A HEALTH INDEX SYSTEM AND METHOD OF PREDICTING HEALTH CONDITION IN UNDERGROUND CABLES

FIELD OF THE INVENTION

[0001] The present invention relates to a system and method for predicting health condition of underground cables, in particular a composite health index (cHI) system and method for predicting the health condition of underground cables.

BACKGROUND OF THE INVENTION

[0002] Underground cables are subjected to high pressure and harsh environmental conditions, which can lead to aging and damage. Therefore, regular checks and scheduled maintenance are required to monitor the condition of the cable. To understand deeply the cable health condition and fault reason, it is important to know the fault component and tangent delta (TD) for analysis purposes.

[0003] For the cable health condition, the TD value represents the energy loss in the cable. This value accounts for a wide range of cable parameters, therefore the TD could ideally present the cable condition. For instance, it shows a lower energy loss with a low TD value, while a higher TD represents a higher energy loss. Therefore, the TD value reflects the actual cable health conditions.

[0004] A health index (HI) system is introduced in utility companies to measure the cable condition and predict the remaining service life of the cable. In conventional HI system, utility companies monitor the cable's health condition through five different levels in the HI system. The five different levels increase by one each step, with 1 identifying healthy cables and 5 indicating unhealthy cables. It is an extension of the IEEE standard in measuring the TD's range, but it fails to indicate the severity of the water tree. Therefore, it is often difficult for utility companies to monitor the health condition of the cable due to a lack of clear guidelines. This causes difficulties in predicting the faulting of the underground cable. Accordingly, utility companies may need to bear high maintenance costs and experience unstable power network usage. Apart from that, the conventional HI system may be time-consuming and infeasible in real applications, since it requires a lot of human effort to compare the TD measurements with the thresholds and determine the health level of the cable.

[0005] United States Patent Publication No. US 10393788 B2 discloses an apparatus and method for diagnosing state of power cable and measuring remaining life thereof using very low frequency (VLF) TD measurement data and for determining a replacement time of a power cable using a 3D matrix exhibiting reproducibility of diagnosis of the state of the power cable. The apparatus and method utilize VLF TD measurement data to diagnose the state of power cable and measure remaining life. However, the apparatus and method do not provide a clear guideline in classifying the grades or level of health in the underground cable. Although TD value along with the normalized skirt value disclose a general scale in the patent invention, the status of the cable is not specified. This could mislead users or workers of the cable condition such as when to require maintenance. Therefore, the maintenance cost may not be able to be estimated due to various manpower and materials costs involved in different scenarios. The apparatus and method in the patent invention assume the remaining life and skirt value have a linear relationship, which is not held in real application. Therefore, there is a need to provide a HI system and method with clear guidelines for monitoring and predicting the health condition of underground cables, which could reduce maintenance costs, provide a stable power network, and reduce instances of sudden energy loss within the location. There is also a need to employ artificial intelligence (AI) to predict the remaining useful life (RUL) of the HI system to provide a reliable indicator.

[0006] China Patent Publication No. 112673265 A discloses a method and system for monitoring health state of power cable accessory based on machine learning. The method and system disclosed monitoring of electrical equipment of an electrical grid and predicting possible fault events for such electrical equipment. The system includes an article of electrical equipment, at least one processor, and a storage device. The electrical equipment article includes one or more sensors configured to generate sensor data indicative of one or more conditions of the electrical equipment article. The storage device includes instructions that, when executed by the at least one processor, cause the at least one processor to: receiving the sensor data; determining a health status of the electrical equipment article based at least in part on the sensor data; and performing an operation in response to determining the health status of the electrical equipment article. However, there is no consideration of TD analysis to determine the health status of the power cable. This may not be reliable in detecting and determining the severity of water tree for the power cable. Therefore, there is a need to provide a HI system and method with clear guidelines for monitoring and predicting the health condition of underground cables by considering water tree severity.

[0007] United States Patent Publication No. 8847606 B2 discloses a method and system for assessing insulation deterioration in live underground power cables. The method includes attaching a coupling device to a live underground power cable and using the coupling device to couple a test signal onto the power cable. The power cable may carry a normal AC power signal at a first frequency, while the test signal may have a second frequency different from the first frequency. The test signal may be detected after it has travelled a distance along the power cable. It may then be analyzed to determine in a change in velocity and/or attenuation of the test signal as a function of the normal AC power signal. The severity of water trees in the power cable may be inferred based on the magnitude of the change. Although the severity of water trees is considered, the RUL suggestion is not provided in the patent invention. The relationship between HI and RUL is crucial to provide a convincing RUL suggestion, which could simultaneously predict and monitor the health condition of the power cable.

SUMMARY OF THE INVENTION

[0008] It is an objective of the present invention to provide a composite HI (cHI) system and method for monitoring and predicting the health condition of underground cables, which can provide clear guidelines and maintenance statuses for the underground cables.

[0009] It is also an objective of the present invention to provide a cHI method and system for monitoring and predicting the health condition of underground cables, which could reduce maintenance costs, provide a stable power network and reduce sudden energy loss within the location.

[0010] It is also a further objective of the present invention to provide a cHI method and system for monitoring and predicting the health condition of underground cables that employ artificial intelligence (AI) to make a prediction of the remaining useful life (RUL) in the HI system, thereby providing a reliable indicator.

[0011] Accordingly, these objectives may be achieved by following the teachings of the present invention. The present invention relates to a processor and a memory communicatively coupled to the processor via a communications bus; a computational model communicatively coupled to the processor, wherein the computational model: receives a plurality of operating parameters for an underground cable; accumulates tangent delta (TD) signal data measured based on the plurality of operating parameters for the underground cable; defines a composite health index (cHI) based upon the accumulated TD signal data, a stability of the TD signal over time and a stability of the TD signal over voltage; calculates remaining useful life (RUL) of the underground cable; analyzes the relationship of the cHI and RUL; and predicts the RUL model using artificial intelligence (AI) based on the analyzed relationship between the cHI and RUL to determine the health condition of the underground cable.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] The features of the invention will be more readily understood and appreciated from the following detailed description when read in conjunction with the accompanying drawings of the preferred embodiment of the present invention, in which:

[0013] **FIG.1** illustrates a flow diagram of the composite HI system in the present invention;

[0014] **FIG.2** illustrates upper and lower bound threshold for composite health index.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0015] For the purposes of promoting and understanding of the principles of the invention, reference will now be made to the embodiments illustrated in the drawings and described in the following written specification. It is understood that the present invention includes any alterations and modifications to the illustrated embodiments and includes further applications of the principles of the invention as would normally occur to one skilled in the art to which the invention pertains.

[0016] The present invention teaches a health index system for predicting health condition in underground cables, comprising of: a processor and a memory communicatively coupled to the processor via a communications bus; a computational model communicatively coupled to the processor, wherein the computational model: receives a plurality of operating parameters for an underground cable; accumulates tangent delta (TD) signal data measured **102** based on the plurality of operating parameters for the underground cable; defines a composite health index (cHI) **104** based upon the accumulated TD signal data, a stability of the TD signal over time and a stability of the TD signal over voltage; calculates remaining useful life (RUL) **106** of the underground cable; analyzes the relationship of the cHI and RUL **108**; and predicts the RUL model **110** using artificial intelligence (AI) based on the analyzed relationship between the cHI and RUL **108** to determine the health condition of the underground cable.

[0017] In a preferred embodiment of the present invention, the underground cable comprises low voltage cross-linked polyethylene (XLPE).

[0018] In a preferred embodiment of the present invention, the TD signal data comprises an upper bound alarm threshold and a lower bound alarm threshold.

[0019] The present invention also teaches a health index method for predicting health condition in underground cables, comprising the steps of: receiving a plurality of operating parameters for an underground cable; accumulating tangent delta (TD) signal data measured **102** based on the plurality of operating parameters for the underground cable; defining a composite health index (cHI) **104** based upon the accumulated TD signal data, a stability of the TD signal over time and a stability of the TD signal over voltage; calculating a remaining useful life (RUL) **106** of the underground cable; analyzing relationship of the cHI and RUL **108**; and predicting the RUL model **110** using artificial intelligence (AI) based on the analyzed relationship between the cHI and RUL **108** to determine the health condition of the underground cable.

[0020] In a preferred embodiment of the present invention, the accumulating of tangent delta (TD) signal data comprising the steps of: testing the TD signal data using a very low frequency (VLF) test; wherein the TD signal data comprises an upper bound alarm threshold and a lower bound alarm threshold.

[0021] In a preferred embodiment of the present invention, the accumulating of tangent delta (TD) signal data further comprising the step of: categorizing the TD signal data to five ranges for indicating level of severity of the underground cable.

[0022] In a preferred embodiment of the present invention, the method further comprising the step of: breaking down the health index into 0, 0~1, and >1 by the upper bound alarm threshold and lower bound alarm threshold to provide an improved description of the cable condition.

[0023] In a preferred embodiment of the present invention, the plurality of operating parameters of the underground cable includes but not limited to capacitance, resistance, geometry, and specification of the cable.

[0024] In a preferred embodiment of the present invention, the determining of the health condition of the underground cable comprises a healthy state, to be monitored state, and required maintenance state.

EXAMPLE

[0025] A flow diagram of the composite HI system is illustrated in **FIG.1**. Accordingly, the flow diagram shows the accumulation of TD signal data measurement **102** based on the plurality of operating parameters of the XLPE underground cable in the present invention. **FIG.1** further shows the definition of cHI **104** based upon the accumulated TD signal, the stability of the TD signal over time and the stability of the TD signal over voltage. The RUL of the XLPE underground cable is further calculated **106**. The relationship between the cHI and RUL is analyzed **108** to predict the RUL model **110** based on the AI method to determine the health condition of the XLPE underground cable.

[0026] The TD signal data in the present invention is divided into five different ranges, each indicating the severity of the cable, such as a range from 0 to 5 with an incline of 1. This gives the system a scale to monitor the quality of the cable in terms of the energy that is discharged. The cHI in the present invention is interpreted as below:

$$cHI = \left(\left(\frac{TD-alarm_{TD}^{l}}{alarm_{TD}^{u}-alrm_{TD}^{l}}\right)^{4} + \left(\frac{STD-alarm_{STD}^{l}}{alarm_{STD}^{u}-alrm_{STD}^{l}}\right)^{4} + \left(\frac{DTD-alarm_{DTD}^{l}}{alarm_{DTD}^{u}-alrm_{DTD}^{l}}\right)^{4}\right)^{\frac{1}{4}} \quad \text{.........(1)}$$

Wherein

cHI is composite health index,

MTD is magnitude of tangent delta,

TDTS is stability of tangent delta over time,

DTD is stability of tangent delta over voltage.

[0027] **Table 1** represents the condition assessment for the health condition of the XLPE underground cable, which comprises no action required, further study advised, and action required. It consists of the upper ($alarm^{u}$) and lower ($alarm^{l}$) bound alarm thresholds. The implementation of the upper and lower bound thresholds breaks down the health index (HI) into 0, 0~1, and >1. This continuous value can provide a better description of the cable condition.

Table 1: Condition assessment for health condition of the XLPE underground cable

Condition assessment	VLF-TD Time Stability (VLF-TDTS) measured by standard deviation at U_0, $[10^{-3}]$		Differential VLF-TD (VLF-DTD) (difference in mean VLF-TD) between 0.5 U_0 and 1.5 U_0 $[10^{-3}]$		Mean VLF-TD at U_0 $[10^{-3}]$
No Action Required	<0.1	and	<5	and	<4
Further Study Advised	0.1 to 0.5	or	5 to 80	or	4 to 50
Action Required	>0.5	or	>80	or	>50

[0028] **FIG.2** illustrates the upper and lower bound thresholds for the composite health index. Accordingly, HI in the range of 0 to [0,1] is considered the lower bound alarm threshold, whereas HI in the range of [0,1] to more than 1 is considered the upper bound alarm threshold.

[0029] The system and method in the present invention provide an improved cHI that increases the accuracy level through examining age of the cable, TD value, and consideration of water tree severity. This provide a clear guideline in determining the level of the health conditions of the underground cable. Said guideline of the health conditions is healthy state, to be monitored state, and required maintenance state. Besides, a scalar value is provided to indicate the cable. By using the concept of a hyper-ellipse inscribed within the hyper-box, a scalar-valued cHI is employed in the present invention. This index works as a projection of the multiple factors into a hyperboloid region as a scalar, considering the violation of TD measurements, making it more feasible and robust.

[0030] A user or utility company may predict the fault in underground cable based on the guideline, which could reduce the cost of the utility and provide higher reliability. The chances of sudden energy loss within the location could be reduced when the user or utility company could predict the fault earlier. Hence, a stable power network is provided by utilizing the system and method in the present invention to predict the health condition of underground cable and ensure the citizen's usage and all other services in the region.

[0031] The system and method in the present invention further provides RUL prediction model **110** in which the relationship between the RUL and cHI could be analyzed **108**. The results show that the RUL decreases when the cHI value increases. In another words, the cables in bad condition (i.e., a high cHI value) have a small RUL. After the analysis of the relationship between the cHI and RUL **108**, the AI method can be employed to learn the hidden features and relationships. As a result, the cHI can not only monitor the cable condition but also provide a reliable indicator for RUL prediction.

[0032] The present invention explained above is not limited to the aforementioned embodiment and drawings, and it will be obvious to those having an ordinary skill in the art of the prevent invention that various replacements, deformations, and changes may be made without departing from the scope of the invention.

CLAIMS

WHAT IS CLAIMED:

1. A health index system for predicting health condition in underground cables, comprising of:

a processor and a memory communicatively coupled to the processor via a communications bus;

a computational model communicatively coupled to the processor, wherein the computational model:

receives a plurality of operating parameters for an underground cable;

accumulates tangent delta (TD) signal data measured (102) based on the plurality of operating parameters for the underground cable;

defines a composite health index (cHI) (104) based upon the accumulated TD signal data, a stability of the TD signal over time and a stability of the TD signal over voltage;

calculates remaining useful life (RUL) (106) of the underground cable;

analyzes the relationship of the cHI and RUL (108); and

predicts the RUL model (110) using artificial intelligence (AI) based on the analyzed relationship between the cHI and RUL (108) to determine the health condition of the underground cable.

2. The health index system for predicting health condition in underground cables, according to claim 1, wherein the underground cable comprises low voltage cross-linked polyethylene (XLPE).

3. The health index system for predicting health condition in underground cables, according to claim 1, wherein the TD signal data comprises an upper bound alarm threshold and a lower bound alarm threshold.

4. A health index method for predicting health condition in underground cables, comprising the steps of:

receiving a plurality of operating parameters for an underground cable;

accumulating tangent delta (TD) signal data measured (102) based on the plurality of operating parameters for the underground cable;

defining a composite health index (cHI) (104) based upon the accumulated TD signal data, a stability of the TD signal over time and a stability of the TD signal over voltage;

calculating a remaining useful life (RUL) (106) of the underground cable;

analyzing relationship of the cHI and RUL (108); and

predicting the RUL model (110) using artificial intelligence (AI) based on the analyzed relationship between the cHI and RUL (108) to determine the health condition of the underground cable.

5. The health index method for predicting health condition in underground cables, according to claim 4, wherein the accumulating of tangent delta (TD) signal data comprising the steps of:

testing the TD signal data using a very low frequency (VLF) test;

wherein the TD signal data comprises an upper bound alarm threshold and a lower bound alarm threshold.

6. The health index method for predicting health condition in underground cables, according to claim 5, wherein the accumulating of tangent delta (TD) signal data further comprising the step of:

categorizing the TD signal data to five ranges for indicating level of severity of the underground cable.

7. The health index method for predicting health condition in underground cables, according to claim 5, wherein the method further comprising the step of:

breaking down the health index into 0, 0~1, and >1 by the upper bound alarm threshold and lower bound alarm threshold to provide an improved description of the cable condition.

8. The health index method for predicting health condition in underground cables, according to claim 4, wherein the plurality of operating parameters of the underground cable include but not limited to capacitance, resistance, geometry,

and specification of the cable.

9. The health index method for predicting health condition in underground cables, according to claim 4, wherein the determining of the health condition of the underground cable comprises a healthy state, to be monitored state, and required maintenance state.

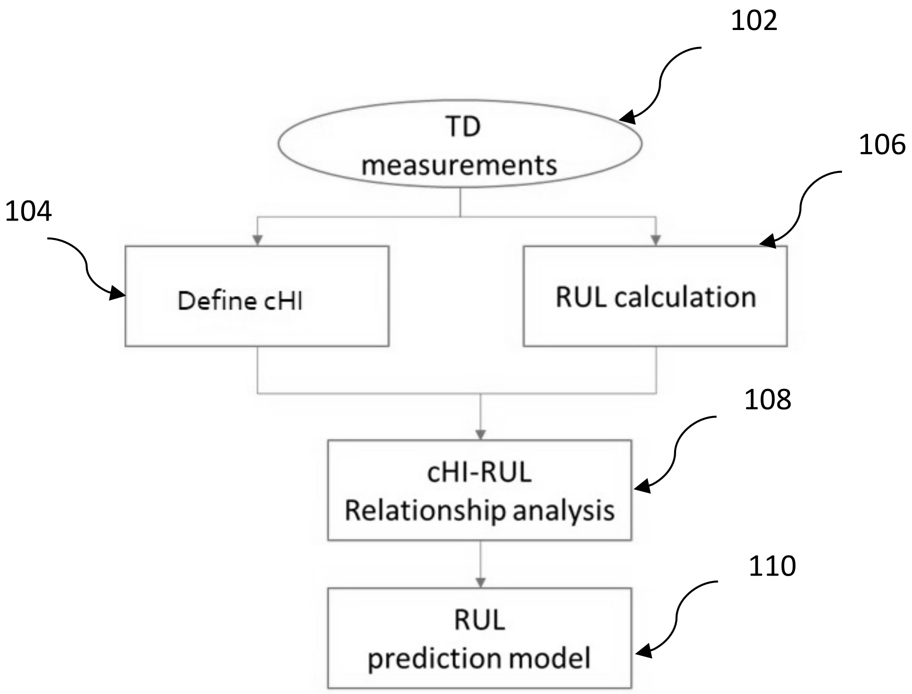
102
TD
measurements
106
104
Define cHI
RUL calculation
108
cHI-RUL
Relationship analysis
110
RUL
prediction model

FIG.1

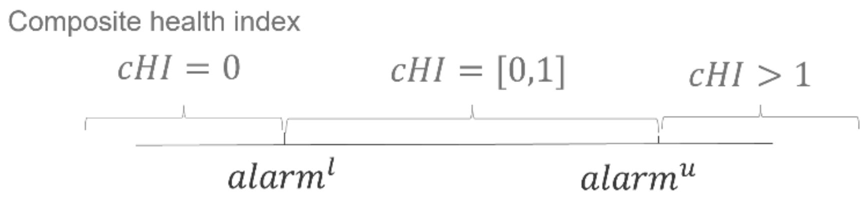

FIG.2