Lifetime Prediction Using Health Index and Conditional Factor for Underground Cable System

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Abstract: There are various prognostic methods developed to predict future condition and remaining life of underground cable system. However, these methods are only based on a single degradation investigation, comparing to practical terms. In addition, there are many types of measurement that could reveal the degradation process. Moreover, the systems may be installed and operated under various kinds of severity in operating condition leading to different degradation behaviors. Therefore, this paper proposes a method, combining health index approach as multiple degradation measurements to evaluate the condition of cable system components with condition index as conditioning usage factor of system, to finally predict the lifetime of underground cable system. The weighting and scoring method, analytical hierarchy process, polynomial and Weibull distribution function are involved in this calculation. The actual technical and operating data with historical testing records had been applied in this paper. Five underground cable system operating in high voltage distribution system were evaluated. The output trend of health indexes is used to identify degradation behavior of those underground cable systems. Finally, the lifetime of the underground cable system could be determined. This work could help power utilities to manage and plan a proper maintenance strategy to upkeep the reliability of their system.

Keywords— Lifetime estimation, health index, conditional factor, Weibull distribution, underground cable.

I. INTRODUCTION

Underground power cables have been widely used in many countries, not only in industrial area but also in transmission and distribution system. The number of new underground cable installation increases significantly to improve aesthetic view, safety and supply reliability of electrical system [1-3]. Nevertheless, deterioration and damage in cable system have increased. Both implicit and explicit factors affect aging and insulation degradation of cable such as installation defect, as well as electrical, thermal, and environmental stresses [4-6]. Thus, to keep the best condition of cable system, system owners need to know the exact condition of their own assets and the end of life of their own properties to plan and manage them in time whether to repair, renovate or replace before damage [7-10]. There are different testing methods are currently used to assess the actual condition of underground cable and its components such as partial discharge, insulation and earth resistance, ampacity and sheath voltage and thermography tests, etc. [7], [11-20]. In power delivery system as shown in Fig.1, there are many equipment and accessories that form as major components of an underground cable system such as underground cable, joint and termination, duct bank, manhole, grounding system, etc.

Failure in underground cable system causes huge impact to customers especially in industrial area due to power interruption. To avoid both technical and economic problems, the percentage health index (%HI) determination method has been applied with underground cable system to estimate actual condition of components and that of the whole system.

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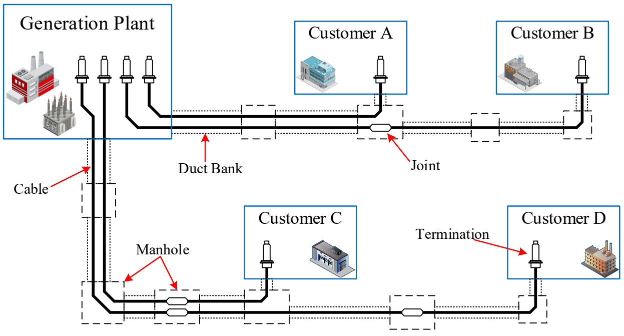

Fig. 1. Simplified underground cable system and components diagram.

In this paper, the condition assessment of underground cable system had been performed by applying the weighting and scoring technique, and the analytic hierarchy process (AHP) to evaluate each equipment and system condition. Five major components of underground cable system as power cable, joint, termination, manhole, and duct bank had been classified. The actual test results of cable, terminator, joint, duck bank and manhole from the considered underground cable system were used as input for the assessment. The periodical %HIs were plotted while %HI-trend was fitted by using polynomial distribution to predict lifetime of any cable system. In addition, technical data and operating data were also considered as conditional factor representing degradation behavior in term of practical usage by using Weibull distribution method. Finally, the lifetime of cable system can be determined by multiplying the proposed %HI fitting function with Weibull estimation function.

II. DATA MANAGEMENT SYSTEM

In this work, there were three significantly concerned data including technical, testing and visual inspection, as well as operating data needed for condition evaluation.

A. Technical Information

The technical information of those aforementioned five major components can be explained as follows. Firstly, the cable's technical data consist of route name, rated voltage, rated current, manufacturer, model type, installation date, number of terminators, number of manholes, and length of the entire route. Secondly, the terminator's technical data consists mainly of name, parent name, bonding type, manufacturer, model type, installation date and location. Next, the termination's technical data consists of name, parent name, location, manufacturer, model, and installation date. Fourthly, the manhole's technical data consists of name, route in manhole, location, manufacturer and model. Finally, the duct bank's technical data consists of name, origination manhole, destination manhole, and number of total duct, used duct, damage duct, spare duct, etc.

B. Testing and Inspection Results

Generally, maintenance of underground cable system has been performed while system is energized to detect and recognize the defects at the actual operating condition and to avoid supply interruption. In this work, there were four effective tests and inspections that were performed during the system maintenance including visual inspection, infrared thermography inspection, sheath current measurement, and partial discharge measurement as shown in Fig. 2. The details were expressed in Table I.

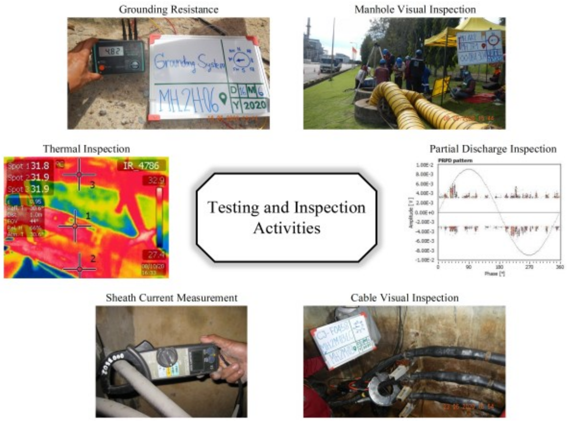

Fig. 2. Examples of testing and inspection activities.

C. Operating Information

To obtain more accurate lifetime estimation, the environmental and operating conditions were significantly concerned in term of practical usage condition. The operating criteria, scores and weights for the assessment are presented in Table II. These represent not only the operating condition of cable system but also risk to the electrical supply system. The environmental and operating conditions consider age in service, percentage of cable loading, number of historical failures, network structure type, and environmental influences. For example, if system has high age in service, high cable loading and no. failure, as well as there are severe environmental impacts as high humidity, high ambient temperature, coverage soil and water; it could be fast degraded and could be used for lower life expectation.

III. ASSESSMENT CRITERIA WITH WEIGHTS AND SCORES

After classification of the major groups of components and their testing methods assigned for each component, it is necessary to interpret the test results to scores of all criteria to calculate the %HI. The score-classification is based on international standard and organization decision. For conditional factor, the criteria including age, loading percentage, number of failures and repairs, network structure, cable length and number of joints, as well as environmental influence of underground cable system was shown in Table I. The scoring for operating criteria was also presented.

TABLE I
TESTING AND INSPECTION WITH SCORING

Testing method	Testing	Weight	Score		
			4 (normal)	2 (moderate)	0 (risk)
partial discharge	PD pattern	10	no PD/corona	surface	internal
	amplitude (internal PD)		<50pC	50-300pC	>300pC
	amplitude (surface PD)	8	<500pC	0.5-2nC	>2nC
	trending of amplitude		stable	slight	significant
infrared thermography	ΔT phase-ambient	10	<10°C	10-15°C	>15°C
	ΔT phase-phase		<7°C	7-10°C	>10°C
sheath current	increment of sheath current	10	<5%	5-10%	>10%
grounding resistance	grounding resistance	5	<10Ω	10-25Ω	25Ω
visual inspection	cable jacket	10	normal	repaired	cracked
	cable supporting structure	4	normal	stained	broken
	cable shield grounding	8	normal	loose	broken
	terminator condition	10	normal	-	bloated
	joint condition	10	normal	dirty	bloated
	manhole gate	7	normal	stained	lost
	manhole wall and floor	7	normal	small crack	broken
	manhole cleaning	3	clean	dirty	flooded
	duct bank water ingress	8	no water	some leakage	high pressure
	duct bank general condition	8	normal	small crack	broken
	number of available ducts	10	many	a few	unavailable

TABLE II
CRITERIA SCORING FOR OPERATING CONDITION

Criteria	Weight	Score		
		4 (normal)	2 (moderate)	0 (risk)
age in service (yrs.)	10	<20	20-30	>30
load percentage (%)	10	<60	60-80	>80
number of failures	8	0	1-3	>3
number of repairs	7	<3	3-6	>6
network structure	6	network	loop	redial
Length (km)	5	<1	1-3	>3
number of terminators	5	<10	10-30	>30
environmental influence	3	no	road, building	vibration

IV. HEALTH INDEX CALCULATION

The underground cable system is necessarily categorized into its major important components to make the data collection become simpler to manage as well as to make the health index calculation to be easier, by analyzing smaller group of data instead of a complex calculation of the whole system. After all the components have been grouped, the condition evaluation still needs some necessary data for its process, including technical information, testing and inspection results, and operation information.

A. Component HI Calculation

The actual condition of each major component in the cable system will be evaluated at this stage by analyzing the routine and inspection test result with the standardized criteria. The component actual condition is presented term of component health index and calculated by using (1).

$$\%HIC = \frac{\sum_{i=1}^{n}\left(s_i \times w_i\right)}{\sum_{i=1}^{n}\left(s_{\max,i} \times w_i\right)} \times 100 \tag{1}$$

where s_i is a score of the test and inspection result i^{th}, $s_{max,i}$ is a maximum score of the test and inspection result i^{th}, w_i is the important weight of the test and inspection result i^{th}, i is the index of test and inspection result, and, the last one, n is the total number of the test and inspection results.

B. System HI Calculation

After all the component health indices have been calculated, the process will select the worst one of each component group to use as the representative of the group for the system health index calculation. Then, the worst component health index of each group will be proceeded to analyze the overall system health index (*%HIS*) condition, resulting in the number format between 0 to 100 as bad to good condition by using (2).

$$\%HIS = \frac{\sum_{j=1}^{m}\left(HIC_j \times w_j\right)}{100} \tag{2}$$

where HIC_j is the worst component health index of the major component group j^{th}, w_j is the important weight of the major component group j^{th}, j is the index of component group, and m is the total number of the major component groups.

V. CONDITIONAL FACTOR CALCULATION

Conditional factor (*CF*) was used for increasing the accuracy of the system lifetime estimation in term of practical usage condition by using as the curve slope bending according to the Weibull distribution analysis state. It could be determined by using (3).

$$CF = \frac{\sum_{c=1}^{p}\left(s_c \times w_c\right)}{\sum_{c=1}^{p}\left(s_{\max,c} \times w_c\right)} \tag{3}$$

where s_c is a score of the operation record item c^{th}, $s_{max,c}$ is a maximum score of the operation record item c^{th}, w_c is the important weight of the operation record item c^{th}, c is the index of operation record item, and p is the total number of the considering operation record items. The diagram for remaining life estimation of underground cable system is illustrated in Fig. 3.

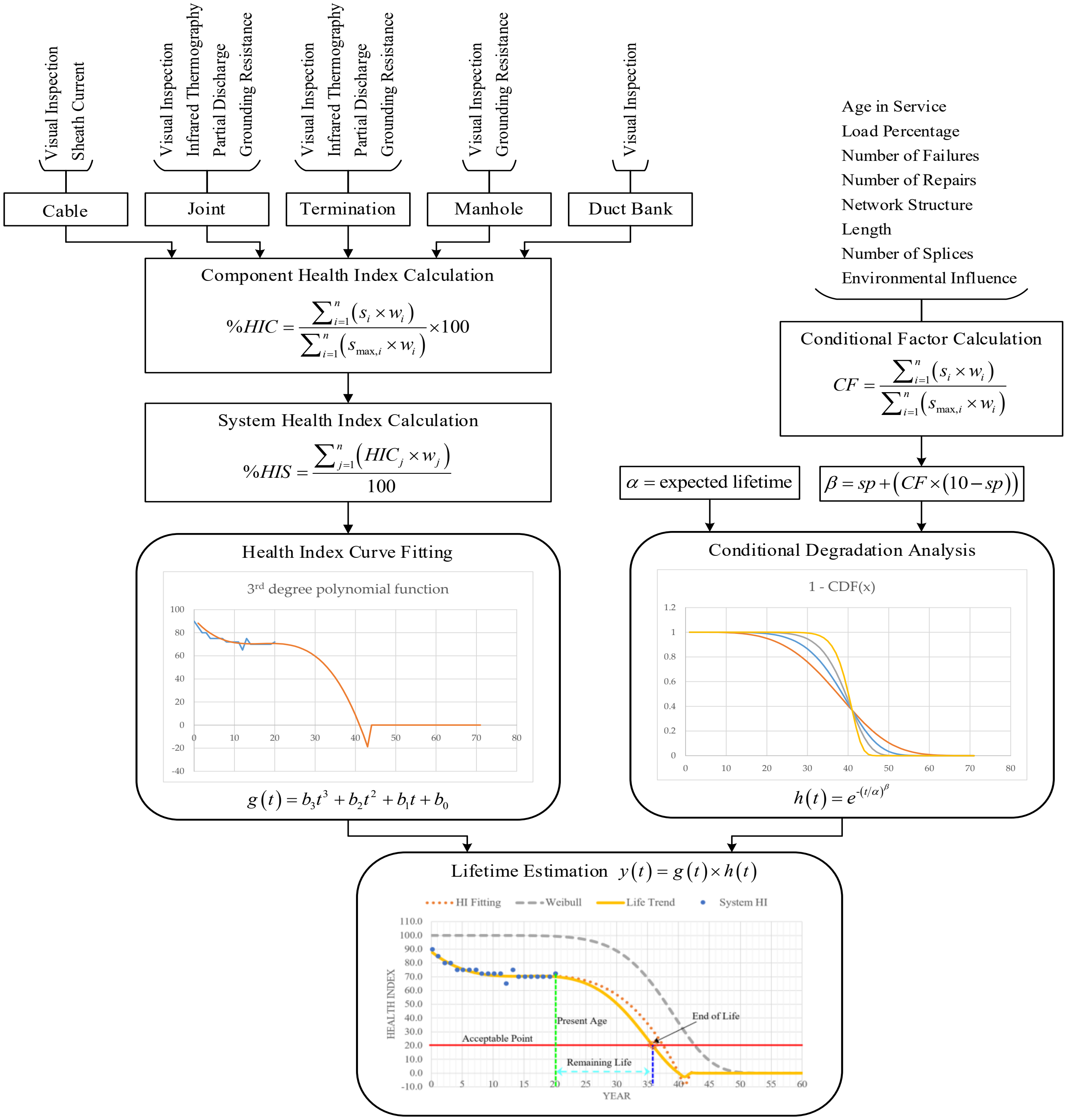

Fig. 3. Underground cable system remaining life estimation diagram.

VI. LIFETIME ESTIMATION

The lifetime of cable system is determined by multiplying the Statistical %HI fitting function with Weibull estimation function as follows.

A. Statistical %HI Curve Fitting

After health index calculation, degradation of cable system can be estimated. The degradation equation of the system can be determined by using regression distribution function, which is not only used to analyze historical system degradation, but also prognosis the trend of %HI in the future for maintenance task and budget management.

After %HI plotting, the %HI curve fitting must be performed by using different types of distribution functions such as linear, exponential, second-order polynomial or third-order polynomial function as shown in Fig. 4. However, the best fitting curve for cable system lifespan is the third order polynomial distribution. According to the regression analysis, it is clearly accepted that the third order polynomial distribution is the most suitable because of the highest coefficient of determination (R^2=0.8822) comparing to other three, with the degradation curve of cable system. It could be written as (4).

$$g(t) = b_3 t^3 + b_2 t^2 + b_1 t + b_0 \tag{4}$$

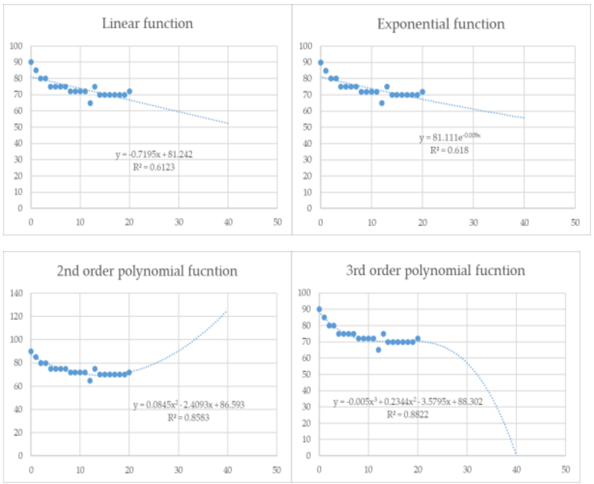

Fig. 4. Regression analysis for HI estimation.

All the parameters in (4) are analyzed by using regression analysis based on historical health index, the greater number of collections refers to the better accuracy and trustworthy of the output.

B. Degradation Behavior Analysis

According to differences of degradation behavior of each cable system, there are many works that used the Weibull distribution to analyze and illustrate graphs of degradation for underground cable system. There are various types of functions in Weibull distribution. The one that is selected to use in this work is 1-CDF(t) which is written in (5) and (6); when the CDF is cumulative distribution function.

$$h(t) = 1 - \mathrm{CDF}(t) \tag{5}$$

$$h(t) = e^{-(t/\alpha)^{\beta}} \tag{6}$$

For this function, it requires two parameters to make a complete equation. The first one is α-parameter, which is an estimated lifetime of equipment and system to adjust cutting point of that fitting curve at 36.79 percent. In this work, it implies to the expected lifetime of cable system. The second one is β-parameter, which is used to adjust the slope of the curve and known as shape parameter referring to degradation behavior of cable system. In addition, it is substituted by the conditional factor of each cable system. Thus, β-parameter is calculated by (7).

$$\beta = sp + \left(CF \times (10 - sp)\right) \tag{7}$$

The different β values give different degradation shape, which is illustrated in Fig. 5. The most appropriate β is 10 leading to a proper lifetime shape according to expected lifetime.

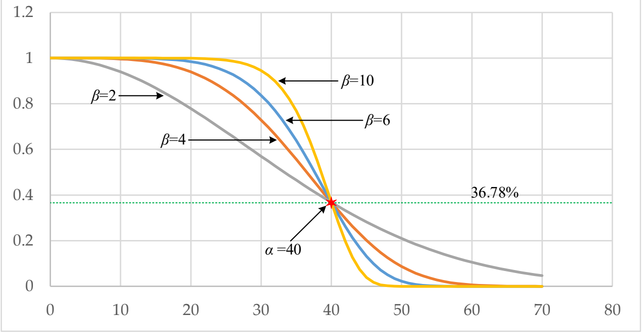

Fig. 5. Example on curve shapes of 1-*CDF*(t) function.

C. Lifetime Curve Forecasting

In the final step, the %HI curve and degradation behavior curve are combined to get a proper lifetime trending of underground cable system by using lifetime function $y(t)$ in (8). The lifetime curve is shown as the yellow line in Fig. 6. The end of life is estimated by using (9) where *AP* is acceptable point of %HI level, t_e is a calculated year upper the *AP*. In Fig. 6, the end of life is estimated as of 20 years.

$$y(t) = g(t) \times h(t) \tag{8}$$

$$LT = t_e + \left(\frac{AP - y(t_e)}{y(t_e+1) - y(t_e)} \right) ; y(t_e) > AP, \text{ limit } 1 \quad (9)$$

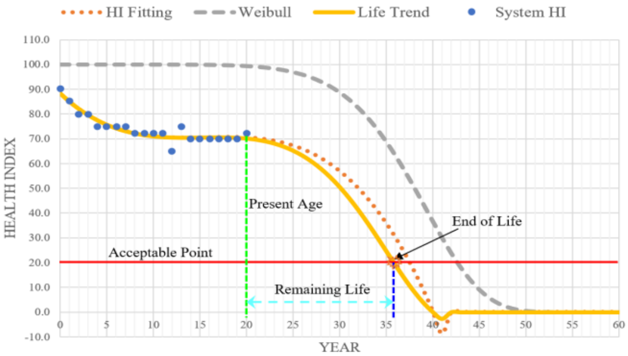

Fig. 6. Lifetime estimation curve.

VII. RESULTS AND DISCUSSION

In this section, %HI calculation of sub-components and overall %HI of cable system as well as %CF of 5 cable feeders is presented. Data of feeder F-01 are written in Table III and Table IV, respectively. The scores of sub-components of F-01 to F-05 are presented in Table V. Finally, %HIs of sub-components and overall %HIs of 5 feeders are shown in Table VI. The overall %HIs of 5 cable systems are plotted in Fig. 7, which the lifetime can be observed. Finally, the lifetime trending of this feeder was investigated over 30 years.

TABLE III
OVERALL %HI OF SYSTEM OF FEEDER F-01

Component group	HIC_j	w_j	%HIsystem (%HIS)
cable	46.88	30	59.28
joint	40.70	30	
termination	100.00	25	
manhole	55.13	10	
duct bank	50.00	5	

TABLE IV
%CF OF FEEDER F-01

Considering item	s_c	w_c	%CF	β
age in service	2	10	0.33	4.67
load percentage	2	10		
number of failures	2	8		
number of repairs	0	7		
network structure	0	6		
length	2	5		
number of terminators	0	5		
environmental influence	2	3		

TABLE V
HEALTH INDICES OF 10 CABLE SYSTEMS

Component	Testing method	Considering value	Weight	Score				
				F-01	F-02	F-03	F-04	F-05
cable	visual inspection	cable jacket	10	2	2	4	4	4
		cable supporting structure	4	2	2	2	2	2
		cable shield grounding	8	4	4	4	4	4
	sheath current	increment of sheath current	10	0	4	4	4	4
%HI of cable ($\%HI_{cable}$)				46.88	78.13	93.75	93.75	93.75
joint	visual inspection	terminator condition	10	4	4	4	4	4
	partial discharge	PD pattern	10	0	4	4	4	4
		PD amplitude or trending	8	0	4	4	4	4
	infrared thermography	ΔT phase-ambient or phase-phase	10	2	4	4	4	4
	grounding resistance	grounding resistance	5	2	2	2	4	4
%HI of joint ($\%HI_{joint}$)				40.7	94.19	94.19	100	100
termination	visual inspection	termination condition	10	4	4	4	4	4
	partial discharge	PD pattern	10	4	4	4	4	4
		PD amplitude or trending	8	4	4	4	4	4
	infrared thermography	ΔT phase-ambient/phase-phase	10	4	2	4	4	4
	grounding resistance	grounding resistance	5	4	4	4	4	4
%HI of termination ($\%HI_{termination}$)				100	88.37	100	100	100
manhole	visual inspection	manhole gate	7	4	4	4	4	4
		manhole wall	7	2	2	2	2	2
		manhole floor	7	2	2	2	2	4
		manhole cleanness	3	0	0	0	0	0
		manhole ground connection	8	2	2	2	4	4
	grounding resistance	grounding resistance	7	2	2	2	4	4
%HI of manhole ($\%HI_{manhole}$)				55.13	55.13	55.13	74.36	83.33
duct bank	visual inspection	duct bank general condition	8	4	4	2	2	2
		duct bank water ingress	8	0	0	0	0	0
		number of available ducts	10	2	2	0	0	0
%HI of duct bank ($\%HI_{duct\text{-}bank}$)				50	50	15.38	15.38	15.38
%HI of cable system ($\%HI_{system}$)				59.28	81.8	87.66	91.33	92.23

TABLE VI
POWER PLANT 1'S CABLE SYSTEM REMAINING LIFE ESTIMATION

%HI	Feeder				
Recorded year	F-01	F-02	F-03	F-04	F-05
0	100	100	100	100	100
1	98.85	99.23	98.85	99.04	99.04
2	96.97	98.65	98.85	98.65	99.04
3	96.01	98.65	98.85	98.65	98.85
4	95.11	96.78	96.97	98.13	98.85
5	95.11	96.01	96.97	97.16	98.65
6	95.11	95.11	96.97	97.16	96.97
7	93.83	93.83	96.01	96.78	96.97
8	93.83	93.83	96.01	96.78	96.78
9	93.83	93.13	96.01	96.01	96.78
10	91.06	91.33	95.11	96.01	96.01
11	91.06	91.06	95.11	96.01	96.01
12	91.06	91.06	95.11	95.05	95.11
13	87.57	87.57	93.83	95.05	95.11
14	87.57	87.53	93.83	95.05	93.89
15	87.57	87.53	93.83	93.89	93.89
16	85.91	86.5	91.06	93.89	93.13
17	76.53	85.91	91.06	93.89	93.13
18	67.16	85.91	91.06	91.33	92.23
19	71.84	77.11	87.66	91.33	92.23
20	59.28	81.8	87.66	91.33	92.23
expected lifetime, α (yr)	40	40	40	40	40
shape parameter, β	4.67	6.15	6.52	6.52	8.37
estimated lifetime (yr)	21.03	29.42	29.88	32.96	37.90
coefficient (R^2)	0.9608	0.9468	0.973	0.974	0.982
acceptable HI (%)	50	50	50	50	50
remaining life (year)	1.03	9.42	9.88	12.96	17.90

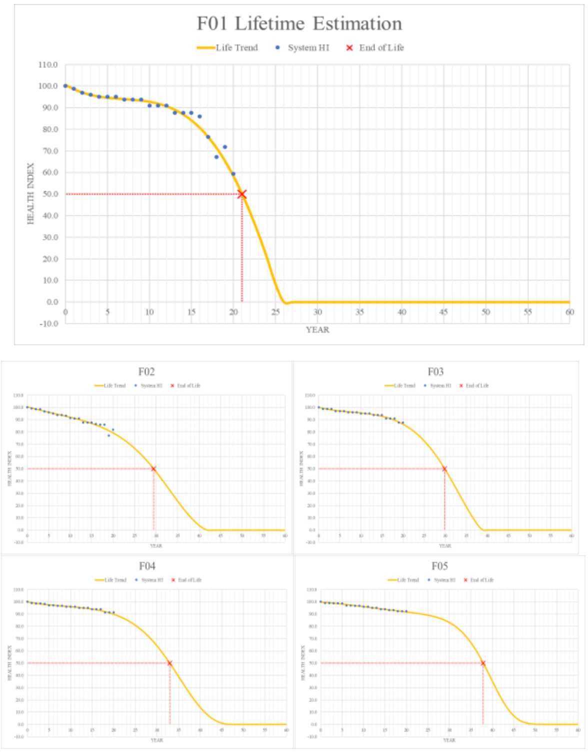

Fig. 7 Cable system lifetime estimation of a power distribution system.

VIII.CONCLUSION

The lifetime and remaining life are estimated by using historical health index of underground cable system. The percentage health indexes of underground cable components and systems are calculated from many diagnostic methods and visual inspection. The weighting and scoring method and the analytical hierarchy process had been applied in the health index calculation. The annual percentage health indexes of each cable feeder are plotted. The trending curve of percentage health indexes is observed and predicted by the 3 rd polynomial distribution function. The percentage conditional factor is additionally concerned in condition evaluation. These factors also affect the remaining life if there are bad operating conditions. Finally, the lifetime function and curve are determined by multiplying the health index estimation function and Weibull estimation function to lastly, determine the lifetime curve of each cable system. From the curve, the lifetime is identified. The utility can quickly focus on the weak cable feeder and system. Consequently, the maintenance tasks can be effectively managed.

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