Detection of Power Disturbances using Mathematical Morphology on Small Data Windows

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***Abstract*—This paper presents a new method for detecting power disturbances in power distribution systems. The proposed method is based on Mathematical Morphology and operates by initially converting the vector signal into a matrix. The mean value of each row of the new matrix is calculated and then compared with the mean value of the normal signal in order to find the time location of any disturbances. The higher mean value of each row indicates the time location of any disturbances. This strategy has been simulated using Matlab for sag, swell, and voltage interruption. The results show immediate detection when any of the three disturbances occurred.**

***Index Terms*—Boundary extraction, dilation, disturbances, erosion, Mathematical Morphology, power quality.**

I. Introduction

In power systems, maintaining good power quality is of critical importance as poor quality power can lead to system instability and also damage equipment connected to the system. The rapid detection and identification of any disturbances in the system such as, voltage dip, interruption, voltage swell, or oscillatory transients, is essential as it allows appropriate protection or compensation methods to be activated which can prevent damage to equipment connected to the system. Some strategies have been applied for detecting and locating power disturbances, such as the wavelet transform [1], [2], embedding strategy [3], TT-transform [4], or pattern recognition classifiers based on a neural network [5].

In this paper, a new strategy in disturbances detection is proposed using a vector to matrix conversion with MM on a small window size. The mean value of each row of the new matrix is then calculated and compared with the mean of the normal signal in order to find the time location of the disturbances. The higher mean value of each row indicates the time location of any disturbances. By using only 4 data samples, the detection process is fast and can be applied as a real time detection method.

II. Proposed Method

The timing of power disturbances in power systems can be detected using the proposed strategy based on MM. The idea behind this strategy is the conversion of a signal to an image and then applying image processing strategies for detecting the disturbances. The signal is initially filtered using a Morphology Filter before conversion to a signal/image matrix. The location of the disturbances can be detected by comparing the mean value of each row of the matrix with the mean value of the normal signal. By choosing only 4 samples from 128 samples per cycle (for a 6.4 kHz sampling frequency) the window size of the detection becomes smaller and is about 1/32 cycle for a 50 Hz power system. Mathematical morphology is used in this strategy which has the advantages of high speed calculations and excellent denoising performance [6]. This means that this strategy can be used for real time disturbance detection.

A. Basic Pronciples of Mathematical Morphology

Assuming A is the input set and B is the structuring element, dilation can be defined as:

$$\delta_B(A) = A \oplus B = \bigcup_{b \in \tilde{B}} (A + b) \tag{1}$$

Dilation is also known as *Minkowski addition*. The effect of dilation is increasing the size of an object.

The erosion of A by B is related to *Minkowski subtraction*. Erosion is defined as:

$$\varepsilon_B(A) = A \ominus B = \bigcap_{b \in B} (A - b) \tag{2}$$

The effect of erosion is the shrinking of an object.

Using combinations of the dilation and erosion operators, the opening and closing operators can be defined. The opening operation can be defined as:

$$A \circ B = (A \ominus B) \oplus B. \tag{3}$$

and the closing operation as:

$$A \bullet B = (A \oplus B) \ominus B. \tag{4}$$

B. Morphological Filter

The input signal needs to be filtered to reduce any noise in the signal. To achieve this, a morphology filter is applied. This filter is a combination of an Open-Closing Filter (OCF) for

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filtering salt noises in signal with impulse noise and a Close-Opening Filter (COF) for filtering peppers noises [7]. Opening suppresses the positive noise impulses, and closing suppresses the negative noise impulses. For the $f(x)$ as a function of the signal, the morphological filter can be denoted as follows:

$$\psi(f) = [OCF(f) + COF(f)]/2 \tag{5}$$

where:

$$OCF(f) = (f \circ b_1) \bullet b_2 \tag{6}$$

$$COF(f) = (f \bullet b_1) \circ b_2 \tag{7}$$

where b_1 and b_2 are structuring element 1 and 2 respectively.

C. Matrix Distribution

1) Vector to Matrix Conversion.: A one-dimensional discrete-time signal is typically represented by an array as a row vector. This function is a row vector, with a $(1 \times n)$ matrix or a horizontal arrangement of numbers. It is also denoted by the vector symbol as follows

$$\mathbf{y} = [y_{1j}]_{j=1,\ldots,n} = [y_{11}\ y_{12}\ \ldots\ y_{1n}] \tag{8}$$

In the proposed method, this row vector is then distributed to a general $(m \times n)$ matrix, and is denoted by the matrix symbol $A = [a_{i,j}]_{i=1,\ldots,m;\ j=1,\ldots,n}$ or

$$A_{m,n} = \begin{pmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,n} \\ a_{2,1} & a_{2,2} & \cdots & a_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m,1} & a_{m,2} & \cdots & a_{m,n} \end{pmatrix} \tag{9}$$

This arrangement is typically used for two-dimensional discrete-time signals or images.

The strategy to make a $(m_0 \times n_0)$ matrix can be described as follows:

First, the length of the matrix should be set as the number of columns of the input vector. The number of columns should be twice the maximum value of the disturbances signal that will be encountered. For handling voltage of disturbances to +-511 volts, the number of columns of the matrix is 1024 using integer values. In practice, this could be data acquired using a 10 bit or greater analog to digital converter. Therefore the range of the voltages will be from -512 to +511 volts.

The number of columns of the vector (n) will be converted to be the number of rows (m_0) of the matrix. In this example, the number of data that will be used is 4, so m_0 is 4.

All values of the signal as a vector $y = [y_{1j}]$ will be rounded as a new vector $y_r = [y_{1k}]$. By matrix distribution, the signal $[y_{1k}]$ will become $[a_{k,n}]$, where $n = C_t + [y_{1k}]$. C_t is the center of the width of the column while $[y_{1k}]$ is a value of each element of the vector. The new matrix can be denoted as follows:

$$A_{(m_0,n_0)} = A_{(4,1024)} = \begin{pmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,1024} \\ a_{2,1} & a_{2,2} & \cdots & a_{2,1024} \\ \vdots & \vdots & \ddots & \vdots \\ a_{4,1} & a_{4,2} & \cdots & a_{4,1024} \end{pmatrix} \tag{10}$$

The starting point of the matrix is located in the first row and in the center of the length of column $(C_t = n/2)$ of the matrix. So, the coordinate of (0,0) will be (a_{1,C_t}) in this matrix. The number of columns of the matrix (n_0) is 1024, then C_t will be 512, as a result, the coordinate of (0,0) will be $(a_{1,512})$.

In this proposed strategy, the value of the signal is converted to **1** as a *white color* in the image matrix while **0** represents a *black* one using this condition:

$$A_{0(m_0,n_0)} = \begin{cases} 1 & \text{for} \quad n = C_t + y_{1k} \\ 0 & \text{for} \quad else \end{cases} \tag{11}$$

where:
y_{1k} = value of the vector after rounding process
$C_t = n/2 = 512$, center column of the matrix
So each element of matrix can be written as:

$$a_{k,n} = a_{k,C_t+(y_{1k})} = 1 \tag{12}$$

Samples that will be used for the looping process s_j from n_i to $\{n_i + 3\}$ can be denoted as follows:

$$s_j = n_i \cdots (n_i + 3) \tag{13}$$

where $i = 3_j - 2$, and $j = 1, 2, ..., (\frac{l}{3} - 3)$ where l is the total number of samples in the signal.

2) Adding Connectivity Points.: Matrix A_0 that is the result from the previous step should be modified to make the points have a connection with each other. Therefore points need to be added to the matrix as follows:

$$A_{1(m_0,n_0)} = 1 \quad \text{from} \quad m_0 = C_t \quad \text{to} \quad m_0 = C_t + y_{1n} \tag{14}$$

3) Boundary Extraction.: After adding connectivity points to the matrix, boundary extraction , ∂A_1,is then applied as follows [8]:

$$\partial(A_1) = A_1 - (A_1 \ominus SE) \tag{15}$$

where SE = Structuring element.

Using this method, where the SE is a flat structuring element, matrix A_1 is transformed to matrix A_2.

4) Points deletion.: After boundary extraction, matrix A_2 still has some points in the center of the matrix that are not representing the values of the signal. To eliminate them, the following formula can be applied:

$$A_{2(N,C_t)} = 0 \tag{16}$$

where N = 1,2,3,4.

5) Double dilation and double erosion.: By deleting axis points, some points that are a representation of the value of the signal will be lost. In order to fix this problem, dilation is applied twice and then followed by the application of erosion twice which can be denoted using this equation:

$$A_3 = ((((A_2 \oplus SE) \oplus SE) \ominus SE) \ominus SE) \tag{17}$$

III. Detecting Time Location of Disturbances

In order to detect the location of the disturbances, the mean value ($\bar{x}$) of each row should be found. In this strategy, the mean value of the signal will be calculated using this formula as follows:

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{18}$$

where x_i is a value of each component of the matrix, and n is the number of columns of the matrix.

The first matrix has one point for every value of the signal that has been converted to a value of 1. The flow of the signal has been changed as a matrix that it goes from up to down, so the mean of every row of the matrix can be calculated. When a disturbance occurs, a sudden change of waveform will happen in the signal. By transforming the matrix, it will be identified as a different gap from another row. Additional points will be added for these gaps, and as a result, the mean of that row becomes higher than the other points. By comparing the mean value of this matrix ($\bar{x}_m$) to the mean value of the normal signal ($\bar{x}_0$), the time location(T_L) of the disturbances can be detected.

$$\mathrm{T}_L = \bar{x}_m > \bar{x}_0 \tag{19}$$

For a noise-free signal, the mean value will be 0.0107 for every row of the matrix. When the signal is contaminated with noise with a SNR at 30dB, the mean value will be higher. After some experiments to determine the optimum filtering process, the mean value of this signal in the matrix is 0.03024. So, the location of the disturbance can be detected when $\bar{x}_m > 0.03024$ for the signal with SNR at more than 30dB.

IV. Simulations and Results

A. Simulations

Simulations of this proposed strategy were undertaken using Matlab. The input signals contained 3 types of disturbances: voltage sags, swell, and voltage interruption (Fig.1). The first condition of the simulation is for signals without noise, and then continued for the signals contain noise by adding Additive White-Gaussian Noise (AWGN) with a SNR (Signal to Noise Ratio) at 30 dB. The value of C_t was set to 512, so n_0 becomes 1024, with a sampling frequency of 6.4 kHz, the size of the window is 1/32 cycle with 4 samples in every looping detection process.

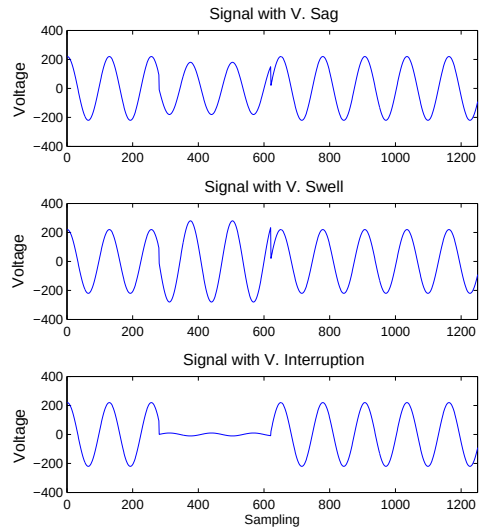

Fig. 1. Signals with voltage sag, swell, and interruption

B. Results

After applying the strategy proposed in this paper the detected time location of the disturbances can be seen in Fig.2. Table I also shows the detection results for all three types of disturbances using the different structuring elements (b_1 and b_2).

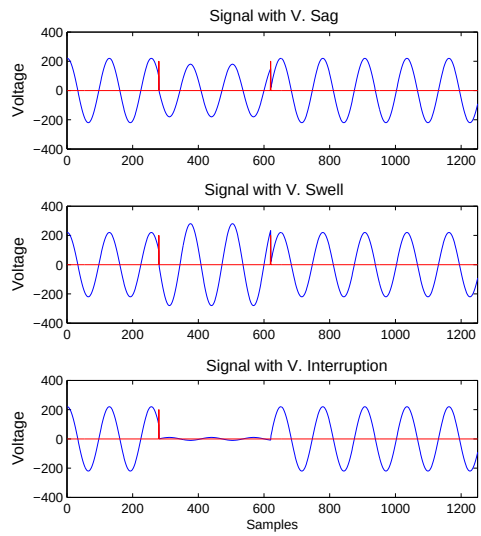

Fig. 2. Detection results

For the different types and radiuses of the structuring elements in the filtering step, the results varied. The best result for disturbances detection can be found using structuring element diamond with size 1. This proposed strategy successfully detects the beginning and end of the voltage sag and swell accurately for both noise-free signals and signals contaminated

TABLE I
SIMULATION RESULTS

PQ Events		Voltge Sag		Voltage Swell		V. Interruption	
		start	end	start	end	start	end
Actual Position		280	620	280	620	280	620
Results for different Structuring Element							
b_1= $\odot$, 1	n-f	280	620	280	620	280	620
b_2= $\odot$, 1	n-n	280	620	x	x	x	x
b_1= $\odot$, 1	n-f	280	620	280	620	280	-
b_2= $\odot$, 2	n-n	280	x	x	x	280	x
b_1= $\odot$, 2	n-f	280	620	280	620	280	-
b_2= $\odot$, 1	n-n	280	x	x	x	280	620
b_1= $\odot$, 2	n-f	280	-	280	620	280	620
b_2= $\odot$, 2	n-n	280	-	x	x	280	620
b_1= $\diamond$, 1	n-f	280	620	280	620	280	-
b_2= $\diamond$, 1	n-n	280	620	280	620	280	-
b_1= $\diamond$, 1	n-f	280	620	280	620	-	-
b_2= $\diamond$, 2	n-n	x	x	x	x	280	x
b_1= $\diamond$, 2	n-f	280	620	280	620	280	-
b_2= $\diamond$, 1	n-n	280	620	x	x	280	620
b_1= $\diamond$, 2	n-f	280	-	280	620	280	-
b_2= $\diamond$, 2	n-n	280	-	x	x	x	x
Note: - = no result found. x = some points are detected including actual points. n-f = noise free signal, n-n = noise $\odot$ = disk; $\diamond$ = diamond							

with contain noise. For the voltage interruption, the starting point of disturbance can be detected accurately by this strategy, but not for finding the end point. This is because the type and length of the structuring element deletes the important part of the signal for locating the ending of this disturbance. This is can be seen in the Table I, when the disk SE rather than the diamond SE can detect this type of disturbance, although the disk SE does not generate the best results for overall performances.

The results of this strategy for detecting time location of the disturbances compared with different methods can be seen in Table II. This table shows that Wavelet method has an error for detecting both the starting and end points of the disturbances. Morphology Edge Detection [9] has also has some errors in the detection of disturbances with an average error of half the sampling frequency. Skeletonization [10] accurately found the time location of the start of the disturbances. The only error being in finding the end point of the voltage interruption. The proposed method also has accurate results for sag and swell detection. For interruption detection, by using diamond type with radius 1 for both SE in the filtering process, this method can detect the starting point of interruption but is unsuccessful at detecting the end point. The Skeletonization method has a better result for detection, but it needs a bigger size of the window (1/2 cycle with 64 samples) while the proposed method just needs 1/32 cycle of a window size or 4 samples only.

V. CONCLUSION

The proposed strategy in detecting the times of power quality disturbances is based on a signal to image matrix conversion. By converting the signal to an image, the detection process is able to use image processing methods. In the proposed method, the disturbance detection is performed using the mean value of each row of the matrix. Only a small data samples of the signal (4 samples) are needed and it makes the size of the window small (1/32 cycle). In addition, by using mathematical morphology that has an excellent speed for calculation, this method can be implemented as a real time detection strategy.

The results show the ability of this strategy in detecting disturbances, especially for swell and sag. For the voltage interruption, the starting point can be found accurately while the end point cannot be determined. For this purpose, it is essential to choose the parameter value and type of structuring element accurately based on the type of disturbance. This strategy has an improvement compared to the Wavelet method or Morphology edge detection strategy.

TABLE II
COMPARISON RESULTS WITH OTHER METHODS IN TIME DOMAIN

Disturbances	Sag		Swell		Interruption	
	start	end	start	end	start	end
Actual Location	280	620	280	620	280	620
Detect. Result	280	620	280	620	280	-
Error for:						
Proposed Method	0	0	0	0	0	-
$Wavelet_{[8]}$	1	1	1	1	1	1
$Morph.Edge_{[8]}$	0.5	0.5	0	1	0	1
$Skeletonization_{[10]}$	0	0	0	0	0	1

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