Switch On-off Automatic Detection Technology Based on Basic Model of Waveform Singularity Detection

Jinzhou Su
Fujian Police College, Fuzhou, Fujian 350007, China
350628578@qq.com

Abstract. During the test of low-voltage switches, numerous waveforms are required to be collected and electrical parameters calculated. Traditional detection methods are inefficient and may result in operational errors. Since the sequencing of the test waveform array is converted to corresponding time points by the sampling frequency conversion, to realize automatic positioning of the cursor in waveform and automatic measurement of the electrical parameters, the key lies in the accurate detection of the singular position in the waveform array. This paper builds the basic model of waveform singularity detection based on the singular value decomposition (SVD) algorithm, integrates automatic detection into the electrical parameter test module, realizing the automatic detection of waveforms and parameters during the low-voltage appliance test. Meanwhile, starting from the automatic detection of the conduction time of the same test current when the alternating current contactor is switched on and off, the anti-interference ability of the model under different types of noise and different noise intensities are tested and analyzed. For all types of noise, reliable, uncertain, and unreliable detection zones exist in the automated detection results. When \( k \) (effective value of the noise / effective value of original waveform) is less than 10\%, all types of noise can be detected in a reliable manner, which effectively J. van der Geer, J.A.J. Hanraads, R.A. Lupton, The art of writing a scientific article, J. Sci. Commun. 163 (2000) 51-59.

1. Introduction
During the test of low-voltage switches, numerous waveforms are required to be collected and electrical parameters calculated. If the positioning calculation is conducted by manually dragging the cursor on each test waveform, instead of by analysing automatically and accurately these waveform parameters, the detection efficiency will turn out to be low, and may also result in operational errors. Since the sequencing of the test waveform array is converted to corresponding time points by the sampling frequency conversion, to realize automatic positioning of the cursor in waveform and automatic measurement of the electrical parameters, the key lies in the accurate detection of the singular position in the waveform array. Because of its unique spatial locality, wavelet transform can effectively detect signal singularity and singular point position, which enjoys a wide application [1-2]. The singular value decomposition (SVD) signal processing method under the Hankel matrix can also detect the singularity of signal, and each component has an incremental vanishing moment. For example, the \( P \) signal component has \( \rho^{-1} \) vanishing moments, which can detect the singular point of
Lip index $a = p - 2$. The SVD algorithm has a better performance than the wavelet transform in some aspects. Therefore, in this paper, based on the SVD algorithm, the basic model of waveform singularity detection is created, and the automatic detection is integrated into the electrical parameter test module to realize the automatic detection of waveforms and parameters during the low-voltage appliance test. It is also possible to realize the real-time monitoring and alarm function of the test process by setting the threshold value of each electrical parameter, thereby improving the detection method of the low-voltage electrical appliance, and elevating the detection efficiency.

2. Basic model of waveform singularity detection

SVD can be considered as a numerical calculation method because of its unique properties and characteristics, which enjoys extensive application in the fields of signal processing analysis, control theory research and digital watermarking technology [3-7]. If there is a signal sequence $X = \{x(1), x(2), \ldots, x(N)\}$, and the sampling interval is equal, the $m \times n$ matrix that can be composed of this sequence is shown below:

$$A = \begin{bmatrix} x(1) & x(2) & \cdots & x(n) \\ x(2) & x(3) & \cdots & x(n+1) \\ \vdots & \vdots & \ddots & \vdots \\ x(m) & x(m+1) & \cdots & x(N) \end{bmatrix} \quad (1)$$

In the formula (1): $m \geq 2$, $n \geq 2$, and $m+n-1 = N$. The matrix $A \in \mathbb{R}^{m \times n}$ is called the Hankel matrix [8], then there are orthogonal matrix $U \in \mathbb{R}^{m \times m}$ and $V \in \mathbb{R}^{n \times n}$. Therefore, the matrix $A$ can be expressed by the following formula:

$$A = U S V^T = \sum_{i=1}^{p} A_i = \sum_{i=1}^{p} u_i \sigma_i v_i^T \quad (2)$$

In equation (2): $u_i$ and $v_i$ are the column vectors of the orthogonal matrix $U$ and $V$; $S = \text{diag}(\sigma_1, \sigma_2, \ldots, \sigma_p)$, $O$ or its transpose, $O$ refers to the zero matrix, and $\sigma_1 \geq \sigma_2 \geq \ldots \geq \sigma_p \geq 0$, then $\sigma_i$ ($i = 1, 2, \ldots, p$) is the singular value of the matrix $A$.

According to the characteristics of the Hankel matrix, if the matrix $A$ is to be restored back to $X$, it is only necessary to connect the row vector $H_1$ of the first row of $A$ to the transposition of the column vector $L_1$ of $A$ that removes the first row of the matrix $A'$, namely $X = [H_1^T \ L_1^T]$. Similarly, the row vector $H_{i,a}$ of $A_i$ connects the transpose of the column vector $L_{i,a}$ of $A_i'$ that $A_i$ removes the first row, and a component $X_i$ of $X$ can be obtained, that is $X_i = [H_{i,a}^T \ L_{i,a}^T]$. The signal sequence $X$ can be simply described as a linear superposition of all component signals $X_i$ obtained by SVD decomposition [9], which is shown as:

$$X = X_1 + X_2 + \cdots + X_p \quad (3)$$

It can be known from equation (3) that one of the component signals can be selected or several component signals can be superposed and then studied to obtain the required information.
Common waveforms of low-voltage appliance switching test can be classified into two basic waveform signals, one is a waveform signal $f_1(x)$ with a single wave, and the other is a waveform signal with variable frequency and amplitude. Take the sampling frequency $f_s = 5000\text{Hz}$ and collect 500 data (ie 100ms), then these two signals can be expressed by the following mathematical formulas:

$$f_1(x) = \begin{cases} 
0 & 0 < x \leq 200 \\
50\sin(2\pi x) & 200 < x \leq 250 \\
0 & 250 < x \leq 500 
\end{cases}$$

(4)

$$f_2(x) = \begin{cases} 
0 & 0 < x \leq 200 \\
20\sin(2\pi x)/x & 200 < x \leq 300 \\
0 & 300 < x \leq 500 
\end{cases}$$

(5)

In equation (4) and (5), the position of the sampling point is indicated as $x$.

Time domain waveforms of two basic signals $f_1(x)$ and $f_2(x)$ are obtained, as shown in Figure 1. Among them, (a) is waveform signal $f_1(x)$, and (b) is waveform signal $f_2(x)$.

![Waveform signal $f_1(x)$](image1)

(a) Waveform signal $f_1(x)$

![Waveform signal $f_2(x)$](image2)

(b) Waveform signal $f_2(x)$

**Figure 1.** Time domain of waveform $f_1(x)$ and $f_2(x)$.

It can be seen from Figure 1 that the characteristics of the starting and ending positions reflecting the fluctuation time in these two time domain waveforms are not significant. If the starting and ending time points are determined by setting threshold value to carry out comparison, it is likely to obtain different results, and may result in misjudgement by the interference of the signal, leading to measurement error.

It is found from the study that only the three components of the two basic time domain waveforms need to be decomposed to obtain the singular points of the starting and ending time. Therefore, the
number of columns $n$ of the Hankel matrix is set to 3, and the SVD decomposition is performed on $f_1(x)$ and $f_2(x)$, and the respective component signals $X_1, X_2, X_3$ are obtained, as shown in Figure 2.

Figure 2. Component signals of $f_1(x)$ and $f_2(x)$. 
It can be seen from Figure 2 that the component signal $X_1$ reflects the original size and shape of the waveform signal $f(x)$, so there is basically no sudden change; the component signal $X_2$ is suddenly changed at the singular point of the waveform, but the sudden change is not significant; and the component signal $X_3$ has two distinct pulses of the sudden change at the singular point of the waveform. Compared with the signal $f(x)$, it effectively indicates the starting and ending position of the waveform. Similarly, the component signals of $f_2(x)$ share similar characteristics.

Therefore, the pulse of sudden change of component signal $X_3$ can be used to realize the automatic detection of the singular position of waveform. The steps are as follows: first, the SVD algorithm is used to conduct singular value decomposition on the collected test waveform to obtain component signal $X_3$; second, by locating the time point when the extreme value occurs in the component signal $X_3$, the first sudden change moment $t_1$ and the second sudden change moment $t_2$, and the waveform duration $t = t_2 - t_1$ are obtained; The third step, through singular value positions of the test waveform corresponding to the time point $t_1$ and $t_2$, a program is generated to realize automatic positioning of the waveform cursor, as well as waveform analysis and automatic calculation of electrical parameters between cursors.

Based on the above calculation steps, this paper builds a basic model of waveform singularity detection based on SVD algorithm through the underlying program of the LabVIEW graphical programming software in the test system. The program is shown in Figure 3.

![Figure 3. Program diagram of the basic model of waveform singularity detection](image)

3. Realization of automatic detection of switching test
The basic model of waveform singularity detection built above is integrated into the electrical parameter test module to realize the automatic detection of the conduction time of the AC contactor during the switching on and off process. Two common test waveforms are collected to analyze the detection of the singular position of the waveform by this model and verify the accuracy of the test results.
3.1. Electrical parameter test module

The automatic detection is integrated into the electrical parameter test module to realize the automatic test of the relevant test waveform and electrical parameters of the low-voltage appliance electromagnetic mechanism and the contact system, as shown in Figure 2-6. Where:

The parameter setting enables intuitive and convenient setting of sampling and channel parameters, as shown in Figure 2-6(a). The name of each channel can be modified to make the meaning of each channel more intuitive. The input range of the capture card can be set to improve the sampling accuracy without exceeding the range. The current and voltage sampling signals are much smaller than the actual value. The value of the “integrator” in the interface can be set to restore the original signal size; through the waveform diagram at the bottom right of the interface, the pre-trigger position of the current sample can be visually displayed and set, and the trigger level is the percentage of the channel range, which can effectively avoid frequent modification of the trigger value when switching the trigger channel.

The measurement and analysis of single-phase, two-phase and three-phase waveforms are shown in Figures 4(b), (c) and (d). The program has functions of waveform continuous sampling and trigger sampling. It can be triggered when the waveform signal exceeds the boundary of the analog window, and collect the designated waveform signal segment. In addition, a manual trigger function is also added to the program, which can be used to collect signals that are stable within a relatively long period. The program has enriched waveform processing capabilities including software filtering to eliminate waveform signal noise, automatic cursor positioning, automatic calculation of parameters between cursors, and free scaling and movement of any area of the waveform, etc. It can automatically generate professional test reports based on test results.

![Figure 4. Part of software interface of the electrical parameter measurement module](image)
3.2. Verification of automatic detection

(1) In the first case, the current is the same when the switch is turned on and off in the test, as shown in the first waveform channel in Figure 5. Among them, $T_1$ is the contact current starting time and $T_2$ is the contact current ending (arc extinguishing) time, the conduction time is $(T_2 - T_1)$. The singular value decomposition of the contact current waveform is carried out to obtain component signal $X_3$, as shown in the second waveform channel in Figure 5.

![Figure 5. Automatic detection of conduction time when the switch-on and switch-off currents are the same](image)

It can be seen from Figure 5 that the component signal $X_3$ obtained by the SVD decomposition of the contact current waveform presents two significant pulses at the singular position of the waveform, and the waveform cursor 1 and the cursor 2 are automatically positioned to the starting and ending positions of the conduction time, and the conduction time is automatically calculated. The automatic detection result at the waveform sampling frequency of 100 kHz is compared with the actual value, as shown in Table 1. It can be seen that the maximum relative error of the automatic detection of the conduction time is 0.52%.

| Test Item     | Singular value detection | Actual value | Relative error (%) |
|---------------|--------------------------|--------------|--------------------|
|               | Sampling point           | Time (ms)    | Sampling point     | Time (ms) | (take absolute value) |
| $T_2$         | 35635                    | 356.35       | 35769              | 357.69    | 0.37                 |
| $T_1$         | 8003                     | 80.03        | 8045               | 80.45     | 0.52                 |
| $T_2 - T_1$   | 27632                    | 276.32       | 27724              | 277.24    | 0.33                 |

(2) In the second case, the currents are different when the switch is turned on and off in the test, as shown in the first waveform channel in Figure 6. $T_3$ is the starting time of the contact test current, $T_4$ is
the ending time of the contact test current, $T_5$ is the starting time of the contact breaking test current, and $T_6$ is the ending time of the contact breaking test current (arc extinguishing). Then, the duration of the contact test current is $(T_4 - T_5)$, the duration of the contact breaking test current is $(T_6 - T_5)$, the interval between the test current and the breaking test current is $(T_5 - T_4)$. The singular value decomposition of the contact current waveform is performed to obtain component signal $X_3$, as shown by the second waveform channel in Figure 6.

![Figure 6.](image)

**Figure 6.** Automatic detection of conduction time when the switch-on and switch-off currents are different

| Table 2. Comparison of test results and actual values in the second case |
|---------------------------------------------------------------|
| **Test Item** | **Singular value detection** | **Actual value** | **Relative error (%)** |
| | Sampling point | Time (ms) | Sampling point | Time (ms) | (take absolute value) |
| $T_6$ | 21517 | 215.17 | 21661 | 216.61 | 0.66 |
| $T_5$ | 13794 | 137.94 | 13882 | 138.82 | 0.63 |
| $T_4$ | 12622 | 126.22 | 12732 | 127.32 | 0.86 |
| $T_3$ | 6638 | 66.38 | 6696 | 66.96 | 0.87 |
| $T_4 - T_3$ | 5984 | 59.84 | 6036 | 60.36 | 0.86 |
| $T_6 - T_5$ | 7723 | 77.23 | 7779 | 77.79 | 0.72 |

Similarly, it can be seen from Figure 6 that the component signal $X_3$ obtained by the SVD decomposition of the contact current waveform exhibits four significant pulses at the singular position of the waveform, and the waveform cursor 1, cursor 2, cursor 3, and cursor 4 are automatically positioned to the starting and ending positions when the current is switched on and off in the test, and the conduction time is automatically calculated. The automatic detection result at the waveform sampling frequency of 100 kHz is compared with the actual value, as shown in Table 2. It can be seen that the maximum relative error of the automatic detection of the conduction time is 0.87%.
It can be seen from the above analysis that the relative error of the automatic detection result of the conduction time based on the waveform singularity detection basic model is less than 1% in the two different test cases of the AC contactor. In the same way, time parameters such as contact closure time, contact breaking time and arcing time are verified, and similar conclusions are obtained. Therefore, the test result satisfies the requirement that the low-voltage appliance standard should have a time measurement accuracy of less than 1%.

4. Anti-interference analysis on automatic detection

Various noises will normally exist in the test sites of low-voltage appliance, therefore, it is necessary to study the anti-interference ability of the basic model of waveform singular value detection. Based on the automatic detection of the conduction time when the switch-on and switch-off currents of AC contactor are the same, the anti-interference ability of the model under different types of the noise and different noise intensities is tested and analyzed.

4.1. Analysis of anti-interference ability of uniform white noise

White noise refers to noise with a uniform distribution of power spectral density over the entire frequency domain, or random noise with the same energy density at all frequencies [10]. By setting the value of $k$ (effective value of noise / effective value of original waveform), the current waveform is superposed with uniform white noise signals of different intensities, and then the component signal $X_3$ waveforms under different intensities of white noise are obtained by SVD singular value decomposition, as shown in Figure 7.

![Figure 7. Comparison of waveform singularity detection under different intensities of white noise](image)

It can be seen from Figure 7 that as the noise intensity increases, the clutter of the component signal $X_3$ increases, and the singular pulse of sudden change becomes less and less obvious. At $k = 14.45\%$, the pulse is almost annihilated by the clutter, and when $k = 18.0\%$, the pulse of sudden
change no longer appears. The pulse of sudden change can be detected normally at $k = 3.6\%$ and $k = 7.2\%$.

4.2. Analysis of anti-interference ability of other types of noise

Similarly, statistics of automatic detection of contact current waveforms superposed with other types of noise, including Gaussian white noise, periodic random noise, Poisson noise, Gamma noise, Bernoulli noise, binomial distribution noise, etc. (each is tested for 10 times) are shown in Table 3.

| Type of noise signal             | Reliable | Uncertain | Unreliable |
|----------------------------------|----------|-----------|------------|
| Uniform white noise              | ≤13      | 13~18     | ≥18        |
| Gaussian white noise             | ≤10      | 10~15     | ≥15        |
| Periodic random noise            | ≤11      | 11~20     | ≥20        |
| Poisson noise                    | ≤15      | 15~20     | ≥20        |
| Gamma noise                      | ≤15      | 15~21     | ≥21        |
| Bernoulli noise                  | ≤16      | 16~21     | ≥21        |
| Binomial distribution noise      | ≤16      | 16~22     | ≥22        |

It can be seen from Table 3 that for various types of noise, automatic detection results exist in the reliable, uncertain and unreliable detection areas. When $k$ is less than 10\% (the noise of low-voltage appliance tests is generally less than this value), all types of noise can be detected in a reliable manner. Therefore, the basic model of waveform singularity detection based on SVD algorithm has satisfactory anti-noise signal interference capability.

5. Conclusion

This paper builds the basic model of waveform singularity detection based on the singular value decomposition (SVD) algorithm, integrates automatic detection into the electrical parameter test module, realizing the automatic detection of waveforms and parameters during the low-voltage appliance test.

(1) The switch-on and switch-off currents of AC contactor are set to be the same and different in the tests. In both cases, the relative error of the model for the automatic detection of the conduction time is less than 1\%. The time parameters such as contact closure time, contact breaking time and arcing time are verified, and similar conclusions are obtained, which meets the requirement that the low-voltage appliance standard should have a time measurement accuracy of not more than 1\%.

(2) Based on the automatic detection of the conduction time when the switch-on and switch-off currents of AC contactor are the same, the anti-interference ability of the model under different types of noise and different noise intensities is tested and analysed.

For all types of noise, there are reliable, uncertain and unreliable detection areas for automatic detection results. When $k$ is less than 10\%, all types of noise can be detected in a reliable manner, which effectively improves the detection efficiency.

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Su Jinzhou (1985- ), male, Anxi, Fujian Province, lecturer. Research Field: Electrical Fire Trace Detection Technology.

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