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Reliability evaluation of power cables considering the restoration characteristic

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ABSTRACT

In this paper Weibull parametric proportional hazard model (PHM) is used to estimate the failure rate of every individual cable based on its age and a set of explanatory factors. The required information for the proposed method is obtained by exploiting available historical cable inventory and failure data. This data-driven method does not require any additional measurements on the cables, and allows the cables to be ranked for maintenance prioritization and repair actions.

Furthermore, the results of reliability analysis of power cables are compared when the cables are considered as repairable or non-repairable components. The paper demonstrates that the methods which estimate the time-to-the-first failure (for non-repairable components) lead to incorrect conclusions about reliability of repairable power cables.

The proposed method is used to evaluate the failure rate of each individual Paper Insulated Lead Cover (PILC) underground cables in a distribution grid in the south of Sweden.

1. Introduction

In power grids, power cables are one of the fundamental but also the most difficult components to monitor [1]. In general, such cables are heavily affected by many factors, for example ionization, thermal and mechanical stresses [2–5]. In case of failures, both pinpointing and repairing faults are expensive and time consuming due to the difficulties in accessing them. This encourages many power distribution companies to switch from reactive maintenance (repair after failures occur) to predictive maintenance (repair before failures occur). Predictive maintenance requires estimation of the remaining lifetime of the cables and the probability of their failures.

There are mainly two approaches to determine the probability of failure in a system or specific component. The first approach is to *measure* the actual condition of the system (on-site testing), while the system is in operation, based on some deterioration parameters. The second approach is to *estimate* the expected lifetime of the system by performing laboratory experiments (stress test), using expert knowledge, or analyzing the history of previous failures.

In case of power systems, both on-site testing [4] and laboratory testing [5–7] methods are costly and complex. For these systems, estimating the lifetime of components based on historical information is usually more cost efficient than measuring the condition of components. In general, utility companies keep records of historical data such as previous events and inventory data (manufacturer information), that can be used for reliability estimation of the systems or their components [8–13].

There are several reliability measures such as failure probability distribution, cumulative distribution, reliability function, and failure rate, etc. In power grids, the reliability measure for power cables is normally expressed by failure rate, which is the number of expected failures per unit in a given time interval [14].

It should be noted that in order to use reliability measures such as failure rate, the nature of the system and the limitations of the methods must be considered [15]. In reliability evaluation, there is a crucial difference between the statistical treatment of repairable and non-repairable systems. A repairable system or component can be restored to satisfactory operation after a failure by repair actions; while, a non-repairable system or component is removed permanently (replaced with a new system or component) after a failure. Ascher and Feingold

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Table 1
Failure statistics of cause of failure and affected components in the history of failure dataset from 2009 until 2015.

Type of Failure	Cause of Failure	Frequency(%)	MTBF(days)
Operational Failure (846 failures)	Fabrication fault	34.59%	5.7
	Fuse break	24.95%	7.91
	Incorrect installation	7.12%	27.72
	Overload	5.59%	35.32
	Incorrect operation	1.35%	136.88
	Lack of maintenance	1.44%	146
	Others	1.17%	168.46
Non-Operational Failure (227 failures)	Digging	14.41%	13.69
	Traffic	1.71%	115.26
	Weather	3.42%	57.63
	Animal	0.72%	273.75
	Others	0.18%	1095

Type of Failure	Affected Component	Frequency(%)	MTBF(days)
All Type of Failure (1110 failures)	Underground cable pillar	48.11%	4.1
	Underground feeder cable	26.94%	7.32
	Underground cable fuse	10.09%	19.55
	Concr.sec.substation indoor man	4.32%	45.63
	OH uninsulated free line	2.70%	73
	Others	7.84%	25.17

[16] and Zapata et al., [15] discussed some common misconceptions regarding the modeling of repairable systems.

The replacement of an underground power cable is very costly and it is not economically efficient to change the entire cable after a failure. Therefore, in case of failures, only the faulty point is replaced by a new segment and the rest of the cable stays untouched. This restoration characteristic of power cables allows distribution companies to keep them in service for more than the manufacturers' recommended lifetime. In fact, as long as the frequency of failures in a specific cable is not high (tradeoff between the cost of multiple repairs and replacing the entire cable), these companies tend to keep the cable in service. Furthermore, power cables after a failure and repair are usually as-bad-as-old, i.e., the repair after each failure does not materially change the condition of the entire cable.

In this paper, the parametric proportional hazard model (PHM) is used to assess the impact of different factors on failure rate and to calculate the failure rate of each individual cable. Then, the cables are ranked based on their failure rate for maintenance prioritization. In particular, three case scenarios, which depend on how to consider power cables and their failures, are compared. The case scenarios are based on considering the cables as: 1. non-repairable components, 2. repairable but decommissioned after the last failure, and 3. repairable components which survive until censoring time. In particular, when analyzing the long time history of power cables' failures, the first and second scenarios are incorrect, and the results of this paper show that conclusions about different factors in PHM and cable ranking will be misleading if they are used.

The factors that are considered in this work as the potentially having impact on the failure rate of cables (covariates) are: age, type of conductor, length, number of joints, the length of paper oil insulation cables compared to the total length of a feeder line, and geographical position. These factors can be captured directly from already available databases such as asset inventory and allow lifetime estimation. Many other factors could be considered, however, in this work we used the mentioned factor because of the simplicity in extracting them from the available databases, without need for actual measurement on the cables.

The proposed reliability ranking approach is used to compute ranking for high voltage (rated at 10 kV) and low voltage (rated at 0.4 kV) Paper Insulated Lead Cover (PILC) underground feeder cables in a distribution power grid in the south of Sweden.

The main contributions of this paper are: (a) to extract event information by exploiting historical data such as cable asset inventory; (b) to estimate the failure rate of every individual cables using PHM; (c) to demonstrate that, although many previous works model time-to-first failure or make different approximations which are designed for non-repairable systems, the results of applying these approaches are misleading for reliability analysis of repairable power cables.

The rest of the paper is organized as follows. In Section 2 the datasets and considered factors are described. The proposed method is explained in Section 3. In Section 4, the results are presented. Finally, the work is concluded in Section 5.

2. Data

2.1. HEM Nät dataset

In this study, the Halmstad Energi och Miljö electricity distribution grid (HEM Nät) in the south of Sweden is considered. There are two types of underground cables used in this grid: Paper Insulated Lead Cover cable (PILC), and Cross-linked Polyethylene cable (PEX). A feeder line, which is defined as the power line between two cable boxes, is considered as the component under observation. These feeder lines may be constructed by one cable or a number of connected cable sections.

Three databases containing *cable inventory*, *historical failure*, and *sub-station maintenance history* are used. The *cable inventory* database contains historical information about the in-service cables that have been installed since 1929. Each cable is described with an ID and the unique feeder line name to which it belongs, as well as additional information such as insulation type, conductor size, length, etc. The *historical failure* database contains some information about events, cessation of a system or components' ability to perform its required function, starting in the year 2000. The *sub-station maintenance history* contains information about the previous maintenance carried out on the sub-stations and connected feeder lines.

Table 1 shows the relative frequency (in percent) of different causes of failures (top) and the faulty components (bottom) from 2009 until the end of 2014. According to these tables, the most common failure during these years is caused by "Fabrication fault" with a frequency of 34.59%. The mean-time-between-failures or MTBF refers to the amount of time that elapses between one failure and the next. To calculate MTBF, the total length of time (in here the number of days from 2009 until 2015) is divided by the total number of failures of the same type [17]. According to the MTBF presented in Table 1, the "Fabrication

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