

METHOD AND SYSTEM FOR ESTIMATING A FAILURE PROBABILITY ASSOCIATED WITH OBJECTS

TECHNICAL FIELD

[0001] Various aspects of this disclosure relate to methods and systems for estimating failure probability associated with objects.

BACKGROUND

[0002] The reliability and resilience operation of the power cables play a key role in transmitting and distributing electricity. Numbers of technologies have been investigated to assess health condition of power cables, such as partial discharge detection, dielectric loss measurement, insulation resistance (IR) test etc. Among all these approaches, IR test has been mostly widely applied in industry due to its easy application and automation. The cable health state is then estimated using the referenced IR guidelines. However, no general accepted IR standard for cable insulation has been published and thus power utilities usually have their own guidelines based on the accumulated experience and lessons.

[0003] A need therefore exists to provide an improved method and a system for estimating failure probability associated with objects.

SUMMARY

[0004] According to a first aspect of the present disclosure, a method for estimating a failure probability associated with objects is provided. The method may include: assigning each of observed objects with a class parameter, the class parameter indicative of a class in a plurality of classes to which the each of observed objects belongs; determining a characteristic value of the each of observed objects; fitting a matrix model to the determined characteristic values in each class of the plurality of classes; optimizing a critical value that is predetermined for each class of the plurality of classes from the matrix model; and estimating the failure probability of the objects by the optimized critical value.

[0005] According to a second aspect of the present disclosure, a data processing system is provided including a communication interface, a memory and a processing unit configured to perform the method described herein.

[0006] According to a third aspect of the present disclosure, a computer program element is provided including program instructions, which, when executed by one or more processors, cause the one or more processors to perform the method described herein.

[0007] According to a fourth aspect of the present disclosure, a computer-readable medium is provided including program instructions, which, when executed by one or more processors, cause the one or more processors to perform the method described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] The invention will be better understood with reference to the detailed description when considered in conjunction with the non-limiting examples and the accompanying drawings, in which:

- FIG. 1 depicts a schematic flow diagram of a method for estimating failure probability associated with objects according to various embodiments of the present disclosure.
- FIG. 2 shows a bathtub curve of Weibull distribution.
- FIG. 3 shows illustrates a method of diminishing returns according to various embodiments of the present disclosure.
- FIG. 4 depicts a schematic block diagram of a system for estimating failure probability associated with objects according to various embodiments of the present disclosure.
- FIG. 5 shows an example computer system.
- FIG. 6 shows graphs of Weibull distribution fitting to all data for (a) 22 kV and (b) 6.6 kV cables.
- FIG. 7 shows graphs of Weibull distribution fitting to all data for (a) 22 kV after grouping with respect to age and (b) 6.6 kV cables after grouping with respect to the material type of cables according to various embodiments of the present disclosure.
- FIG. 8 shows graphs of a total number of (a) True positive (TP) and (b) False positive (FP) according to various embodiments of the present disclosure.

DETAILED DESCRIPTION

[0009] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the disclosure may be practiced. These embodiments are described in sufficient detail to enable those skilled in the

art to practice the disclosure. Other embodiments may be utilized and structural, and logical changes may be made without departing from the scope of the disclosure. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0010] Embodiments described in the context of one of the devices or methods are analogously valid for the other devices or methods. Similarly, embodiments described in the context of a device are analogously valid for a vehicle or a method, and vice-versa.

[0011] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0012] In the context of various embodiments, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

[0013] As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0014] It will be further understood that the terms “comprise” (and any form of comprise, such as “comprises” and “comprising”), “have” (and any form of have, such as “has” and “having”), “include” (and any form of include, such as “includes” and “including”), and “contain” (and any form of contain, such as “contains” and “containing”) are open-ended linking verbs. As a result, a method or device that “comprises,” “has,” “includes” or “contains” one or more steps or elements possesses those one or more steps or elements, but is not limited to possessing only those one or more steps or elements. Likewise, a step of a method or an element of a device that “comprises,” “has,” “includes” or “contains” one or more features possesses those one or more features, but is not limited to possessing only those one or more features. Furthermore, a device or structure that is configured in a certain way is configured in at least that way, but may also be configured in ways that are not listed.

[0015] As used herein, the phrase of the form of “at least one of A or B” may include A or B or both A and B. Correspondingly, the phrase of the form of “at least one of A or B or C”, or including further listed items, may include any and all combinations of one or more of the associated listed items.

[0016] The term “exemplary” may be used herein to mean “serving as an example, instance, or illustration”. Any aspect or design described herein as “exemplary” is not necessarily to be construed as preferred or advantageous over other aspects or designs.

[0017] The terms “at least one” and “one or more” may be understood to include a numerical quantity greater than or equal to one (e.g., one, two, three, four, [...], etc.). The term “a plurality” may be understood to include a numerical quantity greater than or equal to two (e.g., two, three, four, five, [...], etc.). The phrase “at least one of” with regard to a group of elements may be used herein to mean at least one element from the group consisting of the elements. For example, the phrase “at least one of” with regard to a group of elements may be used herein to mean a selection of: one of the listed elements, a plurality of one of the listed elements, a plurality of individual listed elements, or a plurality of a multiple of listed elements.

[0018] The words “plural” and “multiple” in the description and in the claims expressly refer to a quantity greater than one. Accordingly, any phrases explicitly invoking the aforementioned words (e.g., “a plurality of (objects)”, “multiple (objects)”) referring to a quantity of objects expressly refer to more than one of the said objects. The terms “group (of)”, “set (of)”, “collection (of)”, “series (of)”, “sequence (of)”, “grouping (of)”, etc., and the like in the description and in the claims, if any, refer to a quantity equal to or greater than one, i.e. one or more.

[0019] The term “first”, “second”, “third” detailed herein are used to distinguish one element from another similar element and may not necessarily denote order or relative importance, unless otherwise stated. For example, a first transaction data, a second transaction data may be used to distinguish two transactions based on two different foreign currency exchange.

[0020] The term “data” as used herein may be understood to include information in any suitable analog or digital form, e.g., provided as a file, a portion of a file, a set of files, a signal or stream, a portion of a signal or stream, a set of signals or streams, and the like. Further, the term “data” may also be used to mean a reference to information, e.g., in form of a pointer. The term “data”, however, is not limited to the aforementioned examples and may take various forms and represent any information as understood in the art. Any type of information, as described herein, may be handled for example via one or more processors in a suitable way, e.g. as data.

[0021] The term “module” detailed herein refers to, or forms part of, or includes an Application Specific Integrated Circuit (ASIC); an electronic circuit; a combinational logic circuit; a field programmable gate array (FPGA); a processor (shared, dedicated, or group) that executes code; other suitable hardware components that provide the described functionality; or a combination of some or all of the above, such as in a system-on-chip. The term module may include memory (shared, dedicated, or group) that stores code executed by the processor.

[0022] Differences between software and hardware implemented data handling may blur. A processor, controller, and/or circuit detailed herein may be implemented in software, hardware, and/or as a hybrid implementation including software and hardware.

[0023] Unless specifically stated otherwise, and as apparent from the following, it will be appreciated that throughout the present specification, description or discussions utilizing terms such as “performing”, “assigning”, “generating”, “determining”, “fitting”, “estimating” or the like, refer to the actions and processes of a computer system, or similar electronic device, that manipulates and transforms data represented as physical quantities within the computer system into other data similarly represented as physical quantities within the computer system or other information storage, transmission or display devices.

[0024] Some portions of the present disclosure are explicitly or implicitly presented in terms of algorithms and functional or symbolic representations of operations on data within a computer memory. These algorithmic descriptions and functional or symbolic representations are the means used by those skilled in the data processing arts to convey most effectively the substance of their work to others skilled in the art. An algorithm is here, and generally, conceived to be a self-consistent sequence of steps leading to a desired result. The steps are those requiring physical manipulations of physical quantities, such as electrical, magnetic or optical signals capable of being stored, transferred, combined, compared, and otherwise manipulated.

[0025] The present method may provide improved Insulation resistance (IR) guidelines for assessing health condition of power cables. Advantageously, the present method for estimating failure probability associated with objects may predict failure of power cables and/or differentiate healthy and unhealthy cables, thereby preventing power outage, unreliable distribution of power and unsafety operation.

[0026] In various embodiments, Weibull analysis may be applied to relate the failures of the objects (e.g. power cables) with their ages/types and classify the objects with respect to

their ages/types. In other words, failure estimation may be performed on the objects within one class of the plurality of classes with a class parameter indicative of the class. The plurality of classes may include main classification and one or more sub classifications. That may mean the class parameter may include one primary parameter and one or more secondary sub parameters. For example, a class parameter may include a primary parameter classified by an application of the object, e.g. 22 kV, one or two secondary class parameters, e.g. middle age and/or type I material (copper).

[0027] In various embodiments, the class parameters may be predetermined or adjusted when appropriate, for example, during fitting the models (e.g. iteratively). The class parameters may include other features, properties, attributes or aspects that can be used to classify the objects in a manner that such a feature, property, attribute or aspect distinguish some objects from others and the objects having the feature, property, attribute or aspect may behaviour, function or operate similarly.

[0028] Historical failure data may be used to train the Weibull cumulative distribution so as to determine parameters associated with the Weibull cumulative distribution. A respective distribution may be performed for a respective class and accordingly, respective parameters associated with the Weibull cumulative distribution may be determined.

[0029] In various embodiments, the diminishing return method may be applied to identify (e.g. determine, optimize, adjust) a critical IR value to differentiate between objects that are operating (e.g. healthy) and objects that are failing (e.g. unhealthy) for each class (e.g. group). The present method may provide improved IR guidelines include an optimized combination of critical IR values for the plurality of classes.

[0030] The following examples pertain to various aspects of the present disclosure.

[0031] Example 1 is a method for estimating failure probability associated with objects, the method including: assigning each of observed objects with a class parameter, the class parameter indicative of a class in a plurality of classes to which the each of observed objects belongs; determining a characteristic value of the each of observed objects; fitting a matrix model to the determined characteristic values in each class of the plurality of classes; optimizing a critical value that is predetermined for each class of the plurality of classes from the matrix model; and estimating the failure probability of the objects by the optimized critical value.

[0032] In Example 2, the subject matter of Example 1 may optionally include that the plurality of classes include types of material of which the plurality of observed objects are made.

[0033] In Example 3, the subject matter of Example 1 may optionally include that the plurality of classes include age groups which are defined by ages of the plurality of observed objects.

[0034] In Example 4, the subject matter of any one of Examples 1 to 3 may optionally include that fitting the matrix model to the determined characteristic values in the each class of the plurality of classes includes recording fit characteristic values that meet constraints of the matrix model for the each class of the plurality of classes.

[0035] In Example 5, the subject matter of Example 4 may optionally include evaluating a combination of the fit characteristic values for the each class of the plurality classes, wherein each fit characteristic value of the combination is from one class of the plurality of classes and the combination has a fit characteristic value for every class of the plurality of classes.

[0036] In Example 6, the subject matter of Example 5 may optionally include that optimizing the critical value that is predetermined for each class of the plurality of classes from the matrix model comprises setting the critical value for each class of the plurality of classes as the corresponding fit characteristic value of the combination.

[0037] In Example 7, the subject matter of any one of Examples 1 to 6 may optionally include, prior to fitting the matrix to the determined characteristic values, sorting the determined characteristic values in an ascending order.

[0038] In Example 8, the subject matter of any one of Examples 1 to 7 may optionally include that fitting the matrix to the determined characteristic values includes using a diminishing return method.

[0039] In Example 9, the subject matter of any one of Examples 1 to 8 may optionally include that the matrix model comprises a confusion matrix, and wherein a minority of the plurality of observed objects is fitted to a positive class and a majority of the plurality of observed objects is fitted to a negative class.

[0040] In Example 10, the subject matter of Example 9 may optionally include that optimizing the critical value from the matrix model includes optimizing the critical value in a manner that the critical value is decreased.

[0041] In Example 11, the subject matter of any one of Examples 1 to 10 may optionally include determining life-time information for each observed object of a plurality of observed objects; and fitting an analysis model to the life-time information of the plurality of observed objects in each class of the plurality of classes.

[0042] In Example 12, the subject matter of Example 11 may optionally include that the life-time information for each observed object of the plurality of observed objects indicates whether the observed object has failed up to a final time.

[0043] In Example 13, the subject matter of Example 12 may optionally include that the plurality of observed objects include at least one observed object that has failed and at least one observed object that is still operating at the final time.

[0044] In Example 14, the subject matter of Example 13 may optionally include that the life-time information for each observed object of the plurality of observed objects that has failed comprises a time of failure of the observed object.

[0045] In Example 15, the subject matter of Example 13 or Example 14 may optionally include that determining the life-time information comprises generating an adjusted rank for each observed object of the plurality of observed objects that has failed.

[0046] In Example 16, the subject matter of any one of Examples 1 to 15 may optionally include that the analysis model is Weibull cumulative distribution.

[0047] In Example 17, the subject matter of Example 16 when dependent from 3 may optionally include that fitting the analysis model to the life-time information comprises determining parameters of the analysis model and a parameter of the Weibull cumulative distribution has different values for different age group.

[0048] Example 18 is a data processing system including a communication interface, a memory and a processing unit configured to perform the method of any one of claims 1 to 17.

[0049]

[0050] Example 19 is a computer program element comprising program instructions, which, when executed by one or more processors, cause the one or more processors to perform the method as described herein.

[0051] Example 20 is a computer-readable medium comprising program instructions, which, when executed by one or more processors, cause the one or more processors to perform the method as described herein.

[0052] In the following, embodiments will be described in detail.

[0053] FIG. 1 depicts a schematic flow diagram of a method 100 for estimating failure probability associated with objects according to various embodiments of the present disclosure. The method 100 includes: assigning (at step 102) each of observed objects with a class parameter, the class parameter indicative of a class in a plurality of classes to which the each of observed objects belongs; determining (at step 104) a characteristic value of the each of observed objects; fitting (at step 106) a matrix model to the determined characteristic values in each class of the plurality of classes; optimizing (e.g. adjusting) (at step 108) a critical value that is predetermined for each class of the plurality of classes from the matrix model; and estimating (at step 110) the failure probability of the objects by the optimized critical value.

[0054] In the context of various embodiments, the objects may include devices, apparatus, or components thereof, or material things or an assembly thereof that may undesirably deteriorate in quality, functioning or condition as time goes on, for example, wear and tear. In an example, the objects may include electrical cables (e.g. power cables).

[0055] In the context of various embodiments, the observed objects may include objects of interest that are being targeted, analysed, investigated, tested, or experimented on to seek attributes, features, qualities, properties and/or any characteristics data thereof. In some embodiment, the observed objects may include objects that have failed (e.g. failed power cable or cable circuits).

[0056] According to various non-limiting embodiments, the plurality of classes may include types of material of which the plurality of observed objects are made. For example, the electrical cables may be made of copper or aluminium or any suitable metal or compound. Accordingly, the plurality of classes may include copper class, aluminium class or any suitable metal class. The number of the plurality of classes may not be limited. In some embodiments, one or more classes of the plurality of classes may be so defined to include one or more types of materials (e.g. one class includes both platinum and palladium material types).

[0057] According to various non-limiting embodiments, the plurality of classes may include age groups which are defined by ages of the plurality of observed objects (e.g. time since start of operation or time since manufacturing). For example, the ages of the plurality of observed objects may be divided into three groups including young (age group 1), middle age (age group 2) and old (age group 3). Specifically, the young group may include ages from 0 to 10 years old, the middle age group may include 10 years to 40 years old and the old age group may include 40 to 60 years old. Accordingly, each age group may include various time periods (e.g.

10 years or 20 years or 30 years) that may be determined by the method described herein. Further, at the boundaries of each age group (e.g. 10 years old or 40 years), it may be further determined that the boundary may be included in the previous age group or the following age group or both by the method as described herein.

[0058] In some embodiments, an observed object may first be assigned a primary class parameter, for example, according to the type of material of which the observed object is made and then be assigned a secondary class parameter, for example, according to the age of the observed object. The determined characteristic values of a respective class (e.g. indicative by a same primary class parameter and a same secondary class parameter) may fit to a respective matrix model. Life-time information for the observed object may be determined and fitted to an analysis model with a plurality of observed objects having assigned a same primary class parameter and a same secondary class parameter.

[0059] In some embodiments, an observed object may be assigned a primary class parameter, for example, according to the type of material of which the observed object is made and no secondary class parameter will be assigned. The determined characteristic values of a respective class (e.g. indicative by a same primary class parameter regardless of a secondary class parameter) may fit to a respective matrix model. Life-time information for the observed object may be determined and fitted to an analysis model with a plurality of observed objects having assigned a same primary class parameter regardless of secondary class parameters.

[0060] In some embodiments, prior to assigning each of observed objects with a class parameter, the observed objects may be put into groups according to a main classification. For example, power cables may be put into medium voltage group (e.g. distribution systems) and high voltage group (e.g. transmission systems). In some embodiments, prior to assigning each of observed objects with a class parameter, the observed objects may be put into groups according to a main classification and a sub classification. In the example of power cables, the power cables of the medium voltage group may be further put into sub groups including 22 kV group and 6.6 kV group. Hence, the observed objects may be grouped according to a similar characteristic thereof. The main and sub classification may also be considered as class indicated by a class parameter, for example, 22 kV class or 6.6 kV class.

[0061] In the context of various embodiments, the characteristic value of the observed object may refer to a value of a characteristic that distinguishes one observed object from another observed object. For example, for power cables that have failed, insulation resistance

(IR) thereof may be considered as a characteristic that has a value varying between the failed power cables. That is, the power cables may fail at various IR values.

[0062] In the context of various embodiments, the critical value may refer to a threshold value or a guided value that is predetermined for the observed objects for estimating failure probability associated with objects. The critical value may vary for different classes of the plurality of classes. The critical value may be determined in a manner that the object is considered to be failing (e.g. unhealthy) if a characteristic value of the object is less than or equal to the critical value (e.g. by comparison with the critical value) and that the object is considered to continue operating (e.g. healthy) if a characteristic value of the object is greater than or equal to the critical value (e.g. by comparison with the critical value).

[0063] According to various non-limiting embodiments, fitting the matrix model to the determined characteristic values in each class of the plurality of classes may include recording fit characteristic values that meet constraints of the matrix model for each class of the plurality of classes. Hence, for each class of the plurality of classes, there may be multiple characteristic values that meet constraints of the matrix model (e.g. the fit characteristic values). Such fit characteristic values may be indexed in an ascending order in a manner that the greater fit characteristic value the greater index. In other words, prior to fitting the matrix to the determined characteristic values, the method 100 may further include: sorting the determined characteristic values in an ascending order.

[0064] According to various non-limiting embodiments, the method 100 may include evaluating a combination of the fit characteristic values for each class of the plurality of classes. Each fit characteristic value of the combination may be from one class of the plurality of classes and the combination may have a fit characteristic value for every class of the plurality of classes.

[0065] According to various non-limiting embodiments, optimizing the critical value that is predetermined for each class of the plurality of classes from the matrix model may include setting the critical value for each class of the plurality of classes as the corresponding fit characteristic value of the combination.

[0066] According to various non-limiting embodiments, fitting the matrix to the determined characteristic values comprises using a diminishing return method as described hereafter. The matrix may be a confusion matrix, and a minority of the plurality of observed objects may be fitted to a positive class and a majority of the plurality of observed objects fitted to a negative

class. Optimizing the critical value from the matrix model may include optimizing the critical value in a manner that the critical value is decreased. For example, if the plurality of classes include age groups, the critical values for the age groups may decrease as age increases across the age groups.

[0067] According to various non-limiting embodiments, the method 100 may further include using the failure probability to predict, for each observed object of the plurality of observed objects, a probability that the observed object fails within a given time period. The given time period may include a time period of interest, for example, the next 2 or 5 or 10 years.

[0068] According to various non-limiting embodiments, the method 100 may further include using the failure probability to predict, for each observed object of the plurality of observed objects, a remaining useful life of the observed object. The remaining useful life may provide engineers and automated controllers with direct insights on the health status of the object and hence allows making appropriate maintenance and replacement strategies for asset (i.e. object) management.

[0069] According to various non-limiting embodiments, the method 100 may further include using the failure probability to predict a number of the plurality of observed objects which fail within a given time period.

[0070] According to various non-limiting embodiments, the method 100 may include determining life-time information for each observed object of a plurality of observed objects; and fitting an analysis model to the life-time information of the plurality of observed objects in each class of the plurality of classes. That may mean fitting a respective analysis model to the life-time information of the plurality of observed objects in a respective class of the plurality of classes.

[0071] According to various non-limiting embodiments, life-time information for each observed object of the plurality of observed objects may indicate whether the observed object has failed up to a current time (also referred to as final time). The plurality of observed objects may include at least one observed object that has failed and at least one observed object that is still operating at the final time.

[0072] According to various non-limiting embodiments, the life-time information for each observed object of the plurality of observed objects may include information in relation to time-to-failure (e.g. time since start of operation or manufacturing until failure) for observed objects

that have failed (censored) and information in relation to ages of the observed objects that are still operating at the final time.

[0073] According to various non-limiting embodiments, determining the life-time information may include generating an adjusted rank for each observed object of the plurality of observed objects that has failed as described hereafter.

[0074] According to various non-limiting embodiments, the analysis model may be Weibull cumulative distribution. In some embodiments, fitting the analysis model to the life-time information may include determining parameters of the analysis model (e.g. scale parameter (η) and shape parameter (β) of the Weibull cumulative distribution) and a parameter (e.g. the shape parameter (β)) of the Weibull cumulative distribution has different values for different age group.

[0075] Weibull analysis and proportional hazard model (PHM) may be used to analyse the failure events and understand the aging characteristics of critical power assets. The standard Weibull model may be used to estimate the early failure of cable joints. In Weibull analysis, scale (η) and shape (β) may be two parameters of the Weibull model. The scale parameter may indicate the characteristic life-time of a population when 63.2% of the population has failed while the shape parameter reflects the aging rate of the population. The lifespan of a population may be generally described by a Weibull distribution, as shown in the bathtub curve in FIG. 2.

[0076] As shown in FIG. 2, when $\beta < 1$, the failure rate decreases with time representing infant mortality; when $\beta = 1$, the population has a constant failure rate and undergoes a useful phase; when $\beta > 1$, the assets have an increasing failure rate and thus aging related failure can occur.

[0077] According to various non-limiting embodiments, a process of Weibull analysis may be as follows:

- i) calculating the life-time information including the time-to-failure and the age of failed (censored) and survived cables, respectively, denoted as t ;
- ii) providing a failure index (i) assigned in an ascending order to the life-time information;
- iii) calculating adjusted ranks (ARs) with the inclusion of the censored data for each failure event by using:

$$AR_i = (RR_i \times AR_{i-1} + n + 1) / (RR_i + 1) \quad (1)$$

where, i is the order of each failure event and n is the total number of data samples used for Weibull analysis (i.e. the number of the plurality of observed objects). AR_i is the AR for the i th failure; and RR_i is the reverse rank of the i th failure. For the 1st failure data, RR_0 is set as 0;

iv) plotting the Weibull distribution: the logarithm of time-to-failure is typically plotted on x -axis, as shown in equation (2), while the value of each corresponding function value (i.e. y) is computed via equation (3).

The relation between x and y is expressed as in (4).

$$x = \ln(t) \quad (2)$$

$$y = \ln[\ln(1/(1 - AR))] \quad (3)$$

$$y = a + b x \quad (4)$$

where, a is the intercept on y -axis and b is the slope.

v) estimating two parameters of the Weibull distribution: based on the definition of η and β , the Weibull cumulative distribution (CDF), $F(t)$, is provided in (5). Taking the logarithm at both sides of (5) twice, once can obtain (6). Comparing (4) and (6), the Weibull parameters are as in (7) and (8).

$$1 - F(t) = \exp(-(t/\eta)^\beta) \quad (5)$$

$$\ln[\ln(1/(1 - F(t)))] = -\beta \ln(\eta) + \beta \ln(t) \quad (6)$$

$$\beta = b \quad (7)$$

$$\eta = \exp(-a/\beta) \quad (8)$$

[0078] The diminishing return method (DRM) may be generally applied to obtain optimal outputs with respect to inputs. The insulation resistance (IR) test may be used to distinguish between healthy and unhealthy cables, which may be considered as a classification problem. The critical IR values for each group of cables (e.g. in terms of material and/or age of the cables) may be predetermined (e.g. by the current IR guidelines) so that the cables with the characteristic values (i.e. the unique IR values) smaller than or equal to the critical IR values may be classified as ‘unhealthy’. Therefore, similarly to the law of diminishing returns, the critical IR values for each group may be optimized to maximize the detection of the unhealthy cables and minimize the number of wrongly classified healthy cables in the group. A maximized combination of optimized critical IR values (e.g. include an optimized critical IR value for each group) may be determined as the improved IR guidelines. Hence, the solution for optimizing critical IR values may be considered to solve a classification problem. The class

of interest (unhealthy) or the minority of samples may be assigned to the positive class while the negative class may represent the majority examples or the healthy class.

[0079] A confusion matrix used to evaluate the performance of the DRM classification is shown in Table I.

[0080] Table I Confusion matrix for classification

	Predicted Positive (Unhealthy)	Predicted Negative (Healthy)
Real Positive (Unhealthy)	True Positive (TP)	False Negative (FN)
Real Negative (Healthy)	False Positive (FP)	True Negative (TN)

[0081] The constraints for the optimal solution of the DRM may be set as follows:

- (a) The number of TP events at each voltage level (e.g. at 22kV and 6.6kV) should be equal to or higher than the initial number of TP based on the current IR guidelines.
- (b) The number of FP events compared to the initial number of FP based on the current IR guidelines should be equal or less.

[0082] The objective of the optimal solution of the DRM is to maximize the number of TP events. As cable operation duration increases, logically the value of IR reduces and once it is below the accepted level, further diagnostic action is required to prevent cable failures, otherwise outage could likely occur. Thus, the critical IR values are determined based on the IR values of the historical data for failed cables. The unique value of IR (e.g. the characteristic value) is denoted as useful cut-off IR values in the disclosure, that is, the IR value at which the cable failed.

[0083] FIG. 3 illustrates a method 300 of DRM to obtain the critical IR values for the improved IR guidelines.

[0084] At step 302, the process starts. The process may be performed on the plurality of observed objects that have failed. Accordingly, each observed object that has failed may have a characteristic value (e.g. unique IR value).

[0085] At step 304, the critical IR values are predetermined for each group of the plurality of observed objects (e.g. according to the current IR guidelines). Each group may have an assigned class parameter. j represents the group index, $j=1, 2, 3, 4, 5$. That is, 5 exemplary groups (e.g. as shown in Table II) are shown in FIG. 3.

[0086] At step 306, a characteristic value (e.g. unique IR value) of each observed object of the plurality of observed objects having assigned a first class parameter (e.g. in the first group)

is determined. i is the index number of the i th observed object; and n represents the total number of the plurality of observed objects having assigned the class parameter (e.g. in the first group). Further, a characteristic value (e.g. unique IR value) of each observed object of the plurality of observed objects having assigned second, third, fourth and fifth class parameters (e.g. in the second, third, fourth and fifth groups) is determined. i is the index number of the i th observed object; and n represents the total number of the plurality of observed objects having assigned the class parameter (e.g. in the second to fifth groups, respectively). Hence, the characteristic values for the plurality of observed objects are determined. It should be appreciated although 5 exemplary groups are shown herein, it is not limited to 5 groups and any appropriate finite or infinite number is included.

[0087] At step 308, a matrix model (e.g. the confusion matrix) is fitted to the determined characteristic values. In other words, calculate true positive (TP) or false positive (FP) for all groups (e.g. 2 groups in 22 kV and 3 groups in 6.6 kV) by comparing the determined characteristic values with the critical IR values in connection with the corresponding groups. If the characteristic value of the failed cable is less than or equal to the critical IR value, it is classified as TP; and if the characteristic value of the failed cable is greater than the critical IR value, it is classified as FP. That is, calculate a sub-sum of TP and FP for 22 kV (e.g. a main/sub classification), and a sub-sum TP and FP for 6.6 kV (e.g. a main/sub classification). A total sum may be calculated for the plurality of observed objects classified by the main/sub classification.

[0088] At step 310, determine if the characteristic values (e.g. including a characteristic value for each group, i.e. a combination of the characteristic values) renders the above constraints (a) and (b) are met. If not, proceed (at step 306) to a next characteristic value (e.g. a next characteristic value, accordingly forming a new combination of the characteristic values) until all the TP and FP have been evaluated. If yes, proceed to step 312.

[0089] At step 312, record the index number (e.g. kj , $k=i$) of the characteristic value (e.g. a present characteristic value of the i th observed object in group j). In some embodiments, the above-mentioned next characteristic value (e.g. forming the new combination of the characteristic values) is associated with the $(i+1)$ th observed object in group j . In some embodiments, the above-mentioned next characteristic value (e.g. forming the new combination of the characteristic values) is associated with the i th observed object in group $j+1$.

[0090] At step 314, optimize the critical values that are predetermined for the plurality of observed objects (e.g. according to the current IR guidelines) from the matrix model. In other words, set the recorded characteristic values (a combination of characteristic values, each of which is determined for one group of the five groups, i.e. each of which is determined from the plurality of observed objects having the corresponding assigned class parameter of the plurality of class parameters) as the optimized critical values at which the TP has the maximum value.

[0091] At step 316, the process ends.

[0092] According to various non-limiting embodiments, optimizing the critical value from the matrix model may include optimizing the critical value in a manner that the critical value is decreased. In some embodiments, the optimized critical values may decrease for observed objects assigned with increasing age groups.

[0093] While the methods 100, 300 described above is illustrated and described as a series of steps or events, it will be appreciated that any ordering of such steps or events are not to be interpreted in a limiting sense. For example, some steps may occur in different orders and/or concurrently with other steps or events apart from those illustrated and/or described herein. In addition, not all illustrated steps may be required to implement one or more aspects or embodiments described herein. Also, one or more of the steps depicted herein may be carried out in one or more separate acts and/or phases.

[0094] According to various non-limiting embodiments, a data processing system comprising a communication interface, a memory and a processing unit configured to perform the methods 100, 300 as described herein.

[0095] According to various non-limiting embodiments, a computer program element comprising program instructions, which, when executed by one or more processors, cause the one or more processors to perform the methods 100, 300 as described herein.

[0096] According to various non-limiting embodiments, a computer-readable medium comprising program instructions, which, when executed by one or more processors, cause the one or more processors to perform the methods 100, 300 as described herein.

[0097] FIG. 4 depicts a schematic block diagram of a system 400 for estimating failure probability associated with objects according to various embodiments of the present disclosure, corresponding to the above-mentioned method 100 for estimating failure probability associated with objects as described hereinbefore according with reference to FIG. 1 according to various embodiments of the present disclosure. The system 400 comprises: at least one memory 402;

and at least one processor 404 communicatively coupled to the at least one memory 402 and configured to perform the method 100 for estimating failure probability associated with objects as described hereinbefore according to various embodiments of the present disclosure. Accordingly, the at least one processor 404 is configured to: assign (at step 102) each of observed objects with a class parameter, the class parameter indicative of a class in a plurality of classes to which the each of observed objects belongs; determine (at step 104) life-time information for each observed object of a plurality of observed objects having assigned a same class parameter; fit (at step 106) an analysis model to the life-time information of the plurality of observed objects; and estimate (at step 108) the failure probability of the plurality of observed objects from the analysis model.

[0098] It will be appreciated by a person skilled in the art that the at least one processor 404 may be configured to perform various functions or operations through set(s) of instructions (e.g., software modules) executable by the at least one processor 404 to perform various functions or operations. Accordingly, as shown in FIG. 4, the system 400 may comprise: an input module (or an input circuit) 412 configured to receive data (not shown in FIG. 1); a data preparation module (or a data preparation circuit) 414 configured to perform the above-mentioned assigning (at step 102) each of observed objects with a class parameter, the class parameter indicative of a class in a plurality of classes to which the each of observed objects belongs and the above-mentioned determining (at step 104) life-time information for each observed object of a plurality of observed objects having assigned a same class parameter; and a data processing module (or a data processing circuit) 416 configured to perform the above-mentioned fitting (at step 106) an analysis model to the life-time information of the plurality of observed objects, and estimating (at step 108) the failure probability of the plurality of observed objects from the analysis model.

[0099] It will be appreciated by a person skilled in the art that various modules of a system are not necessarily separate modules, and two or more modules may be realized by or implemented as one functional module (e.g., a circuit or a software program) as desired or as appropriate without deviating from the scope of the present disclosure. For example, two or more modules of the system 400 for estimating failure probability associated with objects (e.g., the input module 412, the data preparation module 414 and the data processing module 416) may be realized (e.g., compiled together) as one executable software program (e.g., software application or simply referred to as an “app”), which for example may be stored in the at least

one memory 402 and executable by the at least one processor 404 to perform various functions/operations as described herein according to various embodiments of the present disclosure.

[00100] It will be appreciated by a person skilled in the art that a system may include further modules, for example, the system 400 may include a display module (not shown) configured to displaying the iterative fitting progress in accordance with estimated failure probability thereof according to the steps as described therein.

[00101] In various embodiments, the system 400 for estimating failure probability associated with objects may correspond to the method 100 for estimating failure probability associated with objects as described hereinbefore with reference to FIG. 1 according to various embodiments, therefore, various functions or operations configured to be performed by the least one processor 404 may correspond to various steps or operations of the method 100 for estimating failure probability associated with objects as described hereinbefore according to various embodiments, and thus need not be repeated with respect to the system 400 for estimating failure probability associated with objects for clarity and conciseness. In other words, various embodiments described herein in context of the methods are analogously valid for the corresponding systems, and vice versa.

[00102] For example, in various embodiments, the at least one memory 402 of the system 400 for estimating failure probability associated with objects may have stored therein the input module 412, the data preparation module 414, and/or the data processing module 416, which correspond to one or more steps (or operation(s) or function(s)) of the method 100 for estimating failure probability associated with objects as described herein according to various embodiments, which are executable by the at least one processor 404 to perform the corresponding function(s) or operation(s) as described herein.

[00103] A computing system, a controller, a microcontroller or any other system providing a processing capability may be provided according to various embodiments in the present disclosure. Such a system may be taken to include one or more processors and one or more computer-readable storage mediums. For example, the system 400 for estimating failure probability associated with objects described hereinbefore may include at least one processor (or controller) 404 and at least one computer-readable storage medium (or memory) 402 which are for example used in various processing carried out therein as described herein. A memory or computer-readable storage medium used in various embodiments may be a volatile memory,

for example a DRAM (Dynamic Random Access Memory) or a non-volatile memory, for example a PROM (Programmable Read Only Memory), an EPROM (Erasable PROM), EEPROM (Electrically Erasable PROM), or a flash memory, e.g., a floating gate memory, a charge trapping memory, an MRAM (Magnetoresistive Random Access Memory) or a PCRAM (Phase Change Random Access Memory).

[00104] In various embodiments, a “circuit” may be understood as any kind of a logic implementing entity, which may be special purpose circuitry or a processor executing software stored in a memory, firmware, or any combination thereof. Thus, in an embodiment, a “circuit” may be a hard-wired logic circuit or a programmable logic circuit such as a programmable processor, e.g., a microprocessor (e.g., a Complex Instruction Set Computer (CISC) processor or a Reduced Instruction Set Computer (RISC) processor). A “circuit” may also be a processor executing software, e.g., any kind of computer program, e.g., a computer program using a virtual machine code, e.g., Java. Any other kind of implementation of the respective functions may also be understood as a “circuit” in accordance with various embodiments. Similarly, a “module” may be a portion of a system according to various embodiments and may encompass a “circuit” as described above, or may be understood to be any kind of a logic-implementing entity.

[00105] The present disclosure also discloses various systems (e.g., each may also be embodied as a device or an apparatus), such as the system 400 for estimating failure probability associated with objects, for performing various operations/functions of various methods described herein. Such systems may be specially constructed for the required purposes, or may comprise a general purpose computer or other device selectively activated or reconfigured by a computer program stored in the computer. The algorithms presented herein are not inherently related to any particular computer or other apparatus. Various general-purpose machines may be used with computer programs in accordance with the teachings herein. Alternatively, the construction of more specialized apparatus to perform various method steps may be appropriate.

[00106] In addition, the present disclosure also at least implicitly discloses a computer program or software/functional module, in that it would be apparent to the person skilled in the art that individual steps of various methods described herein may be put into effect by computer code. The computer program is not intended to be limited to any particular programming language and implementation thereof. It will be appreciated that a variety of programming

languages and coding thereof may be used to implement the teachings of the disclosure contained herein. Moreover, the computer program is not intended to be limited to any particular control flow. There are many other variants of the computer program, which can use different control flows without departing from the scope of the disclosure. It will be appreciated by a person skilled in the art that various modules described herein (e.g. the input module 412, the data preparation module 414, the data processing module 416) may be software module(s) realized by computer program(s) or set(s) of instructions executable by a computer processor to perform the required functions, or may be hardware module(s) being functional hardware unit(s) designed to perform the required functions. It will also be appreciated that a combination of hardware and software modules may be implemented.

[00107] Furthermore, two or more of the steps of a computer program/module or method described herein may be performed in parallel rather than sequentially. Such a computer program may be stored on any computer readable medium. The computer readable medium may include storage devices such as magnetic or optical disks, memory chips, or other storage devices suitable for interfacing with a computer. The computer program when loaded and executed on such the computer effectively results in a system or an apparatus that implements various steps of methods described herein.

[00108] In various embodiments, there is provided a computer program product, embodied in one or more computer-readable storage mediums (non-transitory computer-readable storage medium(s)), comprising instructions (e.g., the input module 412, the data preparation module 414, the data processing module 416) executable by one or more computer processors to perform the method 100 for estimating failure probability associated with objects, as described herein with reference to FIG. 1 according to various embodiments. Accordingly, various computer programs or modules described herein may be stored in a computer program product receivable by a system therein, such as the system 400 for estimating failure probability associated with objects as shown in FIG. 4, for execution by at least one processor 404 to perform various functions.

[00109] In various embodiments, the system 400 may be realized by any computer system (e.g., desktop or portable computer system (e.g., mobile device)) including at least one processor and at least one memory, such as an example computer system 500 as schematically shown in FIG. 5 as an example only and without limitation. Various methods/steps or functional modules may be implemented as software, such as a computer program being

executed within the computer system 500, and instructing the computer system 500 (in particular, one or more processors therein) to conduct various functions or operations as described herein according to various embodiments. The computer system 500 may comprise a system unit 502, input devices such as a keyboard and/or a touchscreen 504 and a mouse 506, and a plurality of output devices such as a display 508. The system unit 502 may be connected to a computer network 512 via a suitable transceiver device 514, to enable access to e.g., the Internet or other network systems such as Local Area Network (LAN) or Wide Area Network (WAN). The system unit 502 may include a processor 518 for executing various instructions, a Random Access Memory (RAM) 520 and a Read Only Memory (ROM) 522. The system unit 502 may further include a number of Input/Output (I/O) interfaces, for example I/O interface 524 to the display device 508 and I/O interface 526 to the keyboard 504. The components of the system unit 502 typically communicate via an interconnected bus 528 and in a manner known to a person skilled in the art.

[00110] In order that the present disclosure may be readily understood and put into practical effect, various example embodiments of the present disclosure will be described hereinafter by way of examples only and not limitations. It will be appreciated by a person skilled in the art that the present disclosure may, however, be embodied in various different forms or configurations and should not be construed as limited to the example embodiments set forth hereinafter. Rather, these example embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the present disclosure to those skilled in the art.

[00111] Data is gathered which holds life-time information about the time of failures of the objects (e.g. power cables of a power grid company). The data may for example indicate a time at which the objects (e.g. power cables) have failed. It is therefore also referred to as failure data. An analysis model is fitted to the failure data after preparation (e.g. assigned a class parameter). So, the analysis model may for example model a failure probability per object depending on the life-time (e.g. time since start of operation) of the object. So, the analysis (failure) model can for example predict failure probability associated with objects (e.g. cables) for a given period and/or estimate the remaining useful life (RUL) for the objects.

[00112] 96 failure data of 22 kV cable circuits and 72 failure data of 6.6 kV cable circuits have been collected for Weibull analysis. FIG. 6 show graphs of Weibull distribution fitting to all data for (a) 22 kV and (b) 6.6 kV cables. The values of R-squared test are 0.391 and 0.767

for 22 kV and 6.6 kV for the distribution shown in FIG. 6 (a) and (b), respectively. The goodness-of-fit is poor.

[00113] According to various non-limiting embodiments, the failure data may be put into 22 kV group and 6.6 kV group (e.g. according to a main/sub classification). Each failure may be assigned with one or more class parameters, for example, type 1 for copper or type 2 for aluminum, if the plurality of classes include types of material of which the plurality of observed objects (e.g. cables) are made, alternatively or additionally, AG1 for young age, AG2 for middle age or AG3 for old age, if the plurality of classes include age groups which are defined by ages of the plurality of observed objects (e.g. cables). Various β values is introduced for 22 kV cables as β varies with ages. Table II shows the grouping of 22 kV and 6.6 kV cables with one or more class parameters.

[00114] Table II Grouping of 22 kV and 6.6 kV cables with one or more class parameters

Voltage (kV)	Group information		Group index
	Age	Type	
22	Young (AG1)	Copper (Type 1)	1
	Middle Age (AG2)	Copper (Type 1)	2
	Old (AG3)	Copper (Type 1)	3
6.6	All Age	Copper (Type 1)	4
	All Age	Aluminium (Type 2)	5

[00115] FIG. 7 show graphs of Weibull distribution fitting to all data for (a) 22 kV after grouping with respect to age and (b) 6.6 kV cables after grouping with respect to the material type of cables. The values of R-squared test are 0.909, 0.952 and 0.959 for 22 kV for the distribution shown in FIG. 7 (a), and 0.972 and 0.962 for 6.6 kV for the distribution shown in FIG. 7 (b). The goodness-of-fit is good.

[00116] Based on the current guideline (i.e. the critical value) of the power grid company, the initial number of TP and FP events are summarized in Table III.

[00117] Table III The initial number of TP and FP events

Voltage	TP	FP
22 kV	5	7
6.6 kV	23	110

total	28	117
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[00118] Based on the Weibull analysis of failure events, 15, 22, and 42 unique values of IR have been observed for 22kV, while 31 and 21 unique values of IR for 6.6kV. Thus, there are 13860 (i.e. $=15 \times 22 \times 42$) and 651 (i.e. $=31 \times 21$) permutations of the possible improved IR guidelines for 22 kV and 6.6kV, respectively.

[00119] After applying the DRM method, 65 combinations remain, where each combination has the critical IR values of the five groups. The corresponding TP and FP events for the 65 combinations are shown in FIG. 8 (a) and (b) separately. The black line shows the sum of TP or FP for the five groups. The maximum of TP is achieved at the 49th combination (denoted as 801) and the corresponding FP is 116 (denoted as 803). The maximum may indicate the TP peaks before they drop with additional index of combination, i.e., reached diminishing return point. As shown in Table IV, the improved IR guideline via DRM has been determined and detects 22 more unhealthy cables and reduce one FP.

[00120] Table IV The number of TP and FP events by the combined Weibull-DRM method

Voltage	TP	FP
22 kV	27	47
6.6 kV	23	69
total	50	116

[00121] While the disclosure has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

1. A method for estimating failure probability associated with objects, the method comprising:
assigning each of observed objects with a class parameter, the class parameter indicative of a class in a plurality of classes to which the each of observed objects belongs;
determining a characteristic value of the each of observed objects;
fitting a matrix model to the determined characteristic values in each class of the plurality of classes;
optimizing a critical value that is predetermined for each class of the plurality of classes from the matrix model; and
estimating the failure probability of the objects by the optimized critical value.
2. The method of claim 1, wherein the plurality of classes comprise types of material of which the plurality of observed objects are made.
3. The method of claim 1, wherein the plurality of classes comprise age groups which are defined by ages of the plurality of observed objects.
4. The method of any one of claims 1 to 3, wherein fitting the matrix model to the determined characteristic values in the each class of the plurality of classes includes recording fit characteristic values that meet constraints of the matrix model for the each class of the plurality of classes.
5. The method of claim 4, further comprising:
evaluating a combination of the fit characteristic values for the each class of the plurality of classes, wherein each fit characteristic value of the combination is from one class of the plurality of classes and the combination has a fit characteristic value for every class of the plurality of classes.

6. The method of claim 5, wherein optimizing the critical value that is predetermined for each class of the plurality of classes from the matrix model comprises setting the critical value for each class of the plurality of classes as the corresponding fit characteristic value of the combination.
7. The method of any one of claims 1 to 6, prior to fitting the matrix model to the determined characteristic values, the method further comprising:
sorting the determined characteristic values in an ascending order.
8. The method of any one of claims 1 to 7, wherein fitting the matrix model to the determined characteristic values comprises using a diminishing return method.
9. The method of any one of claims 1 to 8, wherein the matrix model comprises a confusion matrix, and wherein a minority of the plurality of observed objects is fitted to a positive class and a majority of the plurality of observed objects is fitted to a negative class.
10. The method of claim 9, wherein optimizing the critical value from the matrix model comprises optimizing the critical value in a manner that the critical value is decreased.
11. The method of any one of claims 1 to 10, further comprising:
determining life-time information for each observed object of a plurality of observed objects; and
fitting an analysis model to the life-time information of the plurality of observed objects in each class of the plurality of classes.
12. The method of claim 11, wherein the life-time information for each observed object of the plurality of observed objects indicates whether the observed object has failed up to a final time.

13. The method of claim 12, wherein the plurality of observed objects comprise at least one observed object that has failed and at least one observed object that is still operating at the final time.
14. The method of claim 13, wherein the life-time information for each observed object of the plurality of observed objects that has failed comprises a time of failure of the observed object.
15. The method of claim 13 or claim 14, wherein determining the life-time information comprises generating an adjusted rank for each observed object of the plurality of observed objects that has failed.
16. The method of any one of claims 1 to 15, wherein the analysis model is Weibull cumulative distribution.
17. The method of claim 16 when dependent from 3, wherein fitting the analysis model to the life-time information comprises determining parameters of the analysis model and a parameter of the Weibull cumulative distribution has different values for different age group.
18. A data processing system comprising a communication interface, a memory and a processing unit configured to perform the method of any one of claims 1 to 17.
19. A computer program element comprising program instructions, which, when executed by one or more processors, cause the one or more processors to perform the method of claims 1 to 17.
20. A computer-readable medium comprising program instructions, which, when executed by one or more processors, cause the one or more processors to perform the method of any one of claims 1 to 17.