Curve Fitting Analysis of Expulsion Fuse Links through the Cross-Validation Technique

Guilherme Braga da Costa, Augusto Zanin Bertoletti
Universidade Federal de Santa Maria (UFSM)
Santa Maria – RS – Brasil
Email: {guilhermebragadacosta, augustozb1}@gmail.com

Adriano Peres de Morais, Ghendy Cardoso Junior
Universidade Federal de Santa Maria (UFSM)
Santa Maria – RS – Brasil
Email: adriano@ctism.ufsm.br, ghendy@ufsm.br

***Abstract*—The most common protective device in distribution systems is the expulsion fuse link. This work aims to assist the engineer in carrying out expulsion fuse links modeling using curve fitting. The proposed approach used the fuse time-current characteristic to obtain the polynomial function that represent the fuse link model. Preferred K and H fuses were used. The polynomial coefficients was obtained through the MATLAB software. The polynomial order that best represents the fuse link was decided using the cross-validation technique. The technique consists of iteratively partitioning the data set, separating test points and training points on each iteration.**

***Keywords*—expulsion fuse link, time-current characteristic, curve fitting, cross-validation.**

I. INTRODUCTION

Several protective devices, such as breakers, overcurrent relays, reclosers and expulsion fuse links, compose distribution systems. The fuses are low-cost and easily replaced devices. Hence, it is the most common protective device in distribution systems. The concept of expulsion fuse is very simple: a fusible element made of tin or silver melts under high current [1]. The melting time is inversely proportional to the current value. The fuses are mainly used to protect branches, distribution transformers, capacitor bank, voltage regulators and potential transformers.

The expulsion type cutouts are classified as open-fuse cutouts, enclosed-fuse cutouts, and open-link-fuse cutouts. The classification is according to the external appearance and operation method [2]. The fuse link is divided in preferred and nonpreferred current ratings. The current ratings for preferred sizes are given as 6, 10, 15, 25, 40, 65, 100, 140 and 200 A and for nonpreferred sizes as 8, 12, 20, 30, 50 and 80 A. Industry standards specify three types of expulsion fuses: “K”, “T” and “H”. As stated in [3], the type “K” link is consider fast fuse, and the “T” is somewhat slower.

Type H fuses are manufactured in ratings of 0.5, 1, 2, 3, 5, and 8A. According to [3], the primary purpose of a transformer fuse is to disconnect the transformer from the circuit if it fails. The fuse should avoid misoperation from inrush current and cold-load pickup.

Several studies focus on distribution systems protection were published in the recent years. According to [4], when the computational simulations uses fuse links, it is necessary to represent the fuse element using digital models. Normally, the data used are available from the manufacturers on a graphs using logarithmic scale as shown in Fig. 1. Theses graphs contain the fuse time-current characteristics (TCC).

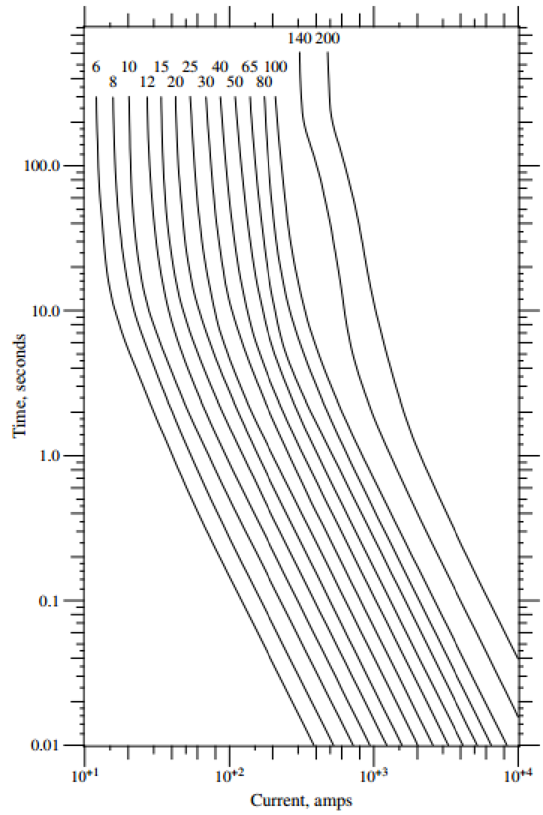

Fig. 1 – Example of MM Curves for K fuse links [3].

The TCC are represented by two curves: the minimum melting curve (MM) and the total clearing curve (TC). The MM curve informs the minimum time versus current required to melt the fuse. The TC curve informs the maximum time versus current required to melt the fuse and extinguish the arc [2].

To assist the engineer in carrying out fuse links modeling, several methodologies were proposed to mathematically model the curves of expulsion fuse links. In [4] is presented an evaluation of the methodologies that use analytical equations to represent this behavior in computational simulations. The main functions used were polynomial, exponential and linear function by parts. The present work used the polynomial function to

The authors are thankful to Brazilian government through Capes (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior). This work was supported by Capes.

978-1-5386-5844-4/18/$31.00 ©2018 IEEE

model the behavior of the expulsion fuse link type K and H in computational simulations. The function was selected because presented the best results according to the criterion of Residual Sum of Squares (RSS) [4].

The polynomial order was selected through the Cross-Validation (CV) technique. According to [5], CV is a technique used to evaluate the predictive capacity of a mathematical model, from a set of data, where some samples are removed as part of the analysis. This technique consists of partitioning the data into two sets: one is used to construct the model, and the other is used to test it, i.e., to verify its generalization capacity. In each partition, the metric used is the Mean Square Error (MSE). In this paper, only the preferred current ratings were used.

This paper is organized in the following manner. Section II introduces the fuse links modeling. Section III describes the methodology approach. Section IV presents the obtained results and the conclusion is drawn in Section VI.

II. Expulsion Fuse Link Modeling

Several articles approach the fuse link modeling. The linear interpolation between two consecutive points was used in [6] and [7]. According [8] and [9], the curve fitting method was used to approximate the segment of interest by linear equation. The linear equation is shown in (1).

$$\log(t) = a.\log(I) + b \quad (1)$$

where t and I for the fuse denote operating time and current respectively, and coefficients a and b can be calculated by a curve fitting method.

The exponential equation also was used to model the fuse links. The authors from [10] and [11], used a curve fitting method to determine a, b, c, e d coefficients in (2) and a_n coefficient in (3) respectively.

$$t = a.e^{bxI} + c.e^{dxI} \quad (2)$$

$$t = \exp(\sum_{n=0}^{4} a_n.(\ln(I))^n) \quad (3)$$

where t is the fuse operating time and I is the fault current seen by the fuse.

In [12] and [13], the authors developed an algorithm to evaluate and identify which of the equations selected provides the smallest adjustment of errors.

The polynomial function was mentioned by [8] and [9]. The authors affirm that a second-order polynomial function can be used to model the fuse link. The equation coefficients was determined through a curve fitting method.

III. Methodology

The Polynomial regression routine used to determine the best polynomial order to fit the curves of each fuse link is shown in Fig. 2. The methodology used follows the steps.

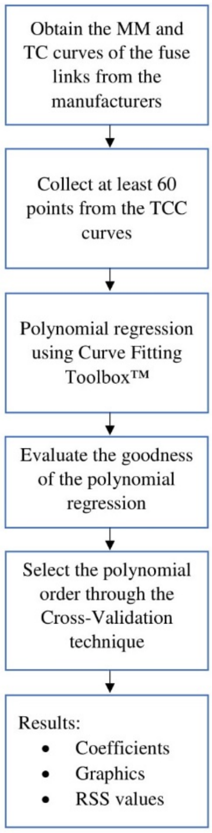

Fig. 2 – Polynomial Regression routine.

A. Data Acquisition

The points used were collected from the TCC curves, which are supplied by manufacturers of fuse link. The WebPlotDigitzer software [14] was used to collect the points. The software was selected because it allows the user setting both axis in logarithmic scale. The present work collected approximately 60 points for each fuse link curve. Five important fuse manufacturers have been considered in this paper, i.e.: S&C Positrol® [15], Cooper Power Systems Kearney™ [16], Eletrofusi Power Systems [17], Delmar Hubbell Power Systems [18] and Indel Bauru [19].

B. Curve Fitting

Through Curve Fitting Toolbox™ present in MATLAB® [20], the polynomial function was implemented to obtain the coefficients. Using (4), an evaluation of the adjustments from the first to the fifteenth order was made using the CV as a comparative parameter. The order with the lowest CV value is selected to represent the fuse link mathematically.

C. Polynomial Function

There are several approaches proposed in the literature for model the expulsion fuse links. In [21] and [22], the authors used the polynomial function to model the fuse link. The curve fitting method was used to determine the p coefficients in (4) for each fuse link.

$$\log(t) = p_0 + p_1.\log(I) + p_2.\log^2(I) + ... + p_n \log(I)^n \quad (4)$$

where t is the fuse link operating time; I is the fault current flowing through the fuse; n is the polynomial order; and p are the fuse coefficients.

D. Cross-Validation (CV)

In [4], the authors used the Least Square Method and the RSS as a comparative parameter to select the polynomial order. The present work used the CV technique to evaluate the accuracy of the polynomial order.

The *K-fold* procedure was used in the CV method. The basic concept is to split the data into K partitions of approximately equal sizes - one partition is used for testing and the *K-1* partitions are used for parameter estimation and the quadratic error calculation. This process is performed K times, so that all data is allocated as a test partition at least once. At the end of the K iterations, the MSE is calculated considering the K partitions [5].

E. Comparative Parameter

It is important to highlight that the procedure described above evaluates the predictive capacity of a given model. As the objective is to evaluate the best polynomial order, the *K-fold* procedure is repeated n times, where n is the highest polynomial order tested, until all MSE are obtained. The polynomial order that presents the lowest MSE is selected. The smaller the MSE, the closer the fit is to the original data. The MSE can be calculated by (5).

$$MSE = E[(T - \theta)^2] \qquad (5)$$

where T denotes an estimate and θ denote the parameter being estimated.

In this way, the authors of this work expect that this study can contribute to the development of studies in distribution system protection, therefore facilitating the modeling of expulsion fuse links.

IV. RESULTS

This section presents the results of the type K and H fuse links curve fitting using the polynomial function given in (4). It is important to note that approximately 60 points were collected for each curve and polynomials order from 1 up to 15 were tested.

Tests have identified that the number of minimum points for a satisfactory fit of the curve are 60 points. When the number of points is less than 60, the curve adjustment is compromised, and it is necessary to increase the degree of the polynomial. An amount greater than 60 points modifies the coefficients of the polynomials, but does not change the quality of the curve fit.

1. Type K Fuse Link

TABLE I shows the polynomial order of MM and TC curves for K fuse link, selected by the CV technique for the three manufacturers. From TABLE I, it can be noticed that it was not possible to obtain the same polynomial order for the different fuse link models; therefore, a previous definition of the order can lead to a less reliable predictive capacity of the mathematical model.

To prove the efficiency of the technique, the MM and TC curve of 6K, 10K, 25K, 40K, 65K and 100K fuse link were plotted for all manufacturers. The graphs are shown in Fig. 5, Fig. 6 and Fig. 7.

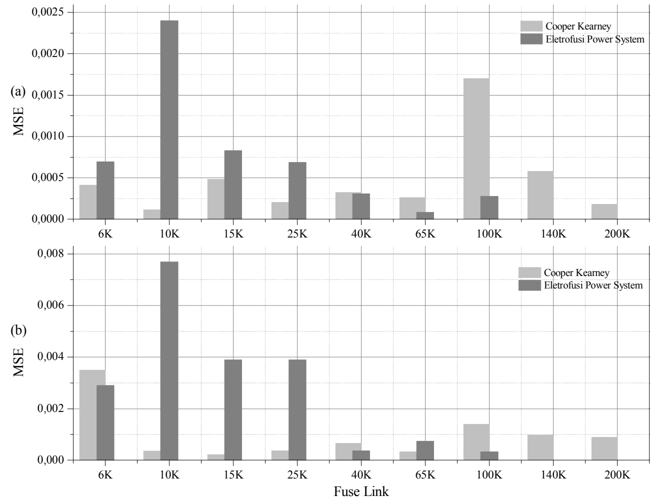

Fig. 3 - Type K Fuse Links x MSE (a) MM curve (b) TC curve.

Through the figures, it is possible to verify the accuracy of the CV technique. The technique allows us to use a small polynomial order if we used another parameter such as RSS for comparison. Fig. 3 shows the MSE results for type K fuse links for Cooper Kearney and Eletrofusi. It is possible to note that all the results are lower than 0.025.

2. Type H Fuse Link

TABLE II shows the polynomial order of MM and TC curves for H fuse link, selected by the CV technique for the three manufacturers. As stated for the K fuse link, it can be observed that it was not possible to achieve the same polynomial order for the fuse link models. Fig. 8, Fig. 9 and Fig. 10 shows the MM and TC curve of 3H and 5H fuse link. The figures confirms the capability of the technique.

Fig. 4 shows the MSE results for type H fuse links for Delmar and Eletrofusi. It is possible to note that all the values are lower than 0.006.

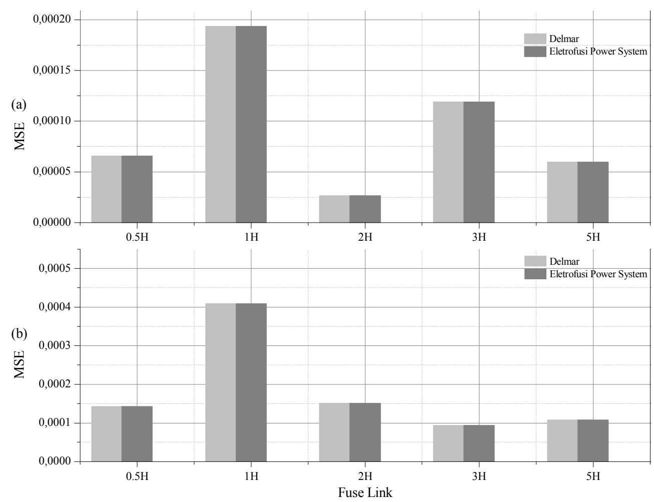

Fig. 4 - Type H Fuse Links x MSE (a) MM curve (b) TC curve.

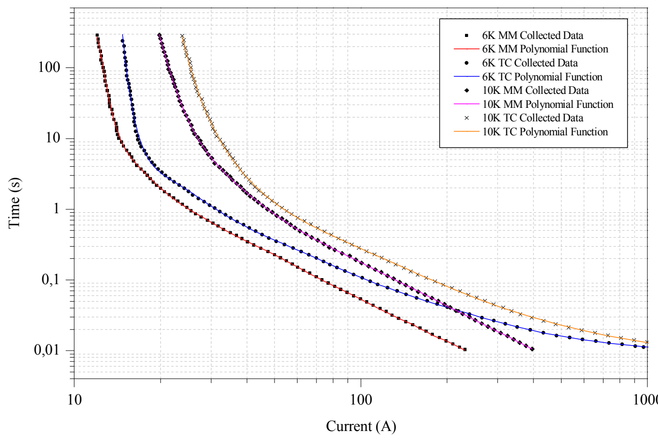

Fig. 5 – 6K and 10K MM and TC curve for Cooper Power Systems Kearney™.

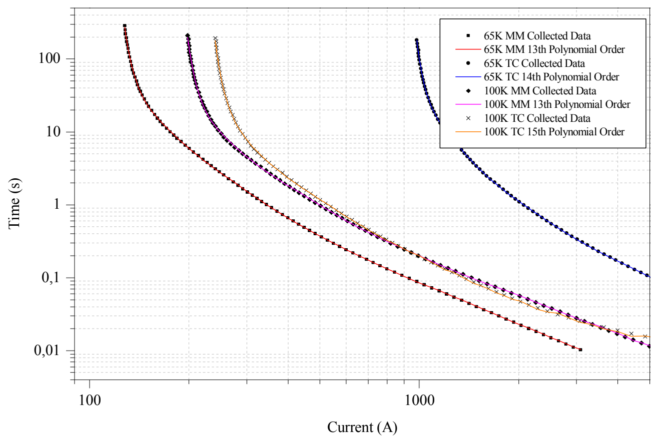

Fig. 6 – 25K and 40K MM and TC curve for S&C Positrol®.

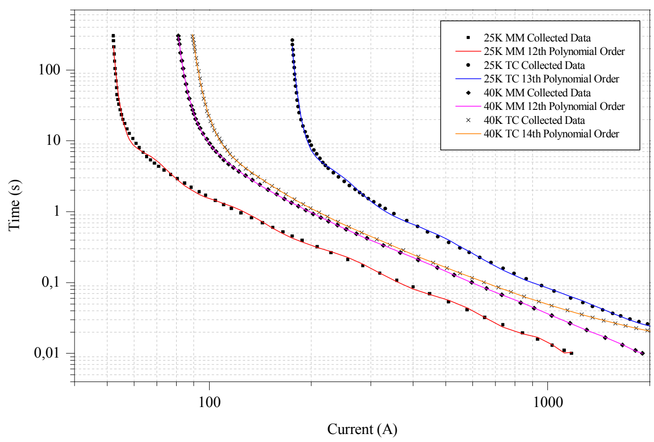

Fig. 7 – 65K and 100K MM and TC curve for Eletrofusi Power Systems.

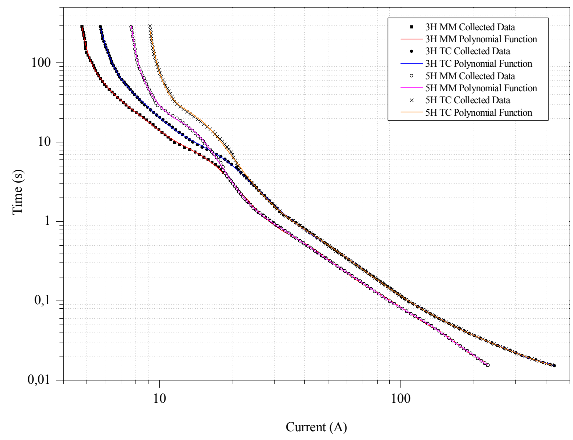

Fig. 8 – 3H and 5H MM and TC curve for Delmar Hubbell Power Systems.

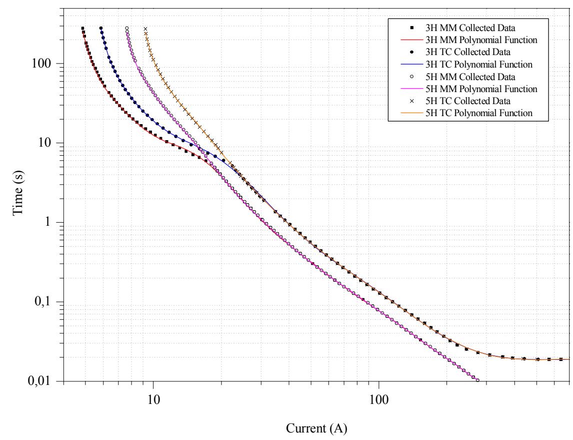

Fig. 9 – 3H and 5H MM and TC curve for Eletrofusi Power Systems.

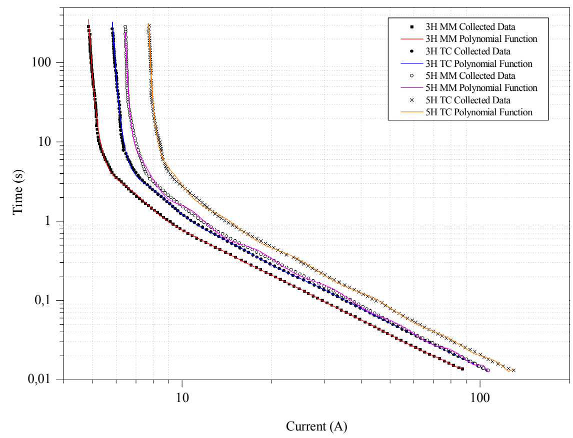

Fig. 10 – 3H and 5H MM and TC curve for Indel Bauru.

TABLE I – POLYNOMIAL ORDER OBTAINED WITH THE CROSS-VALIDATION TECHNIQUE FOR TYPE K FUSE LINK.

	S&C Positrol®		Cooper Power Systems Kearney™		Eletrofusi Power Systems	
Fuse Link	MM	TC	MM	TC	MM	TC
6K	12	15	15	15	14	13
10K	12	15	11	12	14	12
15K	13	12	15	11	14	12
25K	12	13	14	11	14	11
40K	12	14	13	10	14	15
65K	13	14	11	14	13	14
100K	12	13	11	15	13	15
140K	14	14	11	12	-	-
200K	11	11	12	11	-	-

TABLE II – POLYNOMIAL ORDER OBTAINED WITH THE CROSS-VALIDATION TECHNIQUE FOR TYPE H FUSE LINK.

	Delmar Hubbell Power Systems		Eletrofusi Power Systems		Indel Bauru	
Fuse Link	MM	TC	MM	TC	MM	TC
0.5H	15	13	15	15	-	-
1H	15	13	15	15	14	12
2H	15	12	13	15	11	10
3H	15	14	14	15	12	12
5H	14	12	14	15	15	14

V. CONCLUSION

The expulsion fuse links are widely used in the protection of distribution systems, so it is important to represent the computational model of the MM and TC curves with good precision.

The present work used the polynomial function to model the TCC fuse links. Preferred type K and H fuse links were used. Nonetheless, the methodology can be apply to any kind of fuse.

The MATLAB software was used to determine the polynomial coefficients. The polynomial order that presented the smallest deviation for modeling the fuse link through the CV technique was selected. The technique was unable to obtain a single polynomial order for the fuse link models.

In the tests performed, it was observed that the CV technique presents as a general solution a polynomial order different than that polynomial with degree determined only observing the criterion of the smallest RSS errors, quite used in curve fitting literature. However, this does not compromise the overall quality of the solution.

REFERENCES

[1] Leonard L. Grigsby, *Electric Power Generation, Transmission and Distribution, Third Edition*, 3rd ed. Boca Raton: CRC Press, 2012.

[2] Turan Gönen, *Electric Power Distribution Engineering, Third Edition*, 3rd ed. Boca Raton: CRC Press, 2014.

[3] T. A. Short, *Electric Power Distribution Handbook*, Electric P. CRC Press, 2004.

[4] G. B. da Costa, A. C. Marchesan, A. P. de Morais, G. C. Junior, and M. Gallas, "Curve Fitting Analysis of Time-Current Characteristic of Expulsion Fuse Links," *17th Int. Conf. Environ. Electr. Eng.*, p. 6, 2017.

[5] W. L. Martinez and A. R. Martinez, *Computational Statistics Handbook with MATLAB*, 2nd ed. Boca Raton: CRC Press, 2007.

[6] J. J. G. Ledesma, L. R. de Araujo, D. R. R. Penido, and J. L. R. Pereira, "Algorithm for the Analysis of Coordination of Protection for Distribution Systems," *IEEE Lat. Am. Trans.*, vol. 13, no. 7, pp. 2168–2175, Jul. 2015.

[7] E. Campitelli, L. W. Da Silva, R. F. Pereira, and J. S. Mantovani, "Interactive System for Placement and Coordination of Overcurrent Protective Devices," in *IEEE/PES Transmission & Distribution Conference and Exposition: Latin America*, 2006, pp. 1–6.

[8] S. Chaitusaney and A. Yokoyama, "Prevention of Reliability Degradation from Recloser–Fuse Miscoordination Due To Distributed Generation," *IEEE Trans. Power Deliv.*, vol. 23, no. 4, pp. 2545–2554, 2008.

[9] A. F. Naiem, Y. Hegazy, A. Y. Abdelaziz, and M. A. Elsharkawy, "A Classification Technique for Recloser-Fuse Coordination in Distribution Systems With Distributed Generation," *IEEE Trans. Power Deliv.*, vol. 27, no. 1, pp. 176–185, Jan. 2012.

[10] H. A. Abdel-ghany, A. M. Azmy, N. I. Elkalashy, and E. M. Rashad, "Optimizing DG penetration in distribution networks concerning protection schemes and technical impact," *Electr. Power Syst. Res.*, vol. 128, pp. 113–122, 2015.

[11] S. Santoso and T. A. Short, "Identification of fuse and recloser operations in a radial distribution system," *IEEE Trans. Power Deliv.*, vol. 22, no. 4, pp. 2370–2377, 2007.

[12] A. C. Enríquez, E. Vázquez-Martínez, and H. J. Altuve-Ferrer, "Time overcurrent adaptive relay," *Int. J. Electr. Power Energy Syst.*, vol. 25, no. 10, pp. 841–847, 2003.

[13] A. C. Enríquez and E. V. Martínez, "Enhanced time overcurrent coordination," *Electr. Power Syst. Res.*, vol. 76, no. 6–7, pp. 457–465, 2006.

[14] A. Rohatgi, "WebPlotDigitizer," 2017. [Online]. Available: http://arohatgi.info/WebPlotDigitizer/. [Accessed: 02-Feb-2017].

[15] "S&C ELECTRIC COMPANY Positrol Fuse links," 2017. [Online]. Available: http://www.sandc.com/en/products--services/products/positrol-fuse-links/. [Accessed: 02-Jan-2017].

[16] "EATON COOPER POWER KearneyTM," 2017. [Online]. Available: http://www.cooperindustries.com/content/public/en/power_systems/products/fusing/fuse_links/kearney.html. [Accessed: 02-Jan-2017].

[17] "ELETROFUSI POWER SYSTEMS Fuse links," 2017. [Online]. Available: http://www.eletrofusi.com.br/eng/fuse_eng.htm#linkb. [Accessed: 02-Jan-2017].

[18] "Delmar Hubbell Power Systems, Inc.," 2017. [Online]. Available: http://hubbellpowersystems.com.br/PDF/ELOS.PDF. [Accessed: 02-Jan-2017].

[19] "Indel Bauru," 2017. [Online]. Available: http://www.indelbauru.com.br/indel/en/produto/visualizar/codproduto/35/type-h-nema.html. [Accessed: 02-Jan-2017].

[20] Mathworks, "MATrix LABoratory (MATLAB®)." .

[21] Y. Tang and R. Ayyanar, "Verification of Protective Device Coordination in Distribution Systems with Photovoltaic Generation," *IEEE 40th Photovolt. Spec. Conf.*, pp. 2100–2105, 2014.

[22] W. Tian, Chengwei Lei, Y. Zhang, D. Li, R. Fu, and R. Winter, "Data analysis and optimal specification of fuse model for fault study in power systems," in *IEEE Power and Energy Society General Meeting (PESGM)*, 2016, pp. 1–5.