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Curve Fitting of Type-K Expulsion Fuse

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---***ABSTRACT***---
The Minimum Melting Time Curves of type K expulsion fuses were obtained by means of a computational tool. Curve fitting was done by least squares polynomial regression. A problem encountered with Protection Coordination in electrical systems is when the operating curve of the fuses is not available. Visually collected values were used, and times were obtained at which the fuse element melts and interrupts the flow of current. This is convenient for the user to obtain the fuse operating characteristic curves without the need for manual modeling.

KEYWORDS: *Expulsion fuse, operating curve, MMT curve, sample, least squares, regression.*

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I. INTRODUCTION

An Electrical Power System is the network of generating plants, transmission lines and distribution systems that operate together. Its function is to generate, transmit and distribute electrical energy to users. The electrical system must have adequate protection devices that operate safely, accurately and effectively from the generation source to the place of consumption both under normal conditions and under fault conditions. Therefore, it is necessary to place devices that protect the system when a fault occurs and, in this way, minimize damage and protect the user and the equipment installed in said system.

Electrical systems can fail due to various factors such as poor design, poor quality elements, installation errors, lack of maintenance, etc. To reduce the damage caused by failures, appropriate protection devices are selected that meet the appropriate characteristics to protect and provide maximum effectiveness in fault detection. The function of protection is to disconnect the element of the system that has failed.

Overcurrent faults tend to be very destructive, causing irreversible damage to the system and equipment. This requires electrical protection that operates in the shortest possible time to prevent the fault from spreading. This is achieved by interrupting the flow of current through the selection of appropriate devices, as well as the correct coordination of the protections. It is important to consider that each protection device has operating curves, which, depending on the value of the fault current, will be the time in which it interrupts the fault. Therefore, knowing the magnitude of the fault current is very important for selecting the protection device.

The fuse element is the simplest protection device against overcurrent faults. It is made of a metal alloy, which melts for a predetermined value of current passing through it. If any element or segment of the system has a fault, the magnitude of the current passing through the fuse increases, and therefore, it melts, causing the disconnection of the failed element. It is essential to have adequate coordination with the other protections to achieve an optimal level of reliability within the system. Protection coordination is a study that relates the operating times in which the protection acts with respect to the current.

In this work, the Minimum Melting Time (MMT) curves of Type K expulsion fuses are obtained using a computational tool. A problem that exists in the protections coordination in electrical systems is when the operating curve of the fuses and the mathematical model are not available. Visually collected values were used and the times in which the fuse element melts and interrupts the current flow were obtained. This is practical for the user to obtain the characteristic operating curves of the fuse without the need to model them manually.

II. PROTECTION DEVICES

Protection devices are used in electrical power systems to prevent the destruction of equipment or facilities due to a fault that could start simply and then spread uncontrollably in the system. The objective of these devices is to isolate the part where the fault has occurred, limit the damage to the failed equipment, minimize the possibility of a fire, reduce the damage to nearby equipment and minimize the possibility of risk to people. There are different protection devices used in distribution systems such as relays, switches and fuses. In this work we will concentrate on fuses because it is the object of study, specifically expulsion type fuses.

Fuses

Fuses are protection devices that interrupt the flow of electric current greater than the nominal current for which the installation or system component was designed. The part used as a protection element for disconnecting a short circuit is the fuse element, which is constructed of a cross section made of a metal alloy. It melts when a magnitude of current greater than that for which it was designed passes through it. The most common alloys for single-element fuses are tin, copper or silver, and there are different properties of these materials, but the most recommended for this type of fuse is pure tin.

Single-element fuses can basically be subdivided into two types:

- *Low melting point: such as tin, which melts at 232 [°C].*
- *High melting point: such as silver, which melts at 960 [°C] and copper, which melts at 1080 [°C].*

According to the ANSI C37-100-1972 standard, fuses are identified by the following characteristics: *Operating time, Maximum design voltage, Basic impulse level, Operating frequency, Nominal current and Interrupting capacity.*

Fuses have a time-current characteristic operating curve, their response in time is inversely proportional to the magnitude of the current applied to them. All fuse manufacturers provide two characteristic operating curves: *the Minimum Melting Time* (MMT) and *the Maximum Clearing Time* (MCT). The MMT curve is the graphical representation of the time in which the fuse begins to melt due to the action of a given current. This curve is used to coordinate protection devices located after the fuse in the direction of the circulation of the fault current. The MCT curve is the graphical representation of the total time in which the fuse interrupts the circulation of current towards the fault, that is, it considers the time from the beginning of the fusion and the development of the electric arc until it is completely extinguished. This curve is used to coordinate protection devices located before the fuse, in the direction of the circulation of the current towards the fault. A typical fuse time-current curve is shown in figure 1. Two curves are observed: the MMT and the MCT.

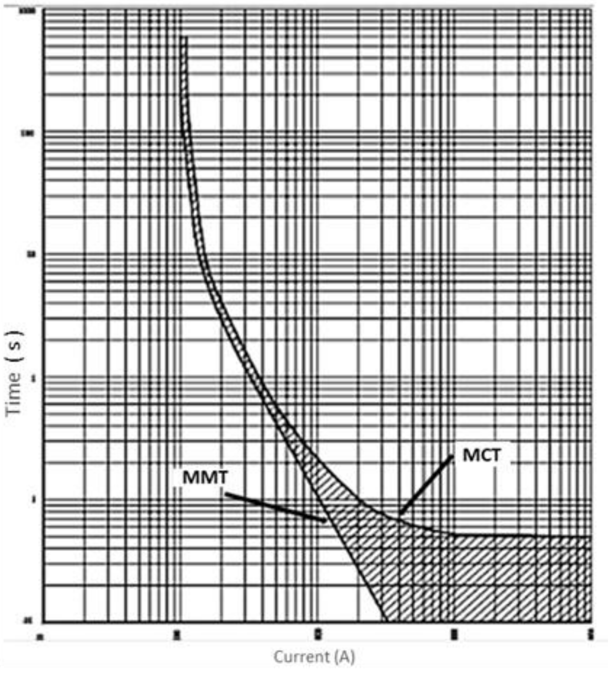


Figure 1. MMT and MCT operating characteristics for a fuse.

Due to their construction and operating characteristics, there is currently a wide variety of fuses, which, depending on the application, satisfy the established technical requirements to a greater or lesser extent.

Expulsion Fuses

The operating principle of the expulsion type fuse is as follows: it is held under mechanical tension by a spring inside a tube of organic material with a gas-producing material as a coating. The spring tension is maintained by means of a high-strength and resistivity tension wire. When a fault occurs the fuse element melts, transferring current to the tension wire which immediately melts, releasing the main spring and the small initial arc is rapidly lengthened by the retraction of the spring. The arc is extinguished by the expulsion effect of the gases released by the walls of the fuse tube, which has a deionizing fiber that produces a gas that insulates the arc.

Time-Current Curves

The curves are determined experimentally as follows: the minimum melting time curve is the mean melting curve minus the manufacturer's tolerance which is approximately 10% with positive variations. The total interruption time is that of the mean melting curve plus the manufacturer's tolerance plus the arcing time, with variations in the negative direction.

All curves are made with a test temperature of 25° C without any pre-load and manufacturers are obliged to supply both sets of curves. Fuses are divided into two basic types: Type "K" for fast characteristics and type "T" for slow characteristics. For this type of fuse elements, ANSI C37, 43 standards define the following operating characteristics:

- **K" and "T" types**. These correspond to fast and slow types respectively. For the operating characteristics of these fuses, three points corresponding to times of 0.1, 10 and 300 s are defined. Additionally, it is standardized that these fuses can carry 150% of their nominal capacity continuously for tin fuses and 100% for silver fuses.

The data to plot the curves are collected visually, taking as reference the interruption times versus the fuse current. The data is obtained by sight, and it is considered that these have errors of appreciation. The variations of these errors can be minimal, but they should not be overlooked, so the numerical method of *least squares* is used to fit the curves and minimize the errors, thus obtaining the optimization of the curves for successful modeling.

III. LEAST SQUARES METHOD

The Least Squares Method is a numerical analysis procedure or technique in which, given a set of data or ordered pairs, the function that best approximates the collected data is determined. Basically, this technique seeks to minimize the sum of the squares of the errors o residuals between the measured "*y*" and the "*y*" calculated with the model. It consists of approximating to a line or curve the points considered to have a certain error, determined by the coordinates (x_i, y_i), which correspond to experimental samples.

The application of this method is practical and by carrying out a polynomial regression of *m* degree, the data can be adjusted to curves that represent the general trend and behavior of the data. An example of how this method fits a curve to a series of data that have a non-linear behavior, is shown in figure 2. In this work the numerical method was applied by adjusting the data to second- and third-degree polynomials.

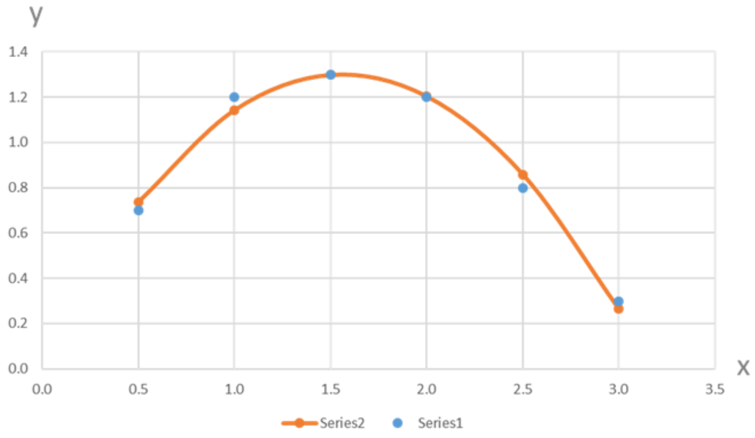


Figure 2. Least squares method with quadratic regression.

IV. APPLIED METHODOLOGY FOR CURVE MODELING

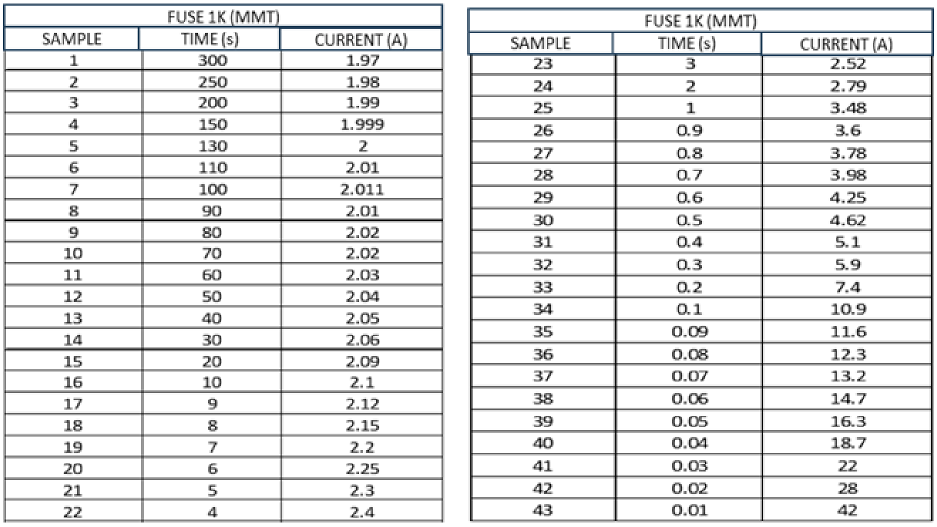
The process starts with the graphical definition of the curve, which is carried out using reference [2] in a visual manner, taking the time-current relationship. The data are collected from the family of K-type fuses, from which the minimum melting times are taken. For curve fitting, the least squares regression method is used. The results of the tests of the MMT curve of the 1K fuse are analyzed to validate the developed methodology. This fuse is used as a general example since the behavior of most of the curves is similar and it could be used to obtain and optimize curves for other types of fuses.

The methodology used is based on segmentation and the number of samples, since having a larger number of samples increases the accuracy of the calculation and facilitates the modeling of the curves. It is important to mention that to achieve the continuous modeling of the graph, it was necessary to consider that the last value of each segment must be the first value of the following segment and each of these segments must have the same number of samples, therefore, the number of segments is conditioned by the number of samples. For the tests, the data observed in Table 1 are used, which corresponds to the MMT curve of the 1K fuse with 43 samples.

V. RESULTS

The graphs resulting from the tests show the modeled curve and the effectiveness of the method in each of them. The tests were performed with 43 samples with different numbers of segments in order to obtain a better approximation of the curve. It is important to mention that tests were performed with different numbers of samples, however, the results of the tests with 43 samples are shown since from this number satisfactory results are obtained. The most significant test cases are shown with *1, 3, 7 and 14 segments*. The 43 visually taken samples of the MMT operating curve of the 1K fuse can be seen in Table 1.

Table 1. Fuse data 1K (MMT) with 43 samples [2].



FUSE 1K (MMT)		
SAMPLE	TIME (s)	CURRENT (A)
1	300	1.97
2	250	1.98
3	200	1.99
4	150	1.999
5	130	2
6	110	2.01
7	100	2.011
8	90	2.01
9	80	2.02
10	70	2.02
11	60	2.03
12	50	2.04
13	40	2.05
14	30	2.06
15	20	2.09
16	10	2.1
17	9	2.12
18	8	2.15
19	7	2.2
20	6	2.25
21	5	2.3
22	4	2.4
23	3	2.52
24	2	2.79
25	1	3.48
26	0.9	3.6
27	0.8	3.78
28	0.7	3.98
29	0.6	4.25
30	0.5	4.62
31	0.4	5.1
32	0.3	5.9
33	0.2	7.4
34	0.1	10.9
35	0.09	11.6
36	0.08	12.3
37	0.07	13.2
38	0.06	14.7
39	0.05	16.3
40	0.04	18.7
41	0.03	22
42	0.02	28
43	0.01	42

- **With 1 segment**

The result of plotting a single segment of the 43 data pairs is shown in Figure 3. However, the behavior of the modeled curve is not useful because the curve fitting is not done properly; the relative errors in most samples are large, with a percentage of 220% and an average of 92.2% being the most critical. It is observed that the modeled curve does not fit the points and does not converge in one interval of the curve.

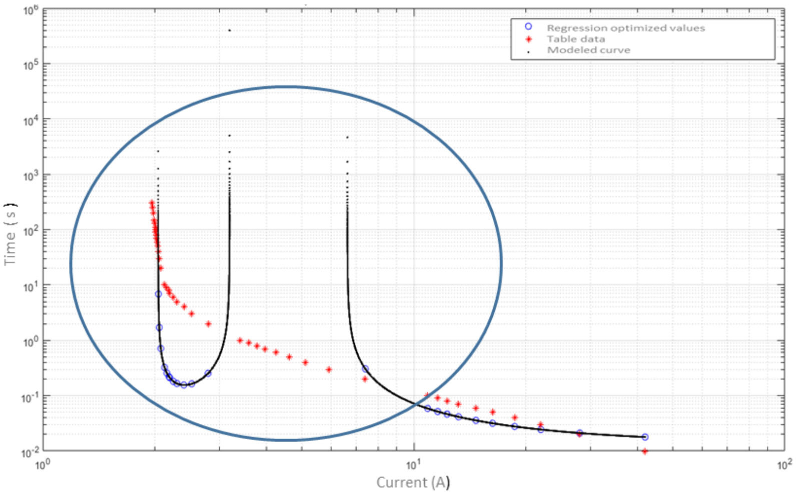


Figure 3. Modeling the 1K-MMT Fuse Curve 43 data with a segment.

• With 3 segments

The test is performed with three segments as shown in Figure 4. The first and second segments tend to fit the behavior of the collected data. However, in the third segment it can be observed that the results are not satisfactory, that is, the method in the third segment does not converge. Given these circumstances, other tests are performed with a larger number of segments.

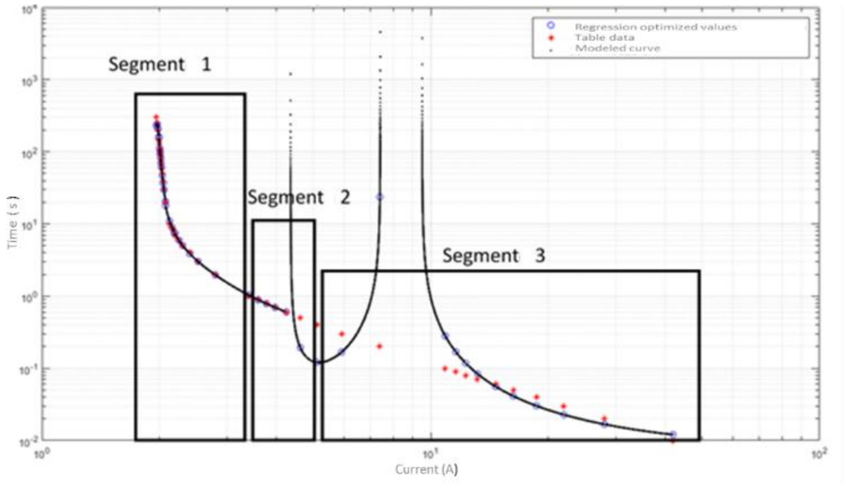


Figure 4. Modeling the 1K-MMT Fuse Curve 43 data with 3 segments.

• With 7 segments

In Figure 5 the results are more satisfactory, the curve adjustment to the data is much better and there is convergence in all segments. However, when the relative error is checked, there are values of up to 7%, which is still considered large. The objective is to bring these errors as close to zero as possible. Therefore, the number of segments continues to increase.

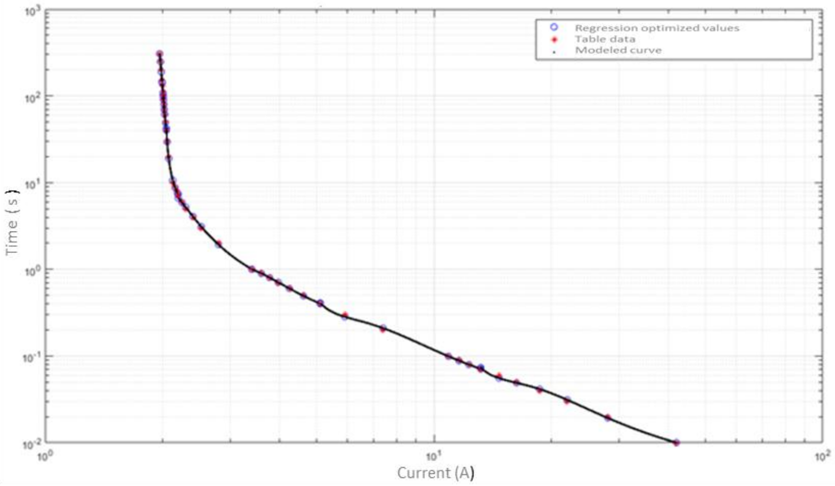


Figure 5. Modeling the 1K-MMT Fuse Curve 43 data with 7 segments.

- **With 14 segments**

In the test with 14 segments, shown in Figure 6, the curve fits the samples or data better, which means that the optimal curve is obtained and that the errors in the samples taken visually are being minimized, which clearly exceeds the previous tests. Finally, it can be said that the number of samples determines the number of possible segments in which the computational tool is able to model the complete curve. Likewise, the number of samples is essential to obtain better results with the applied numerical method and to obtain the inverse time curves of the fuses.

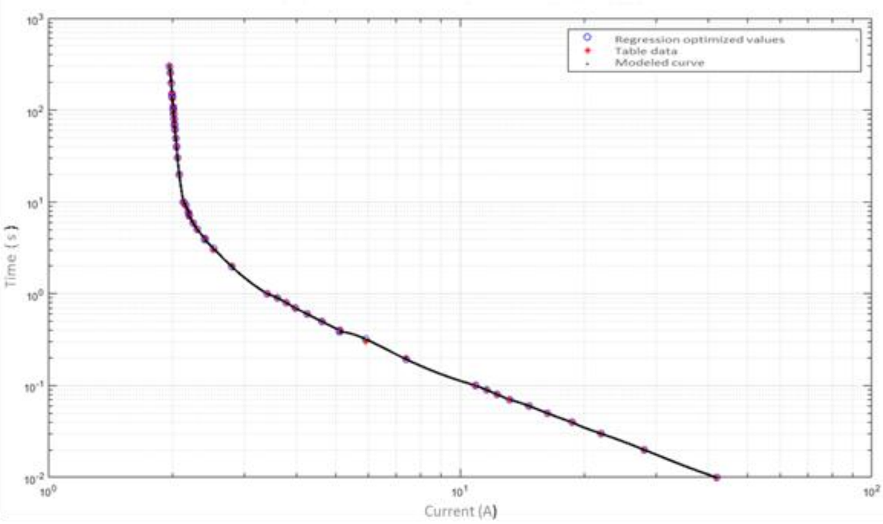


Figure 6. Modeling the 1K-MMT Fuse Curve 43 data with 14 segments.

VI. CONCLUSIONS

From the tests carried out in this work it was possible to see that the optimization of the curve modeling is achieved from 14 segments, with a second-degree polynomial in each of them except in segments 11 and 14 where a third-degree polynomial is used, in this way the relative percentage errors of each pair of data (time-current) are less than 5%.

The number of data collected is adequate, since with a smaller number of data, another number of segments is required, and the curve modeling would be incomplete. Another option may be to increase the number of samples or data obtained to have a better-defined curve with fewer errors.

This curve modeling facilitates obtaining the operating time of type K fuses for a given current; thus, the calculation of protection coordination can be developed, reducing errors. In addition, it allows protection coordination to be carried out in less time, minimizing errors and making possible the adequate simulation of said protection elements.

The numerical method of least squares is efficient in minimizing errors that arise due to the visual collection of data, if the curve is divided into a certain number of segments. It was found that increasing the number of segments improves the reliability of the method.

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