintenance methods is compared for every operation year. And then the optimum maintenance method, the optimum maintenance schedule and the optimum power flow rout are derived.

III. Simulation of Optimum Maintenance Strategy

A. Simulation conditions

Figure 3 shows the 275kV/77kV network model used in the calculation [4]. Each substation (SS) has a double bus arrangement. Three generators (G1, G2 and G3) and three transformers (TR1, TR2 and TR3) are connected to two substations (SS1 and SS2). Step down transformers (TR4 - TR7) are connected to SS3 and SS4. The rated capacity and the length of transmission lines are defined in Fig. 3. The total load connected to each SS is 185 MW. The T&D loss consists of the transformer loss and the Joule loss of transmission lines. The yearly regular maintenance cost is assumed to be 0.8% of the initial equipment price.

The maximum permissible overload capacity of the transformers is assumed to be 140%. Overload operation of a transformer causes the temperature rise at hot spots and degrades insulation paper as described in the literature [5]. As a result, the life of a transformer is shortened. This shortening was considered in the calculation. The customer damage cost depends on users [4]. In this paper, the users were classified as either the important load or the ordinary load. The former is the load in which damage costs are extremely high and/or social impact is great. The cost at the important load is 11.3 k$/kWh. On the other hand, the cost of the ordinary load is 6.2 k$/kWh. The repair cost of TR and circuit breaker (CB) is assumed to be one third of the initial equipment price.

The failure rate λ of CB and TR increases with operation year and its increase becomes large after a certain operation year (Fig. 4 [6, 7]). The following three maintenance strategies were considered: (i) regular maintenance (RG), (ii) overhaul (OH) and (iii) replacement (RP). When equipment is overhauled, the λ value recovers the value before it increases rapidly. The λ value after replacement is equal to that of new equipment. The failure rate λof equipment is listed in Table 1 [8]. The failure rates of a transformer and a circuit breaker are the value of new equipment, and that of a transmission line is the average value. The overhaul cost is referred to the literature [9].

In order to estimate the optimum maintenance strategy, the total T&D cost must be calculated for all combinations of three maintenance method for all CB and TR in the T&D system. However, such calculations are extremely time consuming. So, for simplification of the calculation, equipment having the great impact were extracted.

Using the above-mentioned parameters, the minimum T&D cost and the optimum T&D route were calculated in each maintenance method.

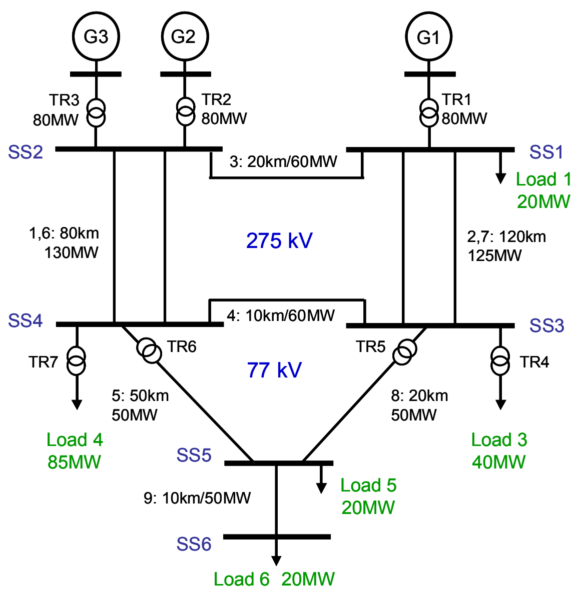

Fig. 3 Electric power network model.

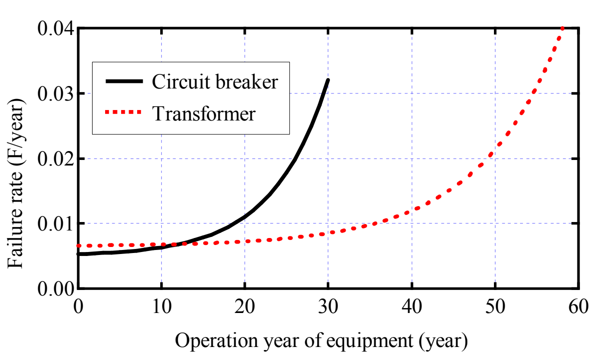

Fig. 4 Failure rate of circuit breakers and transformers.

Table I Failure rate of equipment.

Eqipument	Failure rate λ (F/year)
Transformer	0.0069
Circuit breaker	0.0050
Transmission line	0.0150

B. Comparison of failure impact of equipment

Figure 5 shows the details of the total expected T&D cost in a young operation year in regular maintenance. The cost is expressed by the percentage of the expected total T&D cost in a young operation year in regular maintenance. "Line" and "Load" indicates the CBs connected to "Line" and "Load", respectively. The details indicates the magnitude of the impact on the total T&D cost.

In case of CBs, the T&D cost of CB directly connected to loads is higher than that of CB connected to lines. This high cost is caused by the fact that CB failures always result in the outage of the connected loads. On the other hand, the other CB failures do not induce any outage because electric power can be delivered by way of other lines. The T&D cost of CBs connected to Load 1, Load 5, Load 6 and Line 9 are nearly equal with each other because their connected load size is the same (20 MW).

In the transformer case, TR4 between SS3 and Load 3 and TR7 between SS4 and Load 4 have a larger impact than other TR. This is caused by the same reason as the CB case.

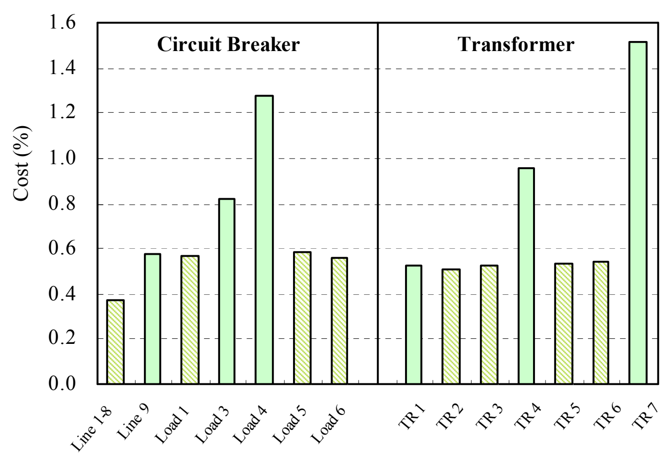

Fig. 5 Details of total T&D cost at CBs and TRs.

C. Optimum maintenance strategy of circuit breaker

To find the optimum maintenance strategy of CB, the expected total T&D cost was calculated by changing the operation years of the extracted three CBs (CB4, CB3 and CB5 which are connected to Load 4, Load 3 and Line 9, respectively). When the operation years of CB3, CB4 and CB5 are changed, the expected total T&D cost per year is shown in Fig. 6. The number of combinations of the three maintenance methods for three CBs is 27. Calculations were carried out for this 27 combinations. Their total T&D cost dispersed in the shaded region in Fig. 6. The solid lines show the five combinations which represent the minimum cost in certain operation years. The cost is normalized by the cost of one year when the failure of equipment is not occurred. When the maintenance methods of CB3-CB4-CB5 are the RG-RG-RG and the OH-OH-OH, the total T&D cost increases rapidly after 15 operation years, and the RG-RG-RG case is more expensive than the OH-OH-OH case. In the RP-RP-RP case, the cost decreases over time. This is caused by the asset-value reduction of the present equipment.

The maintenance method which minimizes the total T&D cost is the optimum method in each operation year. The OH-OH-OH case is suitable between 15 to 22 years. The OH-RP-OH case is the most economical between 22 to 27 years. The RP-RP-OH case for 27 to 32 years and the RP-RP-RP case for over 32 years of operation are recommended. This means that the priority of replacement is CB4 > CB3 > CB5. This difference in prioritization is caused by the outage size induced by the CB failure. CB3, CB4 and CB5 are connected to 40 MW, 85 MW and 20 MW loads, respectively. Since CB failures result in outage directly, CB4 which is connected to the largest load has the highest priority of replacement.

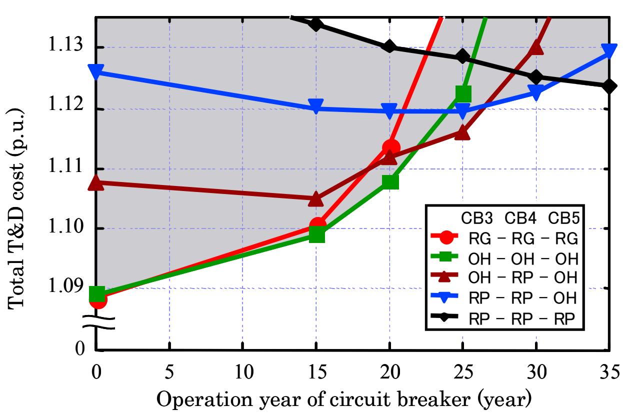

Fig. 6 Relationship between total T&D cost and operation year of CB at different maintenance methods

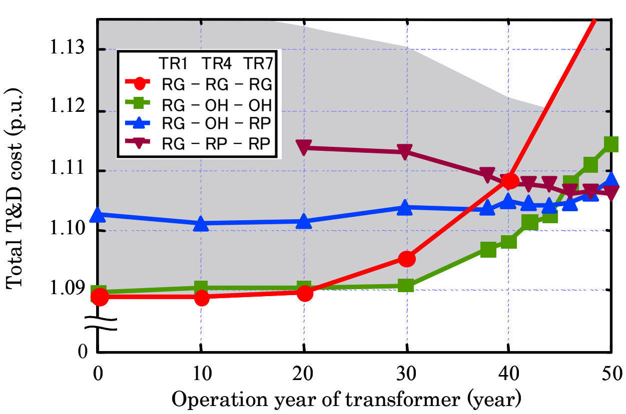

Fig. 7 Relationship between total T&D cost and operation year of TR at different maintenance methods

D. Optimum maintenance strategy of transformer

To find the optimum maintenance strategy of TRs, the above-mentioned procedure was applied to TRs. Extracted three TRs were TR7, TR4 and TR1. When the operation years of TR7, TR4 and TR1 are changed, the expected total T&D cost per year is shown in Fig. 7. The number of combinations of the three maintenance methods for three TRs is 27. Calculations were carried out for this 27 combinations. Their cost dispersed in the shaded region in Fig. 7. The cost is normalized by the cost of one year when the failure of equipment is not occurred. The solid lines show the four combinations which represent the minimum cost in certain operation years.

The cost is the minimum in both RG-RG-RG and RG-OH-OH cases before 20 operation years. The RG-OH-OH is suitable between 20 and 45 operation years. The RG-OH-RP case for over 45 years and the RG-RP-RP case for over 48 years of operation is recommendable. The replacement of TR1 will be postponed until over 50 operation years. This is caused by the fact that the electric power of TR1 can be supplied by TR2 and TR3 in the model system.

IV. Conclusion

The concept of Intelligent Grid Management System (IGMS) based on present equipment performance was proposed to solve the issues concerning economic aspects, maintenance of aged equipment, etc. in the T&D system, and the effectiveness of IGMS was basically demonstrated. The results are summarized as follows;

(1) By using equipment reliability and the T&D network data, T&D network failures were calculated with the sequential Monte Carlo method and the total T&D cost did with nonlinear programming,

(2) The total T&D cost depended on operation years of T&D network components and maintenance methods,

(3) The planning of the suitable maintenance strategies of both circuit breakers and transformers at an arbitrary operation year were derived.

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