Electrical Power and Energy Systems 62 (2014) 556–561

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Short Communication

End-of-life assessment of electric power equipment allowing for non-constant hazard rate – Application to circuit breakers

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ARTICLE INFO

Article history:
Received 7 May 2013
Received in revised form 1 May 2014
Accepted 10 May 2014
Available online 5 June 2014

Keywords:
Reliability
Statistical analysis
Remaining life assessment
Mean residual life
Circuit breaker

ABSTRACT

A statistical methodology is proposed for end-of-life studies of aging populations of electric power equipment. As an example, this methodology is applied to Hydro-Québec's 120- and 161-kV minimum-oil circuit breakers. Non-parametric and parametric statistical methods allowing for a non-constant hazard rate are used to estimate apparatus survival as a function of time since commissioning or manufacturing. This function is then used to estimate hazard rate, mean residual life, mission reliability and life expectancy. This information provides valuable insight for end-of-life management of electric power equipment, which is still usually based on hazard rate estimates independent of age.

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Introduction

End-of-life assessment of aging substation equipment is currently a subject of great interest for utilities. In fact, a CIGRE working group (A3.29) was formed in 2010 to address the topic. Estimates of hazard rate and other reliability functions, such as mean residual life and mission reliability, can provide crucial support for end-of-life management of aging electrical apparatus. These functions help in timing investments in such a way as to avoid high interest payments from investing too early or high failure costs from investing too late.

In the electric power industry, hazard rate is still usually estimated using survey data by dividing the number of events documented during the survey period by time in service covered by the survey (in apparatus-years). See for example recent CIGRÉ surveys [1,2], IEEE's most recent revision of Standard 493 [3] and the Canadian Electricity Association's Equipment Reliability Information System [4,5]. This estimation procedure assumes a constant hazard rate, though a bathtub-shaped curve or increasing function more adequately describes hazard as a function of time.

Another estimation method, very seldom seen in published material on power systems, is to use statistical methods from survival literature [6]. These methods include non-parametric (e.g., Kaplan-Meier, Nelson-Aalen) and parametric (e.g., Weibull distribution) estimation of hazard rate and survival functions [7]. One difficulty with these methods is that the data required is usually not available straightforwardly in business information systems [8].

Not only does the method used to estimate relevant functions vary from study to study, but the event considered varies as well, even among studies focusing on electrical equipment asset management. Obviously, the choice of event has a major impact on results [9].

Given the aging of electrical apparatus currently in service, estimating time remaining until disposal is more relevant than ever. This is especially true for minimum-oil circuit breakers (CBs), among other types of apparatus. Large numbers are still in service worldwide [5,8] and, since this technology was replaced in the mid-seventies, apparatus in service are approaching the end of their service life.

Some studies of minimum-oil CB reliability are available in the literature [4,5,10–12]. In all of these studies except [10], the traditional hazard rate estimation method was used, resulting in constant estimates.

In this paper, we use statistical methods from survival literature to estimate quantities relevant to end-of-life management. All events that lead to disposal of equipment are thus considered; these include, for example, signs of imminent failure and inadequate performance, reliability or maintainability levels.

Since disposal date is not always available in electrical utility databases, as is the case at Hydro-Québec, a data mining operation may be required to estimate this date. We present the algorithm

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http://dx.doi.org/10.1016/j.ijepes.2014.05.016
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we used for this purpose, which can be used with data from other utilities.

We then explain and illustrate how hazard rate, mean residual life and mission reliability can be estimated as functions of time using statistical methods. These three functions can be used instead of constant estimates to proactively manage end-of-life of utility assets.

In the following section, the method for estimating time in service is first described. Details are given regarding the data mining algorithm used on data available in utility information systems. We then go on to describe the theory of survival analysis and provide definitions of the hazard rate, mean residual life and mission reliability functions. Section 'Example of 120- and 161-kV minimum-oil circuit breakers' presents an example based on Hydro-Québec's 120- and 161-kV minimum-oil CBs. Methods and their assumptions are discussed in Section 'Discussion', and conclusions are presented in Section 'Conclusions'.

Data and methods

Estimating time in service

Service starts at commissioning for all apparatus, a time easily obtained from most inventory databases. Time in service of an apparatus still in service at the time of a study is right-censored, which means the apparatus has survived to that point and disposal will take place in the future. Note that time in service of such apparatus must absolutely be considered in order to avoid important biases. The time in service of disposed of equipment ends at the time of disposal, which may be difficult to determine using available data. Given this difficulty and the importance of related estimates, the data available at Hydro-Québec and how it was used are described below. As discussed in the introduction, the event considered is disposal due to major failure or any other end-of-life related reason. This is the relevant event to study for asset management purposes in order, for example, to estimate the number of apparatus to replace in future years. Note that the apparatus studied were not refurbished, so there is no need for special treatment in the analyses.

Available data

The Hydro-Québec inventory database includes descriptive information on all apparatus, as well as commissioning dates and utilization codes. The main utilization code values are "in service" and "disposed of."

Three types of data in the maintenance database are particularly useful in estimating disposal dates: (1) work orders, which describe maintenance jobs performed, what triggered them, their duration and cost, and the date of the work; (2) relocation history, which, for every relocation, includes the original location on the grid, the destination location and the relocation date; and (3) date last modified, generated automatically for the different fields of the database.

Use of available data

The utilization code is used to determine whether an apparatus is in service or has been disposed of. For all apparatus, time in service starts at the commissioning date. If only the year is available, commissioning is considered to have taken place on June 30.

For apparatus still in service when data is retrieved from the database, the time in service ends at the time of retrieval. Event times are thus right-censored for such apparatus. For each apparatus in the disposed of group, the end of time in service is estimated using the three types of data described above, as explained in the following paragraphs and summarized in the algorithm diagram presented in Fig. 1.

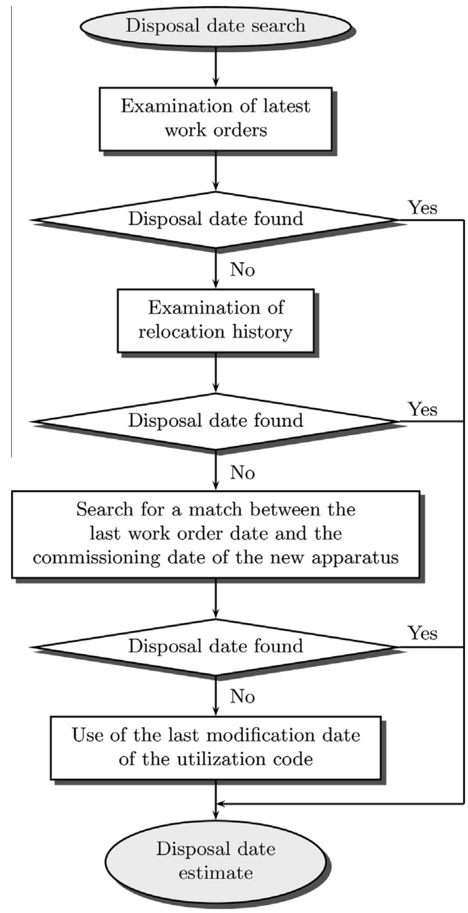

Fig. 1. Algorithm used to estimate disposal date.

The latest work orders are first examined to determine whether any of them involve disposal. If one does, the date of that work order is taken as the disposal date.

If there is no such work order in the database, the relocation history is examined. If relocation from a non-disposal site to a disposal site has occurred, the date of that relocation is considered to be the disposal date.

If the database contains no relevant relocation, the site where the apparatus was last used is determined. If the apparatus currently in use at that site has a commissioning date consistent with the date of the last work order for the disposed of apparatus, that commissioning date is used as the disposal date of the preceding apparatus.

Finally, if the disposal date is still unknown, the date on which the utilization code ("in service" or "disposed of") was last modified is used. Since this date is generated automatically when the person in charge modifies the code in the database, it serves as an upper limit for the disposal date. The lower limit is either the date of the last work order not involving disposal or the date of the last relocation between two non-disposal sites, whichever is the most recent.

Theory of survival analysis

Basic concepts

Let us denote as T the random variable whose value is the time to disposal and as $f(t)$ its probability density function. The survival function is $S(t) = \int_t^{\infty} = f(u)du$ whereas the hazard rate function is

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