Abstract—This paper deals with a threshold setting approach based on Otsu’s image thresholding applicable in different protections. Threshold setting is one of the most important steps in systems protection, which is usually handled using the trial and error method. Although there are many threshold setting techniques suggested in different engineering fields, a vacancy is sensed in power systems protection in this regard. A developed version of Otsu’s image thresholding is suggested, which can be applied to values of a criterion in different scenarios. As a typical example, the level of the second harmonic is considered as the criterion for discriminating between internal faults and inrush current in a power transformer. Using the gathered data from an experimental test bench, the proposed methodology of threshold setting is presented in detail.

Keywords- Fault diagnosis; Otsu’s thresholding method; Power system protection; Power transformer; Threshold setting;

1. Introduction

In electrical power systems, various abnormal conditions appear in different locations and equipment. Power quality issues, transformer energization, and various types of faults in different devices are among these abnormal conditions. Discrimination between these phenomena and other similar normal conditions has been a great concern to ensure the reliability, sturdiness, and cost-effective performance of the systems. One of the most challenging steps for such discrimination is the selection of an optimal threshold for the considered criterion, used for distinguishing normal from abnormal cases. Although this is a common task in all of the diagnostic problems, it has been addressed only a few works regarding power system protection to the best of our knowledge.

In [1], an adaptive threshold setting has been proposed for voltage event classification. The utilized threshold setting has been adapted to the magnitude and phase variations of the voltages during the fault, which reduces the discrimination error. In [2], particle swarm optimization (PSO) has been employed for threshold setting in transmission line fault detection. First, random fault location and inception time are generated for the initial iteration of PSO and the optimal threshold is determined at the end of the final iteration. In [3], a randomized algorithm-based threshold-setting has been proposed for canonical correlation analysis-based fault detection in case of non-Gaussian cases. In [4], a dynamic thresholding technique has been proposed for fault detection aero-engine based on Isolation Forest. In this method, only normal data of aero-engine has been used for training of building the fault detection model.

In [5]–[8], a common threshold setting approach based on Otsu’s thresholding method has been reported. Otsu’s thresholding method is a well-established approach for threshold setting, which has been employed in image processing in special [9]. This method selects a threshold that minimizes the intra-class variance of the thresholded black and white pixels. However, in the proposed method of [5]–[8], the threshold setting is based on the Probability Function Density (PDF) of the data in the classes. In this method, a normal Gaussian distribution is assigned to data of each class, and the intersection of their PDF curves for the normal and abnormal cases is considered as the threshold value. The performance and basis of the method have not been fully addressed in these works.

In this paper, a novel thresholding method is proposed based on the principle of Otsu’s image threshold selection approach [9], called the Otsu-based thresholding (OBT) method. Despite the proposed method in [5]–[8], a reasonable link is provided between the conventional Otsu’s image thresholding approach and the proposed OBT method. A new development of Otsu’s image thresholding is proposed which can be applied to the criterion values in different classes of the diagnostic problems. In the OBT method, first, the desired criterion values are plotted as a scattered plot and a pixel is assigned to each value of the criterion. Then, each pixel is marked by a circle and colorized by a default colormap. Next,
by converting the resultant image into a 256-level grayscale image, Otsu’s thresholding method is applied to the image. Otsu’s method separates the image into two classes based on the color intensity of the existing pixels. An optimal threshold is derived by Otsu’s method, normalized in the range of [0, 1]. Finally, the threshold value is converted into the corresponding criterion value by interpolating the criterion values of the two adjacent points in the grayscale image. To evaluate the performance of the proposed method, a typical example for the separation of inrush current from internal fault current in a power transformer is considered. The well-known second harmonic level in the current signals is considered as the criterion of the problem. To this end, a dataset pool for the discrimination is gathered from a 6 kVA three-phase transformer including twenty inrush cases and thirty fault cases. Then, the criterion values of all cases are calculated and used as the input of the OBT method for finding the optimal threshold. The proposed method is described in detail for this example.

The rest of the paper is organized as follows. Section II explains the proposed OBT method. Otsu’s thresholding method as well as the procedures of the proposed threshold selection are discussed in this section, in detail. In Section III, the results of various scenarios of the considered example are presented and the threshold selection is discussed. Finally, the conclusion of the paper is presented in Section IV.

II. The Proposed Methodology

In this section, first, the basis of Otsu’s image thresholding method is presented. Then, the proposed methodology for the development of the conventional Otsu’s image thresholding method is presented.

A. Otsu’s thresholding method for images

Otsu’s method [9] is a statistical separation analysis, which distingush an image’s pixels into two classes with respect to their intensity values. Using the histogram of the image, an optimal threshold is derived between the separated classes, so that intra-class variance of the classes is maximized [10]. In this regard, we assume a gray-level digital image with a total number of n pixels, a total intensity level of I, and the nth intensity level has ni pixels in the image. The normalized histogram is derived so that,

\[ \sum_{i=0}^{I} p_i = 1, \; p_i \geq 0, \; p_i = n_i / n \]  

Now, suppose a threshold at \( i = T \) intensity level, which classifies the image into \( c_1 \) and \( c_2 \) classes. So, the probability \( P \) and the mean intensity value \( M \) corresponds to each class are derived as follows:

\[ w_{c_1} = P_{c_1} = \sum_{i=0}^{T} p_i = w(T) \]  
\[ w_{c_2} = P_{c_2} = \sum_{i=T+1}^{I} p_i = 1 - w(T) \]  

\[ M_{c_1} = \sum_{i=0}^{T} i P(c_i | i) = \sum_{i=0}^{T} iP(c_i) P(i) / P(c_i) \]  
\[ = \frac{1}{P_{c_1}} \sum_{i=0}^{T} i p_i = M(T) / w(T) \]  
\[ M_{c_2} = \sum_{i=T+1}^{I} i P(c_i | i) = \frac{1}{P_{c_2}} \sum_{i=T+1}^{I} i p_i \]  
\[ = \frac{1}{P_{c_2}} \sum_{i=T+1}^{I} i p_i = M_i - M(T) / (1 - w(T)) \]  

In (3) and (4), \( P(c_i | i) \) and \( P(c_i | i) \) are the probability of \( c_1 \) and \( c_2 \) given \( i \), respectively, and they are considered 1. Also, the terms \( P(i | c_1) \) and \( P(i | c_2) \) are the probability of the \( j \)th intensity level, as respects \( i \) comes from class \( c_1 \) and \( c_2 \), respectively. In these two equations, the Bayes’ formula \( P(X | Y) = P(Y | X) P(X) / P(Y) \) is used. \( P(i) \) is the \( j \)th component of the histogram \( p_i \) or the probability of \( j \)th intensity level. \( M_i \) and \( M(T) \) are the cumulative mean of the entire image, and the cumulative mean up to level \( T \), determined as:

\[ M_i = \sum_{i=0}^{I} i p_i \]  
\[ M(T) = \sum_{i=0}^{T} i p_i \]

The efficiency of the chosen threshold is assessed by a normalized value of class separability as:

\[ \lambda = \frac{\sigma_{s}^2}{\sigma_{i}^2} \]  
where \( \sigma_{s}^2 \) and \( \sigma_{i}^2 \) are the intra-class and total variances of the pixels in the image, respectively, calculated as:

\[ \sigma_{s}^2 = w_{c_1} (M_1 - M_i)^2 + w_{c_2} (M_2 - M_i)^2 \]  
\[ = w_{c_1} w_{c_2} (M_1 - M_2)^2 \]  
\[ \sigma_{i}^2 = \sum_{i=0}^{I} (i - M_i)^2 p_i \]  

According to the second line of (9), the value of \( \sigma_{s}^2 \) is relative to the distance between the two means \( M_1 \) and \( M_2 \). This suggests that the intra-class variance can be a degree of separability between classes. Therefore, an optimal threshold \( T_{opt} \) can be determined in which \( \sigma_{s}^2 \) will be maximized. This threshold splits the classes the best and is obtained as:

\[ \sigma_{s}^2(T_{opt}) = \max_{0<T<1} \left( \frac{\sigma_{s}^2}{\sigma_{i}^2} \right) \]  

B. The proposed OBT method for criterion values

A flowchart of the governed algorithm on the proposed OBT method is presented in Fig. 1. First, the gathered criterion values are plotted as a scattered plot. Then, each
pixel is shown by a circular marker and colorized based on their magnitude using a default color-map. Now, the resultant image is converted into a gray-level image with $2^8 = 256$ color levels. Next, Otsu’s thresholding method for images is employed and among the possible thresholds in the 256 levels, the color level which satisfies (11) is selected as the optimal threshold. The determined threshold color level should be converted to a value for the criterion. Since there are only color levels equal to the number of pixels (criterion values) in the figure, the optimal threshold found by Otsu’s method may not be relevant to one of the existing pixels, necessarily. Hence, an interpolation may be required between the two adjacent existing color levels to the optimal threshold and their corresponding criterion values.

III. Results and discussion

In this section, the test bench description and different considered inrush and fault scenarios are presented. Then, the proposed OBT method procedures are explained and the results are discussed.

A. Test bench explanation:

The schematic of the employed test bench is presented in Fig. 2. The test bench includes a 6 kVA, 50 Hz, and 330 V/330 V three-phase transformer, which provides the access to different points of each phase’s winding in the primary and secondary sides. Two contactors with stop-start buttons were used to enable both inrush and internal fault cases. Three clamp current sensors were utilized to measure the three-phase currents.

![Figure 2. Experimental test bench](image)

![Figure 1. The flowchart of the proposed OBT method](image)

![Figure 1. The flowchart of the proposed OBT method](image)

![Figure 3. Criterion values for all of the scenarios](image)
B. Scenarios:
Different experiments have been carried out in form of different possible scenarios, including various levels of internal faults for each phase, and the inception time of the energization. For internal fault cases, ten different levels of internal faults are considered for each phase, including 1% to 10%.

C. Threshold setting using the proposed OBT method:
After deriving the results of various scenarios experimented by the test bench, magnitudes of the second-order harmonic of the three-phase currents are determined. These values are normalized with respect to the magnitude of the fundamental component to be used as the criterion for discriminating between inrush and integral fault currents. Values of the criterion of the considered scenarios are shown in Fig. 3, for inrush and internal fault cases in red and blue, respectively. Now, these criterion values are plotted as a scatter plot, shown in Fig. 4. In this figure, locations of the considered points for the threshold settings are depicted. As observed, the threshold level should be determined between the pixels 1 and 21 shown in this figure. In the next step, a solid circular marker with the minimum size is assigned to each pixel. Here, for better visualization of the presentation, the size of the circles is considered 100, as shown in Fig. 5. Then, these circles are colorized using a default color-map, called Parula. It is worth mentioning that since the proposed OBT method is quite influenced by every color that exists in the image, the border and the background of the resulting figure should be completely removed. Next, this figure is converted to a gray-level image with 256 color levels. To do so, first, the image is saved as a plain format image (.pgm). Then, this figure is read using imread command as a gray-level image, shown in Fig. 6. It can be seen that the colored circles of Fig. 5 are normalized to 0-255 indices in Fig 6. The highest and lowest indices are assigned to the white and black colors, respectively. But, since there are only 50 pixels in the image, only some of the indices between 0-255 exist in the figure.

Now, by applying Otsu’s method using the global image threshold command (graythresh), the threshold is derived 0.7725. This threshold value is normalized from the 256-gray-level image to the range of [0, 1]. So, it corresponds to a color level as 0.7725×256 = 197.76. This implies that all pixels with color levels below 197.76 are classified as the foreground and the pixels with color levels higher than 197.76 are classified as the background class. As observed in Fig 6., the index 197.76 is located between the 1st and 21th pixels with indices 191 and 205, respectively. Therefore, to derive the exact threshold value of the criterion, an
interpolation between the index values and the corresponding criterion values is required. By interpolating the criterion values of these pixels, the final threshold value is calculated as 0.0755, marked with the dashed line in red in Fig. 6. Finally, the binary image considering this threshold is presented in Fig. 7. In this figure, the foreground class is shown as black pixels and the background class is shown as white pixels.

I. Conclusion

In this paper, a development of Otsu’s image thresholding method was proposed, which can be applied to criterion values of different diagnosis problems. The effectiveness of the proposed OBT method was assessed and discussed considering a typical example for separating internal fault currents from inrush currents in a three-phase transformer. It was shown that this method can be easily adapted to all of the threshold setting problems in power system protection.

References


