Health Index Determination of Aged High Voltage Substation in Distribution System

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***Abstract*—This paper presents condition assessment of high voltage equipment and substation as health index. Major equipment of high voltage substation consists of circuit breaker, disconnecting switch, current transformer, voltage transformer and surge arrester. The condition of equipment is assessed by visual inspection and electrical test. The weighting and scoring method is applied throughout the process of health index calculation. The Analytic Hierarchy Process is used to calculate the weight for each criterion. The conditional score and its weight of each testing are used to calculate the weighting average score. Then, the obtained weighting average score is adjusted by visual inspection, maintenance completeness and failure rate of equipment. The adjusted average score of all equipment in a bay is integrated into bay health index and subsequently adjusted by age and operational stress of bay. Finally, the health index of fifteen substations can be determined.**

Keywords— Condition assessment, health index, major equipment, substation, weighting and scoring method

I. INTRODUCTION

High voltage substation is an important component in transmission and distribution network. That is used to control the flow of electricity as well as to step up or to step down the voltage as required by load. Usually, there are various kinds of equipment working together in a high voltage substation, such as circuit breaker, disconnecting switch, current transformer, voltage transformer, surge arrester and etc. Due to the enormous number of the equipment in the distribution substations, the capital investment is relatively high. During the last decade in Thailand, although the construction of new high voltage substation was a key for serving the increasing electricity demand but their constructions have slowed down because of many concerns, for example, slow growth in economics and electrical demand. Therefore, to keep the existing electrical infrastructure in good condition or to properly replace the aged equipment in time is now of prime concern [1]. In addition, failure of substation or any of its equipment could cause power outage in a large area as well as safety to operating and maintenance personnel. Therefore, the transition from preventive or time-based maintenance to condition-based maintenance is urgently required.

This paper presents condition assessment for high voltage substation and its equipment. The condition of equipment is assessed by visual inspection and electrical test. The weighting and scoring method is applied throughout the process of health index calculation. The Analytic Hierarchy Process (AHP) is used to calculate the weight for each criterion. The conditional score and its associated weight of each testing are used to calculate the weighting average score. Then, the obtained weighting average score is adjusted by visual inspection, maintenance completeness and failure rate of equipment. The adjusted average score of all equipment in a bay is integrated into bay health index and subsequently adjusted by age and operational stress of bay. Finally, the substation health index can be determined as shown in Fig. 1. The developed procedure was implemented in MS Excel program to collect the technical data and to evaluate the performance of equipment and substation.

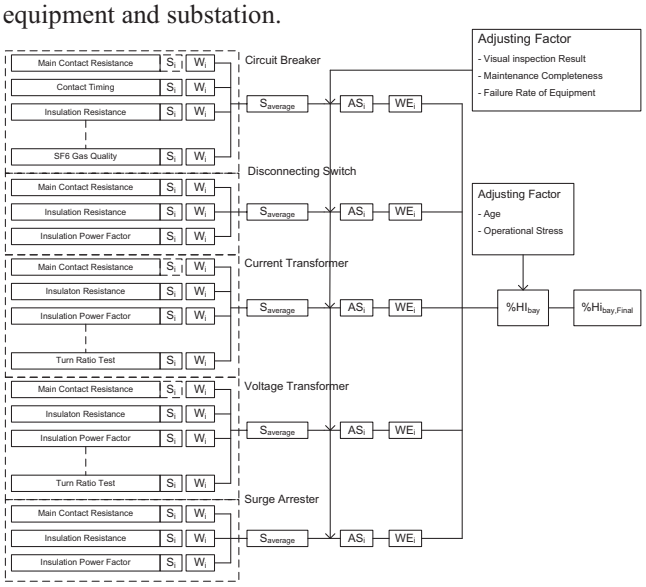

Fig. 1. An overview of the whole working procedure.

II. DATA STRUCTURE AND CONDITION ASSESSMENT OF SUBSTATION

A. Major Equipment of Substation

Before evaluating the condition of substation, major equipment is needed to be classified. Major equipment consists of circuit breaker (CB), disconnecting switch (DS), current transformer (CT), voltage transformer (VT) and surge arrester (SA).

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B. Technical Data and Testing Data

After knowing the major equipment of substation, the technical data is collected for creating a formal database. The technical data of the aforementioned equipment consists of serial number, device code, manufacturer, model/type, manufacturing year and its technical rating. Then the database for inspection and test result was developed and the data was collected in this database as detail in Table I. For example, circuit breaker is tested as visual inspection, main contact timing, main contact resistance, insulation resistance, SF_6 gas tightness and gas quality and etc. Finally, the failure record of all equipment was collected in the third database to access the failure mode, failure consequence and the performed corrective action as listed in Table II.

TABLE I. TESTING DATA FOR EACH EQUIPMENT

Equipment	Testing Data
Circuit breaker	Visual inspection, main contact resistance test, insulation resistance test, insulation power factor test, SF_6 gas tightness and gas quality test, contact timing test
Disconnecting switch	Visual inspection, main contact resistance test, insulation resistance test, insulation power factor test
Current transformer	Visual inspection, main contact resistance test, insulation resistance test, insulation power factor test, oil dielectric strength test, water content, turn ratio test
Voltage transformer	Visual inspection, main contact resistance test, insulation resistance test, insulation power factor test, oil dielectric strength test, turn ratio test
Surge arrester	Visual inspection, main contact resistance test, insulation resistance test, insulation power factor test

TABLE II. LIST OF RECORDED DATA IN FAILURE RECORD

Failure Mode	Failure Consequence	Corrective Action
Normal	-	-
Leakage	Property of gas has changed	Replace
Broken	Function cannot be used	Modify
Unsmooth	Stress can break the component	Lubricate/Cleaning
Dirty	Breakdown can be occurred	Re-condition/Refill
Test failed	Some parts were changed and calibrated before using it	Calibrate
Nonfunctional	Protection cannot be used	Repair

III. METHODOLOGY

In this section, seven test methods are usually performed with several equipment consisting of visual inspection, main contact resistance test, main contact resistance test, insulation resistance test, insulation power factor test, SF_6 gas tightness and gas quality, oil dielectric strength test and turn ratio. The detail of each testing and evaluation criteria is explained as followed.

A. Visual Inspection

Visual inspection is a common method using human senses and simple tools to inspect the equipment. Major equipment inspection consists of function test, cleaning, lubrication drive mechanism, terminal check and all fastening check. The criteria are shown in Table III.

TABLE III. CRITERIA OF VISUAL INSPECTION

No.	Inspection Item	Criteria	
		Good (1)	*Poor (3)*
1	Function test	Normal	Abnormal
2	Cleaning	Normal	Abnormal
3	Lubrication drive mechanism	Normal	Abnormal
4	Terminal check	Normal	Abnormal
5	All fastening check	Normal	Abnormal

B. Main Contact Resistance Test

The high contact resistance is usually caused by rust and loosen or poor connection, which generates heat and power loss. To decrease the resistance, the proper lubrication and cleaning is required. The criterion is presented in Table IV.

TABLE IV. CRITERIA OF MAIN CONTACT RESISTANCE TEST

Measurement	Criteria	
	Good (1)	*Poor (3)*
Main contact resistance	<200μΩ	>200μΩ

C. Insulation Resistance Test

The insulation resistance implies the ability of insulation to withstand the applied voltage. The lower in the insulation resistance informs the degradation of insulation.

TABLE V. CRITERIA OF INSULAITION RESISTANCE TEST

Measurement	Criteria	
	Good (1)	*Poor (3)*
Insulation resistance	>1000MΩ	<1000MΩ

D. Insulation Power Factor or Watt Loss

Generally, the power factor is a number that reflects the efficiency of the dielectric in maintaining its insulation property in an electrical apparatus. Insulation performs this function well when it is clean, dry and void free. When insulation becomes contaminated to a certain degree, the resistive current increases, which lead to the increasing in watt loss and insulation power factor [2].

TABLE VI. CRITERIA OF WATT LOSS TEST OF INSULATION

Measurement	Criteria	
	Good (1)	*Poor (3)*
Watt loss of insulation	<20mW	>20mW

E. SF_6 Gas Tightness and Gas Quality

SF_6 gas is used as insulation and arc extinguisher in the interrupting unit of circuit breaker. To maintain the SF_6 in a good condition, the gas pressure, percentage of SF_6 and dew point must conform to the criteria in Table VII.

TABLE VII. CRITERIA OF SF_6 GAS TIGHINESS AND GAS QUALITY

Measurement	Criteria	
	Good (1)	*Poor (3)*
SF_6 pressure	>5BAR	<5BAR
Percentage of SF_6	>99%	<99%
Dew point	<-10ºC	>-10ºC

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F. Oil Dielctric Strength Test

The oil is the insulation for current transformer and voltage transformer. Contaminated or poor oil condition could lead to the lower in breakdown voltage.

TABLE VIII. CRITERIA OF OIL DIELECTRIC STRENGTH TEST

Measurement	Criteria	
	Good (1)	*Poor (3)*
Breakdown voltage of oil	>100kV	<100kV

G. Turn Ratio Test

The turn ratio measurement could indicate the short turn of insulation in the winding. The criterion of turn ratio test is shown in Table IX.

TABLE IX. CRITERIA OF TURN RATIO

Measurement	Criteria	
	Good (1)	*Poor (3)*
Turn ratio	<5%	>5%

IV. HEALTH INDEX CALCULATION

From the previously mentioned tests, the score will come from the criteria of each test [3]. The weighting of each criterion is obtained by using the Analytical Hierarchy Process or AHP. The weight and score of each criterion will be used to calculate the weighting average score ($S_{average}$), which will be further used to calculated adjusted average score (ASi) by adding the adjusting factor from visual inspection result, degree of complete maintenance and failure rate of equipment model. Then, the ASi is used to calculated bay health index ($\%HI_{bay}$) by adding adjusting factor from age of equipment and operational stress from service. Finally, the $\%HI_{bay,final}$ is calculated the average ($\%HI_{bay,average}$) and worst health ($\%HI_{bay,worst}$) index of bay.

$$S_{average} = \frac{\sum_{i=1}^{N}(WT_i \cdot S_i)}{\sum_{i=1}^{N} WT_i} \quad (1)$$

$$\%HI_{bay} = 100 - \sum_{i=1}^{N} \frac{WE_i \cdot (AS_i - S_{MIN})}{S_{MAX} - S_{MIN}} \quad (2)$$

Where N is the number of test method of equipment, WT_i the weight of each test method, ASi the adjusted average score of major equipment i, WE_i the weight of equipment in a bay, S_{MAX} and S_{MIN} the are the maximum and minimum score values of testing and condition [4].

The health index will be divided into 3 levels as red, yellow and green, which mean bad, poor and good condition respectively. The range of $\%HI_{bay}$ is shown in Table X.

TABLE X. COLOR CODE FOR HEALTH INDEX OF BAY AND SUBSTATION

$\%HI_{substation}$	Condition	Action	Color
75-100%	Good	Normal	Green
25-75%	Poor	Normal maintenance	Yellow
0-25%	Bad	Repair or replace	Red

V. RESULT AND DISCUSSION

In this section, it shows the health index calculation of 3 substations as example. Each substation consists of 5 identical bays. The first substation is new, the second substation is moderately aged and the last substation is old and poor condition. The health index calculation is explained as follows.

Step 1: Calculating the health index of each major equipment

The example shows the calculation of major equipment of 1 bay of the first substation, which is new. It begins with circuit breaker and then the other equipment. By using Eq.1, $W_{average}$ is equal to 1.00.

$$S_{average,circuitbreaker} = \frac{(1\times 8)+(1\times 7)+(1\times 6)+(1\times 5)+(1\times 4)}{(8+7+6+5+4)} = 1.00$$

TABLE XI. AVERAGE WEIGHT OF EACH MAJOR EQUIPMENT IN NEW BAY OF NEW SUBSTATION

Equipment	Testing Method	S_i	W_i	$W_{average}$
Circuit breaker	Main contact resistance test	1	8	1.00
	Insulation resistance test	1	7	
	Insulation power factor test	1	6	
	SF_6 gas tightness and gas quality	1	5	
	Contact timing test	1	4	
Disconnecting switch	Contact resistance test	1	8	1.00
	Insulation resistance test	1	5	
	Insulation power factor test	1	3	
Current transformer	Contact resistance test	1	8	1.00
	Insulation resistance test	1	7	
	Insulation power actor test	1	6	
	Oil dielectric strength test	1	5	
	Turn ratio test	1	3	
Voltage transformer	Contact resistance test	1	8	1.00
	Insulation resistance test	1	7	
	Insulation power factor test	1	6	
	Oil dielectric strength test	1	5	
	Turn ratio test	1	3	
Surge arrester	Contact resistance test	1	8	1.00
	Insulation resistance test	1	5	
	Insulation power factor test	1	3	

Since this first substation is new and in good condition, the conditional score of all testing methods is equal to 1. The visual inspection result, degree of complete maintenance and failure rate of equipment model are negligible. Then, ASi of all major equipment is equal to 1.00. In the second substation, the conditional score of all testing data of circuit breaker is also equal to 1. The visual inspection shows some defective component, maintenance period is prolonged because of critical load and failure rate of equipment model is low. The adjusting factors are assigned as 0.5, 0.03 and

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0.06 for visual inspection, maintenance completeness and failure rate, respectively. Then, *ASi* of circuit breaker is equal to 1.536. Hence, *ASi* of other major equipment in the second substation is equal to 1.56, 1.47, 1.32 and 1.76 respectively. For third substation, its circuit breakers failed in the main contact resistance test. Since there are some tests that failed, the *ASi* of this circuit breaker is equal to 3 automatically. Then it is not necessary to add the adjusting factor anymore. *ASi* of other major equipment in the third substation is equal to 2.10, 2.23, 2.17 and 2.50 respectively.

Step 2: After calculating *ASi* of each major equipment, the $\%HI_{bay}$ can be calculated by using Eq.2. The WE_i is equal to 40%, 20%, 15%, 15% and 10% respectively of major equipment. The maximum and minimum conditional score values are 3 and 1. Then, $\%HI_{bay}$ is equal to 0%, 25.02% and 76.50%, which are first, second and third example bays respectively.

TABLE XII. BAY HEALTH INDEX CALCULATION

Substation No.	Values	CB	DS	CT	VT	SA
1	*ASi*	1.00	1.00	1.00	1.00	1.00
	WEi	40	20	15	15	10
	$\%HI_{bay}$	100%				
2	*ASi*	1.53	1.56	1.47	1.32	1.76
	WEi	40	20	15	15	10
	$\%HI_{bay}$	74.98%				
3	*ASi*	3.00	2.10	2.23	2.17	2.50
	WEi	40	20	15	15	10
	$\%HI_{bay}$	23.50%				

Step 3: Adjusting factors for bay evaluation consist of age and operational stress. For the first substation, there are 5 new bays but they serve an almost full load at equipment rating. Since this substation is new and operated at its full operational stress, the adjusting factors are 0% and 20% for age and operational stress respectively. $\%HI_{bay,final}$ of theses bays is equal to 80%. For the second substation, there are 5 moderately aged bays. They serve at normal load. Then, the adjusting factor for age and operational stress will be 5% and 5%. Then, the $\%HI_{bay,final}$ of theses bays is equal to 64.98%. For the third substation, this substation consists of 5 aged bays. This substation serves the light load. The adjusting factor will be 10% and 0% from age and operational stress. Then, the $\%HI_{bay,final}$ of theses bays is equal to 13.50%.

Step 4: After $\%HI_{bay,final}$ of every bay in a substation is calculated, the average ($\%HI_{average,bay}$) and worst ($\%HI_{worst,bay}$) bay health index are subsequently calculated. For three example substations, $\%HI_{average,bay}$ is equal to 80%, 64.98% and 13.50% respectively because all of its 5 bays have similar bay health index. Since the worst bay health index can show the urgency needs to fix the defect equipment or to renovate the aged and high operational stress equipment. Then, the $\%HI_{substation}$ is selected from the minimum value of bay health index or $\%HI_{worst,bay}$. This substation health index shows the overall condition of substation in good, moderate and poor condition, respectively.

By using the aforementioned method, the health index of fifteen substations are calculated and shown in Table XIII.

TABLE XIII. HEALTH INDEX OF FIFTEEN SUBSTATIONS

Substation No.	$\%HI_{average,bay}$	$\%HI_{substation}$	Condition
1	75.07%	70.21%	Moderate
2	50.76%	23.34%	Poor
3	31.04%	13.50%	Poor
4	51.17%	42.00%	Moderate
5	57.50%	40.00%	Moderate
6	79.67%	75.01%	Poor
7	45.94%	28.75%	Moderate
8	70.00%	40.00%	Moderate
9	53.88%	44.50%	Moderate
10	41.00%	37.00%	Moderate
11	33.04%	27.50%	Moderate
12	26.32%	24.50%	Poor
13	47.36%	42.00%	Moderate
14	52.83%	42.00%	Moderate
15	87.65%	77.30%	Good

As a result, there are two substations, ten substations and three substations in good, moderate and poor condition, respectively. For good condition substation, they are in normal operation with routine maintenance. For moderate condition, adequate maintenance planning is needed. For poor condition, urgent repair or replacement is required.

VI. CONCLUSION

The condition assessment for high voltage substation and its equipment consisting of five major equipment as circuit breaker, disconnecting switch, current transformer, voltage transformer and surge arrester by considering visual inspection and electrical test. The weighting and scoring method is applied to calculate the weighting average score of major equipment. Then, the weighting average score is adjusted by visual inspection, maintenance completeness and failure rate of equipment. The adjusted average score of all equipment in a bay is considered together as bay health index, which is subsequently adjusted by age and operational stress of bay. Finally, the substation health index can be successfully determined. The developed procedure was implemented in MS Excel program to determine the health index of 15 substations in Thailand. This developed tool and its information are useful for an effective maintenance and renovation planning.

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