A PROBABILISTIC STUDY OF THE INFLUENCING FACTORS ON DISTRIBUTION CABLE FAILURES USING COX PROPORTIONAL HAZARD MODEL

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ABSTRACT

Analysis of cable failure data are often limited to calculations of the number of failure per one hundred kilometres in length per year with considerations in some instances of cable length, types and their voltage ratings. This paper proposes the use of Cox Proportional Hazard Model (Cox PHM) for analysis of cable failure data. A set of covariates which have significant effects on the cable failure are considered to demonstrate the appropriateness of the model. This paper analyses failure data related to medium voltage (MV, 10kV) cables collected from two metropolitan cities in China using correlation coefficient and PHM. The paper demonstrates that the proposed method is capable of determining the significant factors that are most relevant with failures using a hypothesis test of 5% of p value. The value of relative risk (Exp(β)) is used to evaluate the significance of influencing factors on cable failure. Results prove that the model is more robust than the Weibull distribution in that failure data does not have to be homogeneous and can help provide guidance for improving future practice in cable procurement, installations and maintenance.

INTRODUCTION

In China, total length of power cables rated 10 kV and above has exceeded three hundred thousand kilometres, most of them being commissioned to urban power transmission and distribution systems over the last 20 years [1] due to the ever-increasing rate of urbanization. In major metropolitan cities, the hundreds of cable related failures which occur each year are mainly early mortalities.

Existing assessment and investigation of power cable in practice are based on simple calculation of the number of failures per one hundred kilometres per year or number of failures per one hundred circuits, with considerations occasionally of voltage ratings, cable types [2] and cable lengths. The outcome of analysis is often inconclusive and misleading as cable failures can be due to a number of factors such as poor practice in installation, manufacturing quality, aging and third party damage [3].
It should be noted that, in China, there are hundreds of cable manufacturers of which the quality assurance is not the same. The 10 kV cables are usually laid in trenches, and that some cities in China lie in areas where the climate belongs to monsoon of subtropical climate zone, with distinct four seasons and plenty rainfall. Waterlogging in the cable trenches result in many 10 kV cables being soaked in the water especially in rainy season when the temperature is also high. In order to provide guidance for future cable procurement, design, installation, and maintenance, it is important to identify scientifically the main factors contributing to cable failure.

Like other power systems assets, the lifetime of cable failures obey the “bathtub curve” which can be divided into “early mortality failure” (0~5 years), “the period of grace” with a low number of casual failures (5~25years) and “aging related failure” (>25years) [4]. The Weibull distribution has been used by John P. Ainscough P. E [5] to analyse the relationship between the number of failures and their time-to-failures so as to predict the number of the failures in future. Crow-AMSAA model has been employed by Yancy Gill [6] to establish a maintenance model of aging cable. Poisson distribution and binomial distribution have been adopted in the report of CIGRE Working Group A3.06 [7] to calculate the probability of failures among high voltage equipment. All these methods analyse time-to-failure of power equipment and assume that failures fit certain types of statistical distribution. When time-to-failure of a particular type of equipment does not fit the required type of distribution, this may be due to the lack of data homogeneity, and results of the analysis would then be compromised. In addition none of the above methodologies give considerations to the contributing or influencing factors that are most relevant to failures. Hence there is a strong need for a novel methodology which is capable of dealing with cable failures with which data is often inhomogeneous and associated with a number of causative mechanisms.

Cox PHM is firstly proposed by Cox [8] in 1972 and widely used in medical domain to study how the influencing factors affect survival time of patients [9] and in reliability analysis [10-11]. Compared with other statistical models as mentioned above, the greatest advantage of Cox PHM is that it can consider the impact of more than one covariate simultaneously, which is exactly the feature required in analysing cable failure data as discussed in the next session.

COX PROPORTIONAL HAZARD MODEL

Cox PHM was proposed to analyse time-dependent and time-independent covariates, along with the hazard function under analysis [12]. The Cox PHM function is as given in Equation (1).

$$h(t,X) = h_0(t)\exp\left(\sum_{k=1}^{n_1}\delta_k \cdot X_k + \sum_{j=1}^{n_2}\gamma_j \cdot X_j\right) \quad (1)$$

Where $h_0(t)$ is the baseline hazard function X_k are time-dependent covariates and X_j are time-independent covariates, whose regression parameters are denoted as δ_k and γ_j respectively, n_1 and n_2 represent the number of time-dependent and time-independent covariates respectively. If the set of data under analysis obeys Weibull distribution [13], then the baseline hazard function $h_0(t)$ can take the form of the Weibull model which has been a popular choice [14-15]. In this case the model is known as a full parameter model. However, in situations when the focus of analysis on relative importance of covariates on the hazard, then $h_0(t)$ can be hidden. In this case the model is referred to as half-parameter Cox PHM [16].

In this paper, only the half parameter Cox PHM model and time-independent covariates are considered as the objective of the current analysis is to identify those factors which are the most significant to failures. The mathematical expression function [16] is given in equation (2) below.

$$h(t,X) = h_0(t)\exp\left(\sum_{i=1}^{n}\beta_i \cdot X_i\right) \quad (2)$$

X_i is the ith covariate that can have an influence on equipment failure and t is time-to-failure of the fault, while β_i is the regression parameter that represents the weighting of covariate on equipment failures. When β_i is positive, it means that ith covariate has a positive correlation with failure. While β_i is negative, it means that ith covariate is negatively correlated with failure. If β_i equals to 0, it means the covariate has no correlation with failure. The greater the value of β_i, the more correlated is its covariate with the failures. SPSS, a specialized statistics software, has been employed in the current work to evaluate the values β_i through regression analysis of failure data.

DATA USED

The cable failure data related to medium voltage (MV, rated at 10kV) distribution cables have been collected from the power supply companies situated in two metropolitan cities in China (city S and W).

The MV cable data of city S consists of a total of 15538 MV cable circuits (10kV) with a length of 3871 kilometers, and 134 failures were observed over the period from April, 2011 to March 2013. Relevant available information include the name of each of the circuits, the date of commissioning, the manufacturer, the type of installation and the circuit length.

Whilst MV cable data collected from city W only include the failure information of 544 cable failures which were registered during the period between January 2012 and September 2014. Other information is missing.

With the available data records, cable failure mechanisms were categorized into poor practice in installation, manufacturing quality, aging, and third-party damage. However there are situations where reasons for failure were not identified and registered as "unknown". As shown in Fig. 1, of all the failures, the percentages of unknown reasons are 25% and 15% for city S and city W respectively.

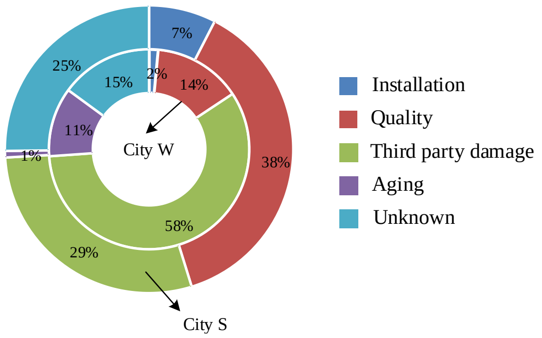

Figure 1 Doughnut chart of failure causes of City S and W

As shown in Fig. 2 and 3, the monthly average temperature and rainfall of city S and W have also been collected in order to study whether the climate has played a major role in the cable failures.

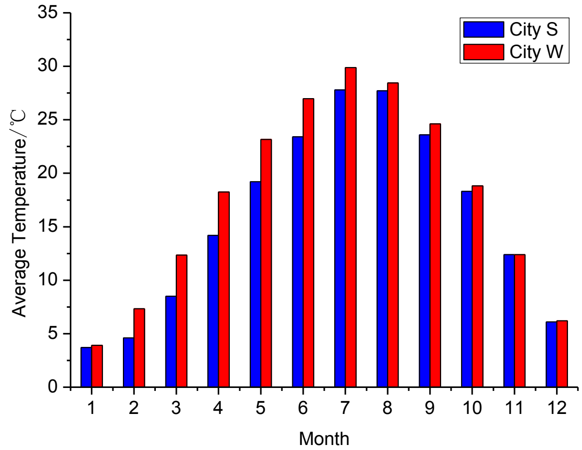

Figure 2 Monthly average temperature of City S and W

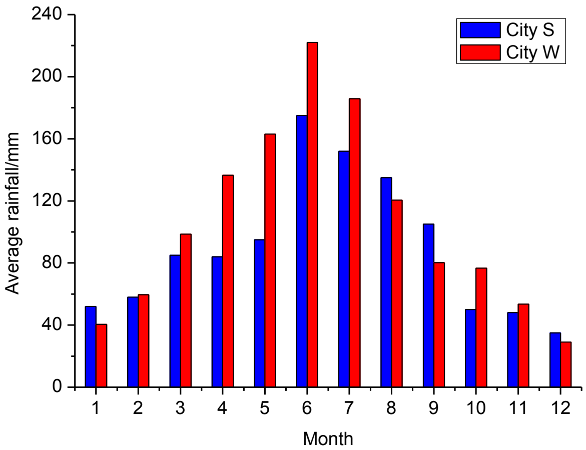

Figure 3 Monthly average rainfall of City S and W

CABLE FAILURE DATA ANALYSIS

Procedure of analysis

As shown in Fig. 4, the procedure of carrying out Cox PHM based data analysis involves determination of covariates, setting of dummy variables, calculation of time-to-failures for each failed cases, and identifying significance of all influencing factors using SPSS. Detailed explanations of the procedures are given in paper [17].

As it has been mentioned in section 3, the potential influencing factors of cable failure include the manufacturer, the type of installation, the circuit length, monthly average temperature and rainfall. But monthly average temperature and rainfall can not be taken as covariates in the Cox PHM due to the fact that the monthly average temperature and rainfall can not correspond with the cables which are still in good condition.

In this paper, correlation analysis of monthly average temperature and rainfall with cable failure will be carried out instead of using Cox PHM. Correlation analysis is a kind of single factor analysis. Here the Pearson correlation index (CI) has been calculated. The classification of relevance can be found in Table 1.

While the cable data of city W include the detailed information, the method of installation, manufacturer and cable length are taken as covariates D, E and F in the Cox PHM.

Table 1 Classification of relevance

Correlation index	Relevance
0.8<|CI|<1.0	Extreme
0.6<|CI|<0.8	Strong
0.4<|CI|<0.6	Moderate
0.2<|CI|<0.4	Weak
0<|CI|<0.2	No relevance

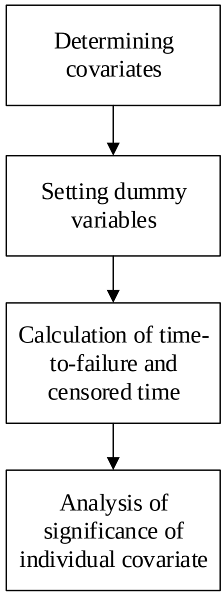

Figure 4 Procedures of using Cox PHM

Results

Table 2 and 3 show the results of correlation analysis of city S and W. It can be found that when all the failures of city S are taken into consideration, the correlation indexes of monthly average temperature and rainfall with failures are 0.727 and 0.643 respectively, indicating strong relevance. While the correlation indexes decrease to 0.693 and 0.337 when only the failures due to installation, quality and aging are considered.

Whereas, the situations of city W are quite different from city S. The correlation indexes of monthly average temperature with all the failures and the failures due to installation, quality and aging are -0.046 and 0.037 respectively, which show that the monthly average temperature has no relevance with the failures in city W. While the results also show that the monthly average rainfall has moderate relevance with the failures due to installation, quality and aging.

As shown in Table 4, when applying step 1 of the PHM (for details of the method please see reference [17]), the Sig values of covariate D, E and F were all zeros. So no covariate should be deleted. It can found that the Sig values of D3, E4, F2, F3 and F4 were 0, 0, 0, 0 and 0.002 respectively, all being less than 0.05.

Table 2 Correlation analysis of monthly average temperature and rainfall with the cable failures in city S

	All the failures	Failures due to installation, quality and aging
Monthly average temperature	0.727	0.693
Monthly average rainfall	0.643	0.337

Table 3 Correlation analysis of monthly average temperature and rainfall with the cable failures in city W

	All the failures	Failures due to installation, quality and aging
Monthly average temperature	-0.046	0.037
Monthly average rainfall	0.324	0.413

In order to determine the most significant dummy variable from F2(0.5~1km), F3(1~1.5km) and F4(>1.5km), their Exp(β) values were compared. F3 was the most relevant with failure because Exp(β) value of F3 was found as the greatest.

From the above results, it can conclude that installation method 3(D3), manufacturer 4(E4) and cable length between 1km and 1.5km (F3) were significant and positively correlated with failures. Cables laid in conduit should be recommended when cables are installed, while Manufacturer 4(E4) should be the last name to be recommended in future cable procurement. The relative risk of failure of the cables with a length of between 1km and 1.5km is the highest. The reason is possibly down to the higher number of third party damages and higher number of cable joints, in relation to per kilometer in cable length, which suffer from higher failure rate.

Table 4 Analysis results of MV cable in city W

Covariate		B	SE	Wald	df	Sig	Exp(β)	95.0% CI for Exp(β) lower	Upper
Step1	D			20.155	4	0			
	D2	0.006	0.319	0	1	0.986	1.006	0.538	1.879
	D3	-2.306	0.532	18.81	1	0	0.100	0.035	0. 283
	D4	0.824	0.745	1.225	1	0.268	2.280	0.530	9.816
	D5	-13.18	821.56	0	1	0.987	0	0	
	E			68.592	5	0			
	E2	0.239	0.280	0.730	1	0.393	1.270	0.734	2.199
	E3	1.445	1.032	1.960	1	0.161	4.242	0.561	32.078
	E4	2.227	0.323	47.476	1	0	9.270	4.920	17.465
	E5	-0.163	0.648	0.063	1	0.802	0.850	0.239	3.024
	E6	-12.06	176.14	0.005	1	0.945	0	0	4E144
	F			67.274	3	0			
	F2	1.022	0.279	13.389	1	0	2.778	1.607	4.802
	F3	2.094	0.279	56.136	1	0	8.118	4.694	14.039
	F4	1.191	0.393	9.177	1	0.002	3.290	1.523	7.109

DISCUSSIONS

The failures are most often caused by third party damage. This category of failures encompasses a variety of failure symptoms. Some cables suffered instant failures and some failures occurred years after damage. The reason for the cases of third party damages being taken into consideration in the paper was that they were related with installation methods and cable length. For example, a cable is more likely to be damaged by rodents if a cable is directly buried. Also, the longer the cable length, the higher is the probability of third party damages. With regards to the significance of factors such as "manufacturer", ignoring failures due to third party damage may yield more useful results.

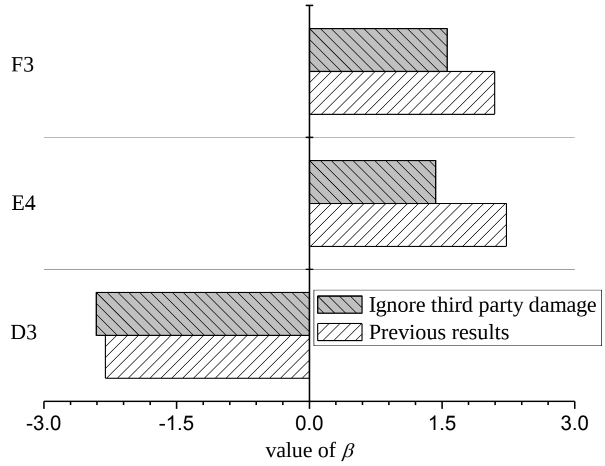

Figure 5 Effects of significant factors with and without consideration of third party damage.

In order to assess the effect of failures due to third party damage on the analysis results, the "state" of MV cables that failed due to third party damage were changed to 0. In other words, these cables were taken as being still in normal operation, with the other settings left unchanged. The significance of covariates D3, E4 and F3 were compared with previous results. As can be seen from Fig. 5, the relative risk of covariates D3, E4 and F3 decreased.

CONCLUSIONS

This paper mainly presented the analysis of cable failures as collected from two metropolitan cities in China. The Cox PHM based approach has been applied to a set of cable early-failure data, and demonstrated that the model can help to quantify the degree of the effect of the selected covariates on cable and cable joint failures. It is capable of providing accurate decisions on outstanding factors, such as a particular manufacturer and/or an installation method, which may be responsible for the failures, especially when more than one factor has an influence on cable failures. The model should help asset managers to deal better with early failures as the model can help to identify weak links, with statistical evidence, in the processes of procurement, design and installation methods.

Correlation analysis has also been carried out on some covariates like monthly average temperature and rainfall prior to the application of the Cox PHM. Results show that the cable failures has some relevance with the monthly average temperature and rainfall. But the results differs from the two cities. More cable data with detailed information from different cities should be collected in order to produce some more interesting and reliable results.

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