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Analysis of Significant Factors on Cable Failure Using Cox Proportional Hazard Model

Zeyang Tang, Chengke Zhou, Senior Member, IEEE, Wei Jiang, Wenjun Zhou, Senior Member, IEEE, Xiaoping Jing, Jianhui Yu, Babakalli Alkali and Bojie Sheng

Abstract—This paper proposes the use of the Cox Proportional Hazard Model (Cox PHM), a statistical model, for the analysis of early-failure data associated with power cables. The Cox PHM analyses simultaneously a set of covariates and identifies those which have significant effects on the cable failures. In order to demonstrate the appropriateness of the model, relevant historical failure data related to Medium Voltage (MV, rated at 10kV) distribution cables and High Voltage (HV, 110kV and 220kV) transmission cables have been collected from a regional electricity company in China. Results prove that the model is more robust than the Weibull distribution in that failure data does not have to be homogeneous. Results also demonstrate that the method can single out a case of poor manufacturing quality with a particular cable joint provider by using the hypothesis test of p-value (5%). The proposed approach can potentially help to resolve any legal dispute that may arise between a manufacturer and a network operator, in addition to providing guidance for improving future practice in cable procurement, design, installations and maintenance.

Index Terms—power cable, cable failures, Cox Proportional Hazard Model, hazard function, influencing factors, covariate.

I. INTRODUCTION

IN China the total length of power cables rated 10 kV and above has exceeded three hundred thousand kilometers, with most of them being commissioned for urban power transmission and distribution systems over the last 20 years [1] due to the ever-increasing rate of urbanization.

Like other power systems assets, the lifetime of cable failures obey the “bathtub curve” which can be divided into “burn-in phase” with a decreasing rate of early failures (0~5 years), “the useful life phase” with a low number of casual failures (5~25years) and “the wear-out phase” with an increasing rate of aging related failures (>25years) [2]. The hundreds of

cable-related failures which occur each year in the major metropolitan cities in China are mainly in the early part of the cable life cycle. Except third party or external damages which happen in a random manner, the causes for these early failures are mainly manufacturing imperfections and poor installation practices [3]-[4], despite the fact that strict procedures and technical standards are followed among cable and cable accessory manufacturers and cable installers [5]. The routine one hour DC voltage withstand test of the oversheath and the 24 hours AC voltage withstand test of the main insulation are also carried out after installation according to IEC-60840 [6] and IEC-62067 [7], but failures due to manufacturing imperfections and poor installation quality have still been encountered [8], as these tests can only reveal major defects that cause rapid breakdowns. Many forms of minor defects that can not be detected during the manufacturing and installation processes will gradually deteriorate and cause failures after a period of operation. These failures, often happen within the first 5 years of the cable life, are also known as early mortalities.

Existing assessment and investigation of power cable failures are based on simple calculation of the number of failures per one hundred kilometers per year or the number of failures per one hundred circuits, with considerations given occasionally to voltage ratings, cable types [9] and cable lengths. The outcome of the analysis is often inconclusive as cable failures can be due to a number of factors [10]. In addition, the existing approaches are unable to single out the most important reasons such as poor quality from a particular manufacturer or poor installation practice from a particular installation service provider with scientific underpinning.

The Weibull distribution has been used by John P. Ainscough P. E [11] to analyze the relationship between the number of failures and their time-to-failures so as to predict the number of the failures in future years. The Crow-AMSAA model has been employed by Yancy Gill [12] to establish a maintenance model of aging cable. The Poisson distribution and the Binomial distribution have been adopted in the report of CIGRE Working Group A3.06 [13] to calculate the probability of failures among high voltage equipment. All these methods analyze failures of power equipment and assume that the failures fit certain types of statistical distribution. When the failures of a particular type of equipment do not fit the required type of distribution, owing to the lack of data homogeneity, results of the analysis would then

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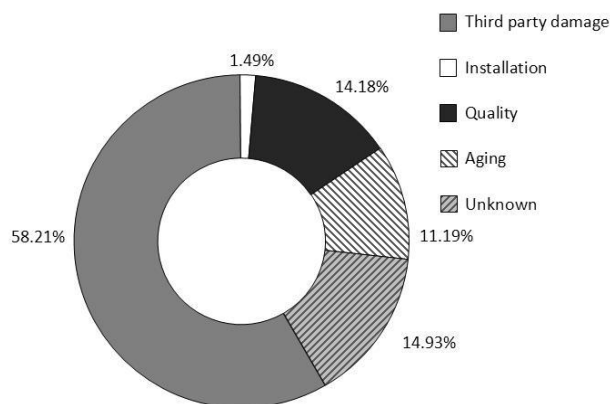
be compromised. In addition, none of the above methodologies give considerations to the contributing or influencing factors that are most relevant to the failures. Hence there is a strong need for a novel methodology which is capable of dealing with cable failures especially when data is inhomogeneous and associated with a number of causative mechanisms. The technical advancement would provide guidance for future cable procurement, design, installation, cable asset management and maintenance. Also it would provide scientific proof in regard to who should have been responsible for the failures when legal disputes between cable manufacturers, installation service providers and network operators occur.

The Cox Proportional Hazard Model (PHM) was firstly proposed by Cox [14] in 1972 and widely used in the medical domain to study how influencing factors affected survival time of patients [15] and in reliability analysis [16]-[17]. Compared with other statistical models as mentioned above, the greatest advantage of the Cox PHM is that it can consider the impact of more than one covariate simultaneously. This is exactly the feature required in analyzing those failure data related to early mortality among power cables as will be discussed in the next session.

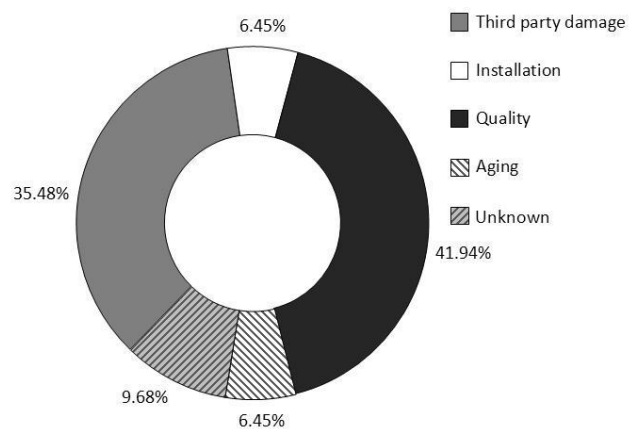
II. CABLE FAILURE DATA COLLECTION AND ANALYSIS

Failure and life data, to be used in this paper, are related to Medium Voltage (MV, rated at 10kV) distribution cables and High Voltage (HV, 110kV and 220kV) transmission cables that have been collected from a regional electricity company in China.

The HV cable data include a total of 285 cable circuits with a length of 409 kilometers and 1068 cable joints. During the period between January 2004 and December 2011, 31 failures were registered.



(a) Composition of MV cable failures



(b) Composition of HV cable failures

Fig. 1. Failure data and a breakdown of failure causes.

Among the 31 HV failures, 18 happened to cable joints with causative mechanisms being registered as manufacturing quality issues (13), poor installation practice (2) and unknown (3), whilst third party or external damage has mainly been responsible for the remaining 13 failures associated with cable body. With the MV cables, 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. There is a lack of details with regard to the number of cable joints and the number of failures which happened to cable joints.

For each of the HV cable joints, relevant information includes the date of commissioning, the manufacturer and the installer. For MV cable circuits, available information includes the name of each of the circuits, the date of commissioning, the manufacturer, the type of installation and the circuit length. The failure data, mostly early mortalities, include date and type (joint or main cable) of each failure and the cause of each of the failures. Further information extracted from the data is presented in Fig. 1.

With the available records, cable failure mechanisms were categorized into poor practice in installation, manufacturing quality, aging, and third party damage [18-19]. However there are situations where reasons for failure were not identified and registered as “unknown”. As can be seen from Fig. 1, of all the failures the percentages of unknown reasons are 14.93% and 9.68% for MV and HV cables respectively.

III. COX PROPORTIONAL HAZARD MODEL

The Cox PHM was proposed to analyze time-dependent and time-independent covariates, along with the hazard function under analysis [20]. The Cox PHM function is given in Equation (1).

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

Where $h_0(t)$ is the baseline hazard function. X_k stands for time-dependent covariates and X_j represents

time-independent covariates, whose regression parameters are denoted as δ_i 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 the Weibull distribution [21]-[22], then the baseline hazard function $h_0(t)$ can take the form of the Weibull model which has been a popular choice [21]-[22]. In this case the model is known as a full parameter model. However, when the focus of an analysis is on relative importance of covariates on the hazard, then $h_0(t)$ can be hidden. In this case the model is referred to as the half-parameter Cox PHM [23].

In this paper, only the half parameter Cox PHM model and time-independent covariates are considered. The objective of the current analysis is to identify those factors which are the most significant to cable failures. The mathematical expression function [23] is given in equation (2).

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

X_i is the i th covariate that can have influence on cable failure, while β_i is the regression parameter that represents the weighting of the i th covariate on the failures. When β_i is positive, it means that i th covariate has a positive correlation with the failures. While β_i is negative, it means that i th covariate is negatively correlated with the failures. If β_i equals to 0, it means the covariate has no correlation with the failures. SPSS, a specialized statistics software, has been employed in the current work to evaluate β_i through regression analysis of the failure data. It is to be noted that although the hazard function $h_0(t)$ is still in Equation (2), it does not need to take a specific form and can be ignored when failure data are analyzed in SPSS.

IV. CABLE FAILURE DATA ANALYSIS

With cable failure data at hand, the procedures of carrying out the Cox PHM involve determination of covariates, setting of dummy variables, calculation of time-to-failures for each failed cases, and identifying the significance of the influencing factors using SPSS. Further explanations of the procedures are as follows.

A. Determining Covariates and Evaluation of Their Weightings in the Cox PHM

TABLE I
COVARIATES TAKEN FOR IN THE PAPER

HV cable joints /covariates	Installer	Joint Manufacturer	
Covariates/symbol	HI (HI1~HI4)	HM (HM1~HM8)	
MV cable circuits/ covariates	Methods of installation	Manufacturer	Cable length
Covariates/symbol	MI (MI1~MI5)	MM (MM1~MM6)	ML (ML1~ML4)

Failures rates related to HV and MV cables have been analysed separately. With the available data, HV cable failures and cable joint failures can be identified, which is not the case with MV cable data.

With HV failures, only the 18 joint failures need to be dealt with. Those failures due to third party damage happen in a random manner and aging failures have been ignored. Further to information provided in Fig. 1, HV joints were produced by 8 manufacturers and installed by 4 different installation companies. Information regarding the methods of installation for HV cables was unavailable and has not been considered. MV failure cables and cable accessories were produced by 6 manufacturers, installed in 5 different methods and cable length are divided into 0~0.5km, 0.5~1km, 1~1.5km and >1.5km. Methods of installation include “laid in cable trenches”, “directly buried”, “in cable conduit”, “overhead support” and “unknown”. The covariates of HV and MV cables are shown in Table I.

B. Setting Dummy Variables

A dummy variable is the one that takes the value 0 or 1, indicating the absence or presence of the categorical effect of a covariate that may shift the outcome. If a covariate contains only two classes, for example, the human gender contains male and female, the dummy variable is unnecessary. In the case of, say, the covariate “length of cable” which include four classes that are (0~0.5km), (0.5~1km), (1~1.5km) and (>1.5km), dummy variables are then necessary when SPSS is used to carry out data regression [24]-[26]. Take the covariate “cable length” as an example, cable lengths of (0~0.5km), (0.5~1km), (1~1.5km) and (>1.5km), are recorded as 1 to 4 respectively. According to the rules of setting dummy variable, when cables of an arbitrary length group, say, a (0~0.5km) or ML1, is chosen as the base for analysis, then the other three length group (ML2, ML3, ML4) are dummy variables. The codes of dummy variables can be formed for use in SPSS as given in Table II. Although the other length group can also be chosen as the base, the results will be the same. These procedures will be applied to other covariates and will not be repeated here.

TABLE II
CODES OF DUMMY VARIABLES IN SPSS WHEN ML1 IS ASSUMED AS THE BASE

Length of cable/km	(ML2)Length of cable(1)	(ML3)Length of cable(2)	(ML4)Length of cable(3)
0~0.5(base)	0	0	0
0.5~1	1	0	0
1~1.5	0	1	0
>1.5	0	0	1

C. Calculation of Time-to-Failure and Censored Time

In this paper, the data collected are the so-called “censored data” in statistics. This means that data include both cables with and without failures till the day that data were collected. The collecting date of HV and MV cables were Dec. 1st 2011 and Feb. 27th 2013 respectively. If a cable had failed before the collecting date, then the time-to-failure of the cable can be

calculated. With those cables still in normal operation till the collecting date, then the censored life time (between the date of commissioning and the date of data collection) of the cable was calculated. An example of the data set associated with HV cable joints after pre-processing of data and before carrying out regression is provided in Table A in Appendix at the end of the paper.

D. Analysis of Significance of Individual Covariates

When a particular covariate is analyzed to assess whether it has a significant effect on the failures, the Hypothesis Test [27] is applied. The Hypothesis Test includes a null hypothesis and an alternative hypothesis. The p-value [28], a statistical tool for significance testing, is adopted here in the Hypothesis test. A predetermined significance level is set as 0.05, meaning when the p-value is below 0.05, the null hypothesis is refused because the chance of the null hypothesis being true is too small. However when p-value is greater than 0.05, the null hypothesis should be accepted. Here the null hypothesis is taken as “a covariate’s β value (as shown in equation (2)) is equal to 0” and the alternative hypothesis is taken as the “covariate’s β value is not equal to 0”. The covariate’s β value is estimated using the Maximum Likelihood Estimation method.

E. Analysis of HV Cable Joints

Table III illustrates the results produced from the regression analysis of failure data using SPSS, where SE is the standard error of β . Wald is the value of the Wald statistics in the hypothesis test in the software package SPSS. DF is the degree of freedom. SIG is the p value of the hypothesis test. $\text{Exp}(\beta)$ signifies the relative risk. 95% CI means 95% confidence interval. The “backward stepwise” option has been chosen in SPSS in order to delete the covariates which are not significantly correlated with failure.

TABLE III
ANALYSIS RESULTS OF HV CABLE JOINT

Covariate	β	SE	Wald	DF	SIG	Exp(β)	95.0% CI for Exp(β)	
							lower	upper
Step1 HI			4.695	3	0.196			
HI1	-2.562	1.307	3.840	1	0.050	0.077	0.006	1.00
HI2	-1.704	1.255	1.845	1	0.174	0.182	0.016	2.127
HI3	-1.354	1.235	1.202	1	0.273	0.258	0.023	2.906
HM			12.795	7	0.077			
HM1	1.867	1.376	1.842	1	0.175	6.469	0.437	95.868
HM2	2.248	0.936	5.765	1	0.016	9.471	1.511	59.35
HM3	3.533	1.172	9.087	1	0.003	34.218	3.441	340.25
HM4	-10.104	1123	0	1	0.993	0	0	
HM5	-11.365	751.2	0	1	0.988	0	0	
HM6	2.013	1.358	2.195	1	0.138	7.482	0.522	107.2
HM7	0.963	0.910	1.118	1	0.290	2.619	0.440	15.593

Step2 HM			18.218	7	0.011			
HM1	2.063	1.241	2.764	1	0.096	7.871	0.691	89.631
HM2	2.043	0.818	6.232	1	0.013	7.711	1.551	38.337
HM3	3.544	1.035	11.736	1	0.001	34.609	4.556	262.91
HM4	-10.651	1119.9	0	1	0.992	0	0	
HM5	-11.290	849.29	0	1	0.989	0	0	
HM6	1.885	1.234	2.331	1	0.127	6.584	0.586	73.99
HM7	0.611	0.837	0.533	1	0.465	1.842	0.357	9.496

Two steps have been taken in SPSS. In step 1, the significance of covariates HI and HM were analyzed simultaneously. The SIG values of covariate HI and HM were found to be 0.196 and 0.077 respectively, both exceeded 0.05. HI is ignored in the process of “backward stepwise” regression because the SIG value of HI is greater than that of HM.

In step 2, only the covariate HM was analyzed. It can be found from Table V, HM2 and HM3, their SIG values were 0.013 and 0.001 respectively, both less than 0.05. For all the other covariates, as their SIG values were greater than 0.05, their effects were assumed as insignificant and therefore ignored.

For HM2, its $\text{Exp}(\beta)$ value was 7.711 meaning that the failure hazard of the cables manufactured by manufacturer 2(HM2) was 7.711 times of manufacturer 8(HM8). Meanwhile, the $\text{Exp}(\beta)$ value of HM3 is 34.609 which means that the failure hazard using the cable joints produced by the 3th manufacturer (HM3) was 34.069 times of manufacturer 8(HM8).

It can be concluded that manufacturer 2(HM2) and manufacturer 3(HM3) were significantly and positively correlated with the failures. The installation companies and other manufacturers were found to be less correlated with the cable joint failures. It is worth noting that the particular cable joint manufacturer (HM3) eventually accepted its responsibility in the failures after a long standing legal dispute. The cause of the joint failures was recognized as poor design of the stress cones.

F. Analysis of MV Cable Circuits

As shown in Table IV, the SIG values of covariate MI, MM and ML were all zeros. So no covariate should be ignored.

TABLE IV
ANALYSIS RESULTS OF MV CABLE CIRCUIT

Covariate	β	SE	Wald	DF	SIG	Exp(β)	95.0% CI for Exp(β)	
							lower	upper
Step1 MI			20.155	4	0			
MI2	0.006	0.319	0	1	0.986	1.006	0.538	1.879
MI3	-2.306	0.532	18.81	1	0	0.100	0.035	0.283
MI4	0.824	0.745	1.225	1	0.268	2.280	0.530	9.816
MI5	-13.187	821.56	0	1	0.987	0	0	

MM		68.592	5	0					
MM2	0.239	0.280	0.730	1	0.393	1.270	0.734	2.199	
MM3	1.445	1.032	1.960	1	0.161	4.242	0.561	32.078	
MM4	2.227	0.323	47.476	1	0	9.270	4.920	17.465	
MM5	-0.163	0.648	0.063	1	0.802	0.850	0.239	3.024	
MM6	-12.065	176.14	0.005	1	0.945	0	0	4E144	
ML		67.274	3	0					
ML2	1.022	0.279	13.389	1	0	2.778	1.607	4.802	
ML3	2.094	0.279	56.136	1	0	8.118	4.694	14.039	
ML4	1.191	0.393	9.177	1	0.002	3.290	1.523	7.109	

It can be found that the SIG values of MI3, MM4, ML2, ML3 and ML4 were 0, 0, 0, 0 and 0.002 respectively, with all being less than 0.05. In order to identify the most significant dummy variable from ML2, ML3 and ML4, their $\text{Exp}(\beta)$ values were compared. ML3 was the most relevant with failure because the $\text{Exp}(\beta)$ value of ML3 was found to be the greatest.

From the above results, it can be concluded that installation method 3(MI3), manufacturer 4(MM4) and cable length of between 1km and 1.5km (ML3) were significantly correlated with failures. Cables laid in conduit should be recommended when cables are installed, while Manufacturer 4(MM4) should be the last name to be recommended in future cable procurement. Higher failure rates have been found to be associated with cables with a length between 1km and 1.5km. The reason is due to the higher number of third party damages.

V. DISCUSSIONS

A. The Impact of Sample Size

It was found during the investigations that the results of the PHM based analysis depend greatly on the data sample size at hand. Take the HV cable joints as an example, the total number of cable joints was 1068, while the number of failed cable joints was 18. When the sample size of 18 was taken, i.e. only failed cable joints were considered as cable joint samples during the evaluation of covariate HM3, the significance value was 0.460. While all the 1068 cable joints were taken as the data sample, the SIG value of covariate HM3 was 0.001 which was less than 0.05, meaning that the covariates had effect on failures. Clearly the correct data sample should be taken if meaningful results are to be generated.

B. The Effect Due to Third Party Damage on Analysis Results

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 why the cases of third party damages have been taken into consideration in the paper was because 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 regard to the significance of factors such as “manufacturer”, ignoring failures due to third party damage may yield more useful results.

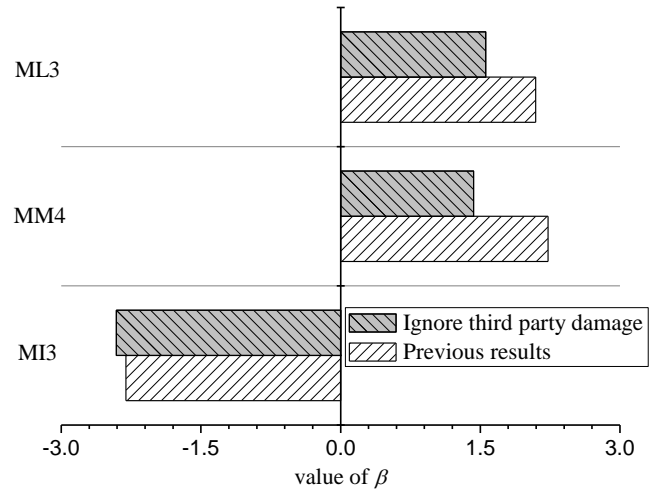


Fig. 2. Effects of significant factors with and without consideration of third party damage.

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. The other settings were left unchanged. The significances of covariates MI3, MM4 and ML3 were compared with previous results. As can be seen from Fig. 2, the relative risk of covariates MI3, MM4 and ML3 decreased.

VI. CONCLUSIONS

The paper presented a Cox PHM based approach to the analysis of 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 the 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 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 scientific evidence in the processes of procurement, design and installation methods.

Compared with the Weibull distribution, the Cox PHM is more adaptive and robust because it is a semi-parameter model which does not need to know the distribution of data. The covariates used in the Cox PHM should contain the entire cable sample. Otherwise, analysis can lead to misleading results.

APPENDIX

TABLE A
DATA INPUT TO SPSS (HV CABLE)

No	Time-to-failure/ censored time	Installer	Joint manufacturer	State of cable
1	2100	2	8	1
2	620	3	3	1
3	6020	2	2	0
4	6086	3	1	0
5	2676	3	1	1
6	2676	2	2	1
7	-19	3	5	1
8	43	3	7	1
9	65	2	7	1
10	4250	1	2	1
11	262	4	8	1
12	0	3	3	1
13	730	3	7	0
14	97	2	7	0
15	4250	3	2	1
16	168	2	4	0
17	354	3	7	1
18	981	3	7	0
19	2629	3	7	1
20	2313	1	7	0
21	4532	2	7	0
22	259	2	6	1
23	194	1	2	1
24	5	1	7	1
25	125	2	7	0
26	5232	3	2	0
27	968	3	2	1
28	2744	3	2	1
29	964	1	7	0
30	1148	2	7	0
31	562	2	7	0
:	:	:	:	:
1068	1198	4	8	0

(Note: the numbers in the third and fourth column of the table are taken in accordance to the rules given in Table I. In the final column of the table, the cable has failed when its "state" is given as 1 and is still in healthy or operational condition when it is 0.)

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