Study on Identification of Defect Types in XLPE Cable with Weibull Distribution

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Abstract. In order to monitor the insulation condition of XLPE cables which have been one of the most popular equipment used in power transition, a method is proposed in this paper to identify the insulation defects accurately by analysing the Weibull distribution of partial discharge (PD) signals. Experiments were applied on a 10kV 30m XLPE cable and three typical types of insulation defect models were designed and tested. The discharge pulse signals of each defect model were collected and their Weibull parameters were analysed and estimated with the ordinary least square estimation method. Several common pattern recognition methods such as support vector machine (SVM), artificial neural network (ANN) as well as classification and regression tree (CART) were used to test the accuracy of the extracted Weibull parameters. The results verified that it is effective to use the parameters of Weibull distribution for defect identification of XLPE cables and the features are suitable for common pattern recognition models.

1. Introduction

XLPE cables have been widely used in power system for power transition due to excellent insulating property [1,2]. However, insulation defects are hard to avoid and prone to lead serious accidents [3]. Defects will cause partial discharges (PD) in XLPE cables [4]. Therefore, measurement and analysis of PD signals is the most important method to realize the condition monitoring on the insulation of XLPE cables [5]. Pulse current method is the most reliable detection method to detect PD signals. It is very helpful to identify the defect types so that the maintenance staff can select and adopt the corresponding plan to repair the XLPE cable promptly and correctly. This paper proposed a method to analysis the PD signals and identify the defect types in XLPE cables with Weibull distribution. A lot of estimation methods have been studied and adopted to estimate the parameters of Weibull distribution, such as maximum likelihood estimation method, correlation coefficient optimization estimation method, moment estimation method, and ordinary least square estimation method [6-9]. Among these methods, the ordinary least squares method is the most effective technique that has been widely used [9,10]. This paper uses this method to estimate the scale and shape parameters of the Weibull distribution model as features of PD signals. The common pattern recognition models have been applied on identification of insulation defects. Experiments were conducted on a 10kV XLPE cable with three kinds of defects designed. The results showed that the features analysed with Weibull
distribution had great and stable accuracy of identification while using different pattern recognition models.

2. **Weibull feature extraction**

2.1 **Weibull Distribution**

There are various forms of Weibull distribution, such as single-parameter, bi-parameter, tri-parameter, and mixing form. Tri-parameter Weibull distribution is the form with shape parameter $\beta$, scale parameter $\eta$ and location parameter $\gamma$. The probability density function (PDF) of tri-parameter form is [6]

$$f(x)=\frac{\beta}{\eta} \left(\frac{x-\gamma}{\eta}\right)^{\beta-1} \exp\left[-\left(\frac{x-\gamma}{\eta}\right)^{\beta}\right]$$

and the cumulative density function (CDF) is [6]

$$F(x)=1-\exp\left[-\left(\frac{x-\gamma}{\eta}\right)^{\beta}\right]$$

in which $\beta > 0$, $\eta > 0$, and $\gamma \geq 0$. Shape parameter $\beta$ plays the role of shaping the curve of PDF approximately. Scale parameter $\eta$ determines to enlarge or decrease the size of the shaped curve. Location parameter $\gamma$ means the safe period $[0, \gamma]$ in which the object will not break down. It is obtained based on the failure and maintenance records of XLPE cables. For condition monitoring, location parameter should be set as 0, then, the Weibull distribution turns into the bi-parameter form. The PDF is [7]

$$f(x)=\frac{\beta}{\eta} \left(\frac{x}{\eta}\right)^{\beta-1} \exp\left[-\left(\frac{x}{\eta}\right)^{\beta}\right]$$

and the CDF is [7]

$$F(x)=1-\exp\left[-\left(\frac{x}{\eta}\right)^{\beta}\right]$$

The PDF graph of bi-parameter Weibull distribution is shown as Figure 1. It is clear that the influence of $\beta$ on the shape of the curve and the effect of $\eta$ on the scale of the curve.

![Graphs of the PDF of bi-parameter Weibull distribution](image)

**Figure 1.** Graphs of the PDF of bi-parameter Weibull distribution

2.2 **Weibull Feature Extraction**

In order to extract the prominent distribution characteristics, Weibull is adopted to analyse pulse PD signals of XLPE cables.

Firstly, Hilbert transform is used to extract the envelop of the pulse signals. For a piece of time series signals $x(t)$, its Hilbert transform is

$$y(t)=\frac{1}{\pi} \int_{-\infty}^{\infty} \frac{x(\tau)}{\tau-t} \, dt$$

While using theorem of mean, it can be estimated as
\[ y(t) = \frac{1}{\pi t} x(t) \]  

The envelop of \( x(t) \) is
\[ X(t) = \sqrt{x(t)^2 + y(t)^2} \]  

Secondly, determine whether the signal fits Weibull distribution. Use the envelop \( X \) to make Weibull distribution, so the CDF turns to [8]
\[ F(x) = 1 - \exp\left[ -\left(\frac{X}{\eta}\right)^\beta \right] \]  

Move the terms on both sides to turn the equation into
\[ 1 - F(x) = \exp\left[ -\left(\frac{X}{\eta}\right)^\beta \right] \]  

Then take its natural logarithm [8]
\[ \ln\left(-\ln(1-F(X))\right) = \beta \ln \left(\frac{X}{\eta}\right) = \beta \ln X - \beta \ln \eta \]  

Set \( y = \ln\left(-\ln(1-F(X))\right) \) and \( z = \ln X \), it turns to [8]
\[ y = \beta z - \beta \ln \eta = A z + B \]  

where the slope \( A = \beta \) and the intercept \( B = -\beta \ln \eta \). If the envelop \( X \) satisfies (11) and gets an approximately straight line on the plane of \( y - z \), it is verified that \( X \) fits Weibull distribution.

Thirdly, ordinary least squares technique is used to estimate the shape parameter and scale parameter. The regression coefficients \( A, B \) of the linear function (11) can be estimated through ordinary least squares technique, then, \( \beta \) and \( \eta \) can be obtained:
\[ \begin{align*}
\beta &= A = \sum_{i=1}^{n} z_i y_i - n \bar{z} \bar{y} \\
\eta &= \exp\left(-\frac{B}{A}\right) = \exp\left(-\frac{\bar{y} - A \bar{z}}{\sum_{i=1}^{n} z_i y_i - n \bar{z} \bar{y}}\right)
\end{align*} \]  

where \( \bar{z} = \frac{1}{n} \sum_{i=1}^{n} z_i \), \( \bar{y} = \frac{1}{n} \sum_{i=1}^{n} y_i \).

Finally, test the fitting degree of the Weibull distribution with estimated parameters. With \( y(z_i^0) = \ln\left(-\ln(1-F(X_i))\right) \) and \( \bar{y}(z_i) = \beta (z_i - \ln \bar{y}) \), the coefficient of determination \( R^2 \) is chosen as the index of fitting:
\[ R^2 = 1 - \frac{\sum_{i=0}^{n} (y(z_i^0) - \bar{y}(z_i^0))^2}{\sum_{i=0}^{n} (y(z_i^0))^2 - \frac{1}{n} \left(\sum_{i=0}^{n} y(z_i^0)\right)^2} \]  

where \( z_i^0 = \ln X_i^0 \), \( z_i = \ln X_i \), \( X_i \) is the pulse amplitude of the collected signal and \( X_i^0 \) represents the pulse amplitude ascending. \( n_i \) represents the number of pulses. The value of \( R^2 \) is in the range of [0, 1]. The closer \( R^2 \) gets to 1, the more the estimated Weibull distribution fits the signal.

3. Experimental Setup
The experiment was conducted on a 10kV XLPE cable with the length of 30 meters. Needle inserted into insulation, needle on the core and cuts on the surface of insulation are the common insulation defects occurring in the operation of XLPE cables. Figure 2 indicates the diagram of the defects in an XLPE cable.
These three kinds of defect models were designed and produced as follows and Figure 3 indicates the process of making these defect models.

(1) Needle on the core of cable. Three types of metal needle with the length of 50mm were made and mounted on the core of cable by bottom. The curvature radius of the tip of the needle was 50μm, 100μm, 150μm respectively.

(2) Needle inserted into XLPE insulation. A needle was inserted into XLPE insulation layer of the cable by piercing the PVC sheath, copper strip and semiconductor layer. Three types of model were made according to the different depth inserted into XLPE insulation, which was 2mm, 2.5mm and 3mm respectively.

(3) Cuts on the insulation. As cuts on the outer layer of semiconductor had damageable effects on the XLPE insulation, three types of incised cuts were made with the shape of depth 1.3mm, 2.1mm, 3mm, length 12.1mm, 12.8mm, 18.8mm and width 11.3mm, 12.4mm 14.8mm respectively.

According to IEC60270, the steps of the experiment based on pulse current detection are as follows:

1) Connect all the equipment as Figure 4 with the defect model on the cable.
2) Increase the voltage applied to the cable slowly and observe the PD detector.
3) While PD occurs, maintain the applied voltage for 5 minutes and then decrease the applied voltage to zero.
4) Increase the applied voltage again until PD signals occur.
5) Maintain the applied voltage for 1 minute to make discharging of cable stable and collect the pulse signals for 4000 frequency cycles.
6) Decrease the voltage to zero, disconnect the equipment and change the defect model.
7) Repeat step 1~6 until all the defect models have been tested.
4. Results and Analysis
During the experience, the applied voltage at which the cable with defect model started to discharge and the partial discharge quantity were recorded and shown in Table 1.

**Table 1. Information recorded during the experience**

| Defect type                  | U(kV) | Q(pC) |
|------------------------------|-------|-------|
| Needle on the core of cable  | 50μm  | 2     | 15   |
|                              | 100μm | 2.5   | 21   |
|                              | 150μm | 4     | 32   |
|                              | 2mm   | 8     | 20   |
| Needle inserted into XLPE insulation | 2.5mm | 5     | 42   |
|                              | 3mm   | 4     | 65   |
| Cuts on the insulation       |       |       |      |
| d=1.3mm, l=12.1mm, w=11.3mm | 8     | 200   |
| d=2.1mm, l=12.8mm, w=12.4mm  | 7     | 400   |
| d=3mm, l=18.8mm, w=14.8mm    | 4     | 500   |

Use the method described in Section 2.2 to estimate the parameters of Weibull distribution of each piece of signal. The estimated Weibull parameters are the features for pattern recognition. Several pattern recognition models were adopted to test the effect of the features extracted with Weibull distribution. Table 2 indicates the accuracy of each model to identify the defect types of XLPE cables.

**Table 2. Identification accuracy of different pattern recognition models**

| Pattern Recognition Model | Accuracy |
|----------------------------|----------|
| SVM                        | 91.2%    |
| ANN                        | 92.8%    |
| CART                       | 90.4%    |

It is clear that even though the accuracy of different models varies, all of them is more than 90% which verifies that the parameters of Weibull distribution are effective to defect diagnosis of XLPE cables.

5. Conclusion
The method of analysing the Weibull parameters of PD signals to identify the insulation defects of XLPE cables was proposed in the paper and verified by the experiments conducted on a 10kV XLPE cable with three typical defects. The results showed that the accuracy of Weibull parameters for defect identification was high and stable with different pattern recognition models. Therefore, the feasibility of using Weibull parameters for monitoring on insulation condition of XLPE cables.
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