Optimization of Asset Management in High Voltage Substation Based on Equipment Monitoring and Power System Operation

Yotaro Suzuki, Hiroki Kojima, Naoki Hayakawa, Fumihiro Endo, Hitoshi Okubo
Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan
suzuki-y@okubo.nuee.nagoya-u.ac.jp

Abstract— **This paper presents a new optimization approach of maintenance strategy for equipment in a transmission and distribution (T&D) system. In this approach, a present and future equipment performance is estimated by using monitoring data, and impacts of performance in each equipment on a whole T&D system are evaluated. By minimizing the impacts, suitable maintenance procedures and timing are derived. This approach is applied to a circuit breaker (CB) in an electric network, and its significance and usefulness are presented.**

Asset Management, Diagnosis, Maintenance, Circuit Breaker, Substation, Electric Power System

I. INTRODUCTION

Today, the steady increase of the demand for electric power requires high level of reliability and quality of electric power supply. A transmission and distribution (T&D) system is composed of much aged equipment, and its suitable maintenance is demanded to ensure the reliability of a T&D system. The reliability of a T&D system normally increases with the maintenance cost. On the other hand, the damage cost due to outage decreases as the system reliability increases. Our important task is to correctly operate and control T&D systems by maintaining the balance between cost efficiency and quality of electric power supply.

Many approaches were presented [1-3] to conduct condition-based maintenance and reliability-centered maintenance. Recently, importance of impact of individual equipment failure on the whole T&D system has been recognized. The authors have proposed the "Intelligent Grid Management System (IGMS)", and fundamental research continues [4-9]. Instead of regarding equipment failures as isolated incidents, IGMS analyzes failures in terms of their impact on the entire system and provides the most economically feasible maintenance strategies, including T&D routes. Hitherto, simulations have been performed to obtain the optimum T&D routes and failure impacts (i.e. T&D cost) by considering the current level of performance and reliability of equipment, and it is concluded that the reliability of equipment greatly affects the results.

In this paper, the concept and algorithm of IGMS are presented. To clarify its effectiveness, IGMS is applied to circuit breakers (CBs) in a T&D system, and their optimum maintenance strategies are conducted by using their monitoring data.

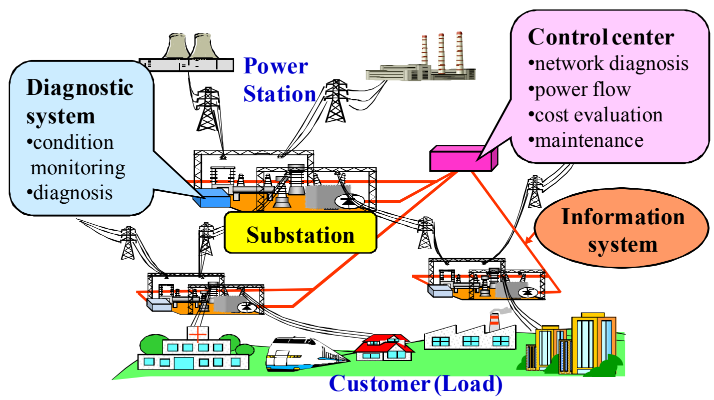

Figure 1. Concept of Intelligent Grid Management System (IGMS)

II. CONCEPT AND ALGORITHM OF IGMS

Figure 1 shows the concept of IGMS. To maintain the balance between cost efficiency and quality of electric power supply, it is necessary to know the present and future performance of all equipment in the T&D system, and to operate, control and maintain the T&D system based on them. Their performance is monitored by a diagnostic system installed at each substation, and diagnosed results are transmitted to a control center. At the control center, an entire T&D system is comprehensively analyzed in many aspects such as T&D loss, reliability, overloading, T&D cost and so on. The T&D system is controlled and operated at optimum efficiency according to the analysis. Furthermore, the type of maintenance is estimated for each equipment, and optimum maintenance strategy is derived.

Figure 2 shows the algorithm of IGMS, which consists of 5 basic steps.

(Step 1) The present and future equipment reliability is estimated based on the diagnosed results and the historical data by using the statistical techniques and the hidden Markov model.

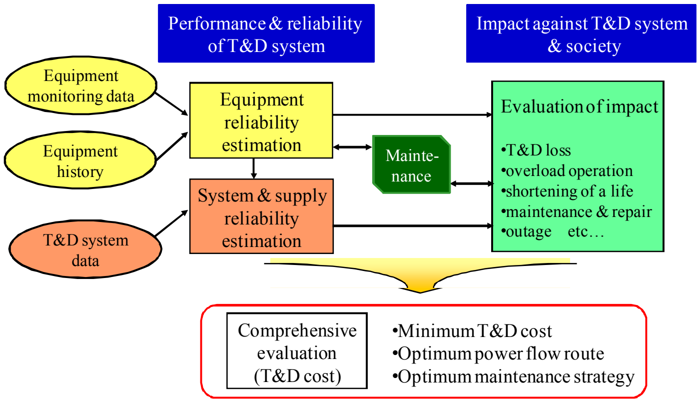

Figure 2. Algorithm for optimization of cost and reliability in IGMS

(Step 2) Failure patterns of the T&D system are calculated chronologically with the sequential Monte Carlo simulation by using T&D system data and estimated equipment performance.

(Step 3) According to the failure patterns in step 2, all events happened in the T&D system are evaluated as cost. The sum of all cost (T&D cost) is minimized and the minimizing conditions are derived.

(Step 4) As maintenance improves equipment performance and reliability, steps 1 to 3 are repeated whenever maintenance is performed.

(Step 5) The minimal T&D cost and the corresponding conditions are extracted from all the calculated values obtained in steps 1 to 4. The extracted result suggests the optimum maintenance strategy and the optimum T&D routes. How to find the optimum solution is described later.

The T&D cost z consists of many cost components. By minimizing z with a nonlinear programming, the minimal T&D cost and the optimum T&D route are estimated. The objective function is expressed in eq. (1).

$$\min z = \sum_{ij} a_{ij}(X_{ij}) + \sum_{ij} b_{ij}(X_{ij}) + \sum_{ij} c_{ij}(X_{ij}) + \sum_{k} d_k(X_k) + \sum_{k} e_k(X_k) + \sum_{m} f_m + \sum_{n} g_n \qquad \cdots(1)$$

Where, the first and second terms on the right side correspond to the costs of the T&D loss at the normal system operation and the T&D loss at the overload operation, respectively. The third term is the damage caused by a shortened service life due to the overload operation. The fourth term is customer's outage cost and the fifth is the owner's outage cost. The sixth term is the maintenance cost, and the seventh is the repair cost of failed equipment and possible damages to further components. X_{ij} is the transmission power from substation i (SS_i) to SS_j. X_k is the outage power of load k.

Strength of insulation paper is degraded by temperature rise of oil. So service life of a transformer is shortened by overload operation. This shortened service life is estimated according to references [10, 11] and converted the cost based on equipment cost and normal life expectancy of insulation paper. Customer damage due to the interruption of power supply are described in detail in reference [12], and maintenance cost and equipment cost are given in references [2, 13].

III. State Estimation of Circuit Breaker

A majority of CB failures are related to the operating mechanism [14]. A CB operation is triggered by a dc command signal to a coil that moves a latch or opens a valve, which releases the mechanical energy of the drive. A record of a coil current wave contains a large amount of information to evaluate the state of the operating mechanism. The important information appears in the time from the start of trip signal to events (i.e. latch release, armature stop, auxiliary contact opening etc.).

An example of such time measured with a monitoring system is expressed in Figure 3. Time T is normalized with the average time at the initial CB operations. The mean value and dispersion of T increase with the number of CB operations. The minimal value of T is almost constant up to 350 CB operations. The maximal value of T appears after 150 CB operations.

Change of T with the number of CB operations can be expressed with Weibull statistics in eq. (2).

$$F(T) = 1 - \exp\left[-\left(\frac{T-\gamma}{\alpha}\right)^{\beta}\right] \qquad \cdots(2)$$

where α, β, and γ are scale parameter, shape parameter and location parameter, respectively. Figure 4 shows the trend of Weibull parameters. The value of α gradually increases with the number of CB operations. The value of β rapidly decreases with the number of CB operations, and becomes almost constant at the number larger than 100. These indicate the increase of the mean value and the standard deviation of T as the number of CB operations increases. Relations of α and β to the number of CB operations are expressed in eqs. (3) and (4).

$$\alpha(N) = A\exp(BN) \qquad \cdots(3)$$

$$\beta(N) = C\exp(-DN) + 1 \qquad \cdots(4)$$

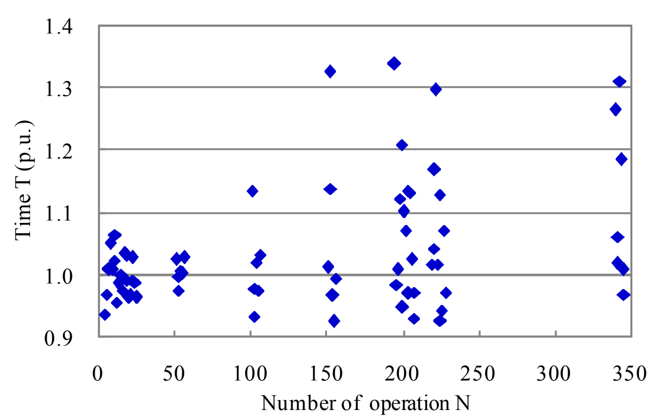

Figure 3. Relationship between trip signal time T and number of operation of circuit breaker

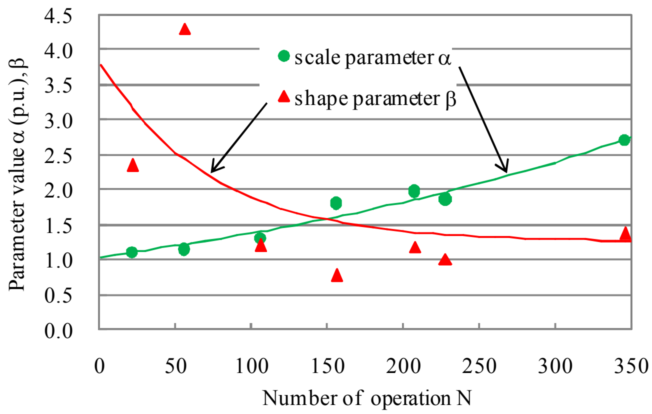

Figure 4. Trends of Weibull parameters with number of operation of circuit breaker

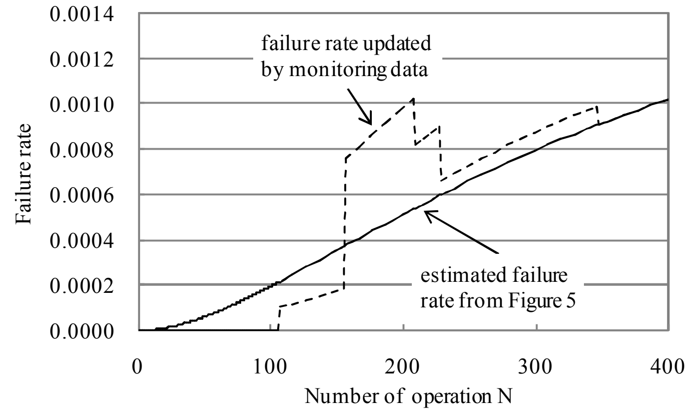

Figure 6. Estimated failure rate of operating mechanism of circuit breaker

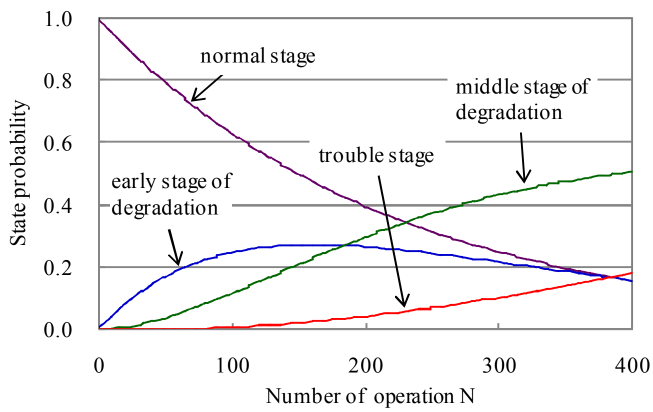

Figure 5. State probability of a circuit breaker

where A, B, C, and D are constants. The γ value is constant. These equations express the character of the monitored CB.

When these values are clarified, the CB state is calculated with the hidden Markov model (HMM). The CB is classified in four stages; the normal stage, the early stage of degradation, the middle stage of degradation and the trouble stage. The appearance probability of four stages is calculated with HMM, and the result is shown in Figure 5. The normal stage is dominant at the low number of CB operations, and gradually decreases with the number of CB operations. The middle stage of degradation is dominant at the number more than 200. Probability of the trouble stage is extremely low. Actually, this CB was operated successfully more than 350 times.

The failure rate λ during the CB operation of N_1 and N_2 is derived with the following eq. (5).

$$\lambda(N) = \frac{P(N_2) - P(N_1)}{1 - P(N_1)} \quad , \quad N_1 < N < N_2 \qquad \cdots(5)$$

where P(N) is the probability of the trouble stage at N times operations of CB. The estimated failure rate from Figure 5 is shown as solid line in Figure 6, and increases gradually with the number of CB operations.

The small number of CB operation corresponds to time right after sufficient maintenance. When the number of CB operations (i.e. the number of monitoring) after maintenance is not sufficiently large, values of coefficients in eqs. (3) and (4) must be estimated with the latest monitoring data and historical ones. The state probability of CB was calculated at every monitoring, and the failure rate of CB was derived. The derived failure rate is expressed by broken line in Figure 6. The failure rate is updated at every monitoring. And it shows a zigzag line, which disperses around the solid line in Figure 6. When CB is monitored many times, the failure rate converges on the value expressed in a solid line in Figure 6.

Failures of CB are caused by operating mechanism, insulation, gas leakage and so on. Therefore, in this paper, the failure rate λ_1 of CB was determined by considering these causes.

IV. Outline of Simulated Electric Power System Model

Figure 7 shows a model for the evaluated 275kV/77kV T&D system [12]. This model contains three power stations and six substations (SS1-SS6). The total load is 185 MW. The substations have the double-bus configuration. The analysis covers three maintenance types: regular maintenance (RG), overhaul (OH), and replacement (RP), and the yearly T&D cost is minimized in order to determine the optimum type and

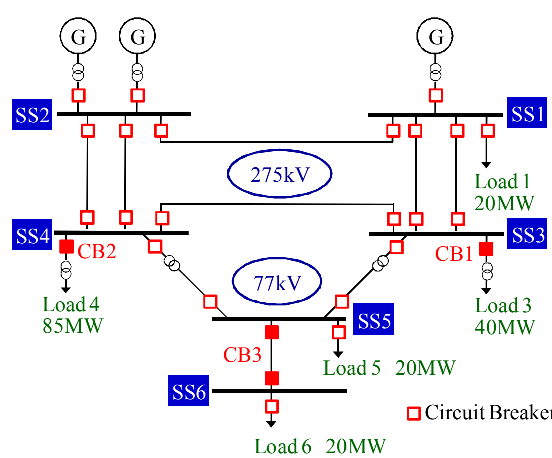

Figure 7. T&D network model [12]

timing for maintenance. The simulation assumes that CB is recovered by 7 years after OH, and CB returns to the first year of operation after RP.

To estimate the optimum maintenance strategy, the T&D cost must be calculated for all combinations of three maintenance methods for all CBs. However, such calculation requires large amounts of time. For simplification of calculation, three CBs with greater failure impacts were selected for evaluating the optimum type and timing for maintenance. The selected CBs (CB 1, CB 2, and CB 3) are shown in Figure 7. CB 3 is composed of two CBs which are placed at both ends of the line. Since the ages of CBs are not constant and not uniform in a T&D system, random numbers are generated from the distribution of manufacturing years of CB in a certain country, and the resulting ages are assigned to CBs. The assigned ages of CB 1-2-3 were 20-10-15 years, respectively.

When the performance of CB was not monitored, the failure rate surveyed by CIGRE [15] was applied (Figure 8). The failure rate of selected CBs gradually increases with operation years. The failure rates for other types of equipment are assumed to be constant, as listed in Table 1 [16, 17].

V. Derivation of Optimum Maintenance Strategy

We assumed that only one of three CBs was monitored and had the failure rate λ_1. Using the method described section 3, failure rate of CB can be calculated. But we have only one monitoring data, so we assumed that other two CBs had the failure rate λ_0 in Figure 8. Four patterns of combination of the failure rates in Table 2 were considered. The monitored CB was assumed to receive detail inspection and maintenance every 6 years. And after that, the failure rate was assumed to follow the value λ_1. Therefore, the present time after detail inspection of CB 1 at pattern 1, CB 2 at pattern 2, and CB 3 at pattern 3 is assumed to be 2, 4, and 3 years, respectively. Furthermore, it is considered that the monitored CB is operated 20 times for a year.

Figure 9 shows the T&D cost curves for different combinations of maintenance method at pattern 1. The vertical axis shows the yearly T&D cost, which is normalized by the T&D cost of one year operation without failure. The horizontal axis shows the future time from the present. The number of combination of three maintenance methods for three CBs is 27. Calculations were performed for these 27 combinations. Five curves show only the combinations where the T&D cost is minimal at certain years. T&D cost curves for other combinations are distributed among these five curves. T&D cost curves increase with operation time. The curve which corresponds to the minimal cost changes with operation time. At an arbitrary year, the optimum combination of maintenance types is obtained as a curve which corresponds to the minimal T&D cost for that year.

The curve of RG-OH-OH rapidly increases with time. After five years, the T&D cost of OH-OH-OH is the minimal combination. This predicts that the optimum maintenance type of CB 1 is OH around 5 years. This indicates that the time after the previous inspection and maintenance is 7 years. As CB 2 is

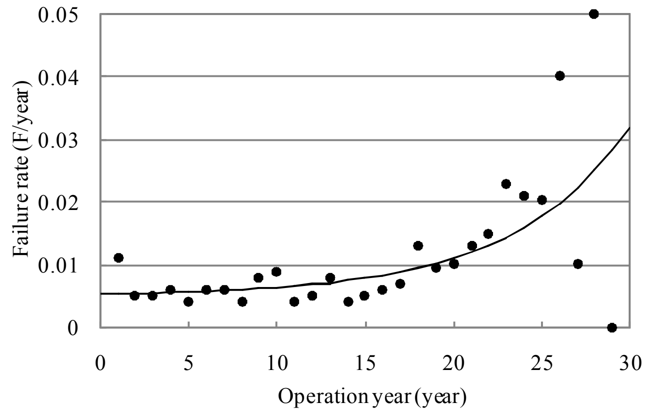

Figure 8. Failure rate λ_0 of circuit breaker [15]

Table 1 Failure rate of equipment [16, 17]

Equipment	Failure rate (F/year)
Transmission line	0.0150
Transformer	0.0066
Disconnector	0.0084
Bus	0.0047

Table 2 Simulation patterns

Pattern	Failure rate		
	CB1	CB2	CB3
1	λ_1	λ_0	λ_0
2	λ_0	λ_1	λ_0
3	λ_0	λ_0	λ_1
4	λ_0	λ_0	λ_0

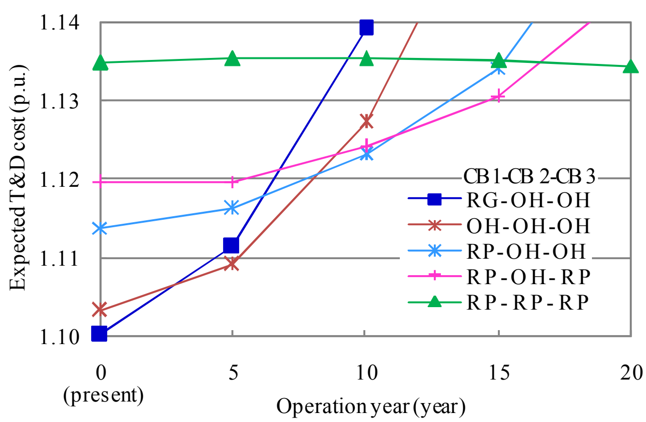

Figure 9. Relationship between T&D cost and operation year for circuit breakers at pattern 1

connected to a large load (85MW), early OH is desirable to prevent load interruption. If CB 1 is not overhauled, its replacement is suitable around 8 years. In this way, the optimum maintenance time can be derived. At pattern 1, the optimum OH time of CB 1-2-3 is 3 to 5-1-1 years, and the optimum RP time is 8-17-11 years.

Figure 10 shows the T&D cost curves for different combinations of maintenance method at pattern 4. At pattern 4, no three CBs are monitored. When at least RG is contained in a maintenance scheme, the T&D cost is larger than that of OH-OH-OH. Therefore, the T&D cost is smallest at OH of three CBs until after 10 years. For about 10 to 15 years, the maintenance type RP-OH-RP of CB 1-2-3 is suitable, because this combination shows the minimal T&D cost. The optimum RP time of CB 1-2-3 is 11-17-11 years.

Table 3 shows the optimum OH and RP time at each pattern listed in Table 2. The optimum RP time of monitored CB at pattern 1, 2, and 3 is earlier than that at pattern 4. CB 2 must be overhauled in one year because CB 2 is connected to a large load (85MW). Though the load size of CB 3 is small (i.e. 20 MW), OH in one year is estimated. This is caused by the fact that CB 3 consists of two CBs connected in series as mentioned above, and the failure rate becomes about twice the rate of one CB. By comparing patterns 1 and 4, OH of CB 1 can be postponed by several years. Replacement of CB 1 must be earlier by 3 years. In other patterns, the effect of CB monitoring on maintenance method and timing is obvious.

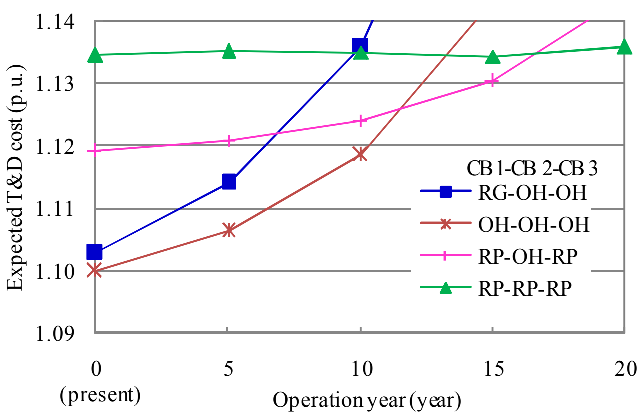

Figure 10. Relationship between T&D cost and operation year for circuit breakers at pattern 4

Table 3 Optimum maintenance time of circuit breaker

Pattern	Optimum maintenance time (year)					
	Overhaul			Replacement		
	CB1	CB2	CB3	CB1	CB2	CB3
1	3-5	1	1	8	17	11
2	1	1	1	11	13	11
3	1	1	1	11	17	8-10
4	1	1	1	11	17	11

VI. Conclusion

The key issue for operation and control of T&D systems is to find the optimum balance between cost efficiency and power quality. To help solve the issue, "Intelligent Grid Management System (IGMS)" was presented. Fundamental study on IGMS was carried out, and following results are obtained.

(1). IGMS analyzed the influence of individual equipment failures on a whole T&D system including customers. IGMS was applied to a T&D system model, and provided the most economically feasible maintenance strategy.

(2). Based on monitoring data of trip signal time of CB, the failure rate of CB was estimated with statistical methods. This failure rate was applied to IGMS, and the optimum maintenance strategies of CBs were predicted depending on their ages. The derived maintenance strategies differed from those when no CB was monitored. If monitoring data is obtained, actual equipment can be applied to IGMS.

References

[1] M. Schwan, K. Schilling, A.A. de Melo, "Reliability centered asset management in distribution networks – Process and application examples", CIRED, No. 0682, 2007

[2] G. Balzer, et al., "Selection of an optimal maintenance and replacement strategy of H. V. equipment by a risk assessment process", CIGRE, B3-103, 2006

[3] D.G. Pérez, G.L. Hurtado, M.A. del Rey López de la Torre, "New asset management practices for T&D utilities within deregulated power markets", CIGRE, B3-105, 2008

[4] F. Endo, et al., "Optimization of asset maintenance strategies and power flow operation based on condition diagnoses", 16th ISH, F-1, 2009

[5] F. Endo, et al., "Optimized asset management of high voltage substations and power network operation based on equipment performance", Cigre 6th Southern Africa Regional Conference, C201, 2009

[6] F. Endo, et al., "Optimum operation and maintenance of power grid based on equipment diagnoses", IEEE PowerTech, No. 281, 2007

[7] F. Endo, et al., "Application of equipment diagnoses to operation and management planning of power grid", 15th ISH, T6-749, 2007

[8] F. Endo, et al., "Optimization of asser management and power system operation based on equipment performance", CMD2008, F2-5, 2008

[9] M. Kanamitsu, et al., "Optimum operation and maintenance of power grid based on equipment diagnoses", ISETS, 23H04-05, 2007

[10] IEEE standard C57.91-1995 IEEE guide for loading mineral-oil-immersed transformer

[11] Facilities Eng. Branch Denver Office, "Permissible Loading of Oil-Immersed Transformers and Regulators", Facilities Instructions Standard and Techniques, 2000

[12] R. Billinton, "Evaluation of reliability worth in an electric power system", Reliability Eng. and System Safety, Vol. 46, pp. 15-23, 1994

[13] J.E. Dable and D.R. Brown, "Electric power substation capital cost", Pacific Northwest National Lab. Rep., Dec., 1997

[14] Satish Natti, et al., "Transmission system equipment maintenace: on-line use of circuit breaker condition data", IEEE PES GM, 2007

[15] "Report on the second international survey on high voltage gas insulated substations (GIS) service experience", CIGRE, WG23.02, 2000

[16] A. Carvalho, et al., "Functional specification as driver for technical / economical optimisation of substation", CIGRE, 23-101, 2000

[17] D. J. Woodcock, "The key to condition-based asset starategies for power transformers", Weidmann Annual Technical Conference, 2002