Distortion-Based Detection of High Impedance Fault in Distribution Systems

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Abstract—Detection of the high impedance fault (HIF) in distribution systems is significant for power utilization safety. In addition to the low fault currents, traditional approaches are invalid to detect HIFs also due to the diverse characteristics, including the slight HIF nonlinearity during the weak arcing process, the distortion offset caused by the lag of heat dissipation, and the interference of background noise. This paper proposes a distortion-based algorithm to improve the reliability of HIF detection under various conditions. Firstly, the challenges brought by the diversity of HIF distortions are explained according to the field experiments in a 10 kV real-world distribution system. HIFs are classified into five types according to the distortions of their current waveforms. Secondly, a definition of interval slope is introduced to describe waveform distortions. The interval slope is extracted by combining methods of linear least square filtering (LLSF) and Grubbs-criterion-based robust local regression smoothing (Grubbs-RLRS), so that the distortions under different fault conditions can be uniformly described. Thirdly, an algorithm is proposed to judge the features presented by the interval slope, and distinguish from non-fault conditions. Finally, the reliability and security of the proposed algorithm are thoroughly analyzed with real-world HIFs and the simulated HIFs obtained in IEEE 34-bus and IEEE 123-bus systems. Results show the improvements of the proposed algorithm by the comparisons with other advanced algorithms.

Index Terms—High impedance fault, distribution systems, fault detection, diverse distortion, interval slope.

I. INTRODUCTION

High impedance faults (HIFs) frequently happen on overhead transmission lines in medium-voltage (MV, 3-35 kV) distribution systems. Generally, the HIF is caused by the touch between the conductor and surface of high impedance material when a line drops to the ground or contacts with a tree. The high impedance materials of grounding surfaces, like the soil, sand, asphalt, concrete, cement and tree limb, etc., will restrict current in the range of less than 1 ampere to tens of amperes [1]. Practically, it makes most of protection devices invalid. According to recorded statistics [2], [3], about 10%-20% of the faults in distribution systems are HIFs, which will be higher if considering unrecoded situations. Risks of fire hazard and human injury [4] make it necessary and significant to enhance the reliability of HIF detection.

In most countries, more than one type of neutral exists in distribution systems, mainly including the isolated neutral, resonant neutral, and low-resistor-earthed neutral. Therefore, based on the equivalent circuits of different neutral systems [5]–[7], many algorithms detect HIFs by expressing voltages (or currents) with mathematic equations, and then deriving the changes of amplitudes or phases after fault happens [8]–[10]. These model-based approaches are mathematically supported and logically demonstrated. However, they are usually applicable only in systems with specific neutrals. Meanwhile, simplified equivalences of systems and inherently weak features of HIFs make fault detections more dependent on high-precision measurements, which is usually challenging in technology and cost. Besides, these model-based approaches usually regard HIFs as linear resistors, which is questionable as the nonlinearity of HIFs bring considerable errors to measuring accuracy.

Another group of approaches is classified as the pattern recognition methodology. They focus on detecting HIFs through the nonlinearities of signals [11], which have attracted wide attention since the 1970s. The nonlinearity is usually caused by the AC electric arc [1] when a line conductor makes poor contacts with the grounding surface and breakdowns the air. For this reason, the HIF is also called the high impedance arc fault [12]. Nonlinearities of HIFs can generate harmonics, waveform distortions, and sometimes are combined with unstable arcing intermittences [13]. Early works have summarized the anomalies of low-order harmonics after fault, including even-order harmonics [14], odd-order harmonics [15], and inter-harmonics [16]. Considering the complicated and unpredictable performance of intermittent arcs, some algorithms utilize the randomness of low-order harmonics to identify fluctuations during the intermittent arcing process [14], [16]. However, harmonics caused by noises and electronic equipment often invalidate the harmonic-based approaches, and the randomness of HIFs is usually inconspicuous for some stable arcs [13]. In recent decades, with the development of sampling techniques, researchers tend to utilize high-frequency harmonics, like the algorithms based on various wavelet transforms or other time-frequency analyses.
Practically, the nonlinearity of HIFs is introduced. The verification of detection reliability is carried out in Section IV by comparing the proposed algorithms to others. Finally, conclusions are drawn in Section V.

II. CHARACTERISTICS AND CHALLENGES

A. Analysis With Real-World HIFs

In a real-world 10 kV distribution system with a power frequency of 50 Hz, a certain number of HIFs are artificially experimented. Measuring devices are deployed as shown in the topology (Fig. 1), which record data in the sampling frequency of 6.4 kHz. HIFs are experimented about 30 meters away from M5 (about 80 meters for electrical distance), by grounding the conductors to different surface materials, including dry/wet soil, dry/wet cement, dry/wet reinforced concrete, dry/wet grass, and dry asphalt concrete, etc. Besides, three neutrals shown in Fig. 1 are all selected for experiments. Load current at the faulty feeder L5 is about 20 A. Branches on L1-L4, i.e., the healthy feeders, are omitted in Fig. 1 for concision.

Arcing nonlinearity is one of the prominent features of HIFs. In stable situations, the nonlinearity is presented as the periodic ‘zero-off phenomenon’ when arc current is near the zero-crossing. During this period, the ionization in the arc gap is weakened due to the low current levels, resulting in a decrease of arc diameter and increase of arc resistance. Therefore, distortions of current waveform will exhibit. As voltage increases after zero-crossing, the arc ionization is enhanced, the arc resistance decreases, and distortions of current gradually recover [28]. As a result, distortion intervals of fault current exist near both sides of zero-crossings, which tend to make the current waveform be parallel to the horizontal axis.

For real-world HIFs, current distortions are affected by various factors, particularly by ground materials and humidity [11]. Besides the typical ‘zero-off phenomenon’, another three features usually existing in the practical HIF distortions also need to be concerned about, including: 1) slight distortions in the HIFs with weak arcs; 2) offset of distortions; 3) ineffective distortions caused by arcing processes or noises.

1) Slight Distortions: Practically, the nonlinearity of HIF contains not only the impact of air arc but also the ionization of solid dielectric (ground materials) [23], [27]. When an arc in the open air is obvious, the heat dissipation is fast and causes more rapid arc resistance variation. Then the current distortion is thereby severer (Fig. 2(a)–(b)). When the air arc is weak, the nonlinearity is principally caused by the ionization of solid dielectric and the distortion is slighter (Fig. 2(c)–(e)). The slight distortions are commonly smoother and cannot generate many high-frequency harmonics. Therefore, many high-frequency-based algorithms that have been widely researched in recent decades [18]–[20] might be invalid on this condition. For example, we use wavelet transform to extract high-frequency components. Fig. 3 exhibits a comparison between two real-world HIFs. Denote their currents as \( s(n) \). The high-frequency components from 1 kHz to 5 kHz are described as the absolute value of the
Fig. 2. Current waveforms of HIFs tested in the real-world 10 kV distribution system: (a) wet asphalt concrete, isolated neutral; (b) wet soil, low-resistor-earthed neutral; (c) dry soil, isolated neutral; (d) wet cement, low-resistor-earthed neutral; (e) dry grass, resonant neutral; (f) wet grass, resonant neutral; (g) dry cement, resonant neutral; (h) dry cement pole, isolated neutral; (i) dry soil, resonant neutral.

Fig. 3. Anomalies in the high-frequency region of HIFs, which are grounded to different surfaces at a network with resonant neutral (fault happens at 0s): (a) wet soil, (b) dry asphalt concrete.

The wavelet coefficient:

\[ |WT_{fb}(a,b)| = \sum_n \left| s(n) \cdot \frac{1}{\sqrt{a}} \psi \left( \frac{n-b}{a} \right) \right| \]  

where, \( \psi \left( \frac{n-b}{a} \right) \) represents the wavelet base, and the db4 wavelet is selected. \( a \) and \( b \) are respectively the scale and displacement factors, corresponding to the frequency and time in Fig. 3. \( a \in \left[ \frac{f_1}{f_s}, \frac{f_2}{f_s} \right] \), where \( f_1 = 1 \text{kHz} \), \( f_2 = 5 \text{kHz} \) and \( f_s \) represents the sampling frequency equaling 6.4 kHz. \( b \) represents the whole sampling points.

For the HIF in Fig. 3(a), where the arc is obvious and presents severer distortions, high-frequency components show considerable anomalies compared to the pre-fault state (before 0 seconds). In this situation, HIFs can be well detected. Nevertheless, for HIFs with slighter distortions like in Fig. 3(b), high-frequency components are significantly weakened, so that pre-fault conditions fail to be distinguished. Moreover, when slighter distortions are accompanied by lower currents, high-frequency components would be easier to be covered by noises.

2) Offsets of Distortions: Ideally, the current distortion caused by ‘zero-off phenomenon’ should be near and symmetric to the zero-crossing. Practically, due to various capabilities of heat dissipation in the ionization space, the differences between dissipated powers and energizing powers will make arc resistance increases at different times. Therefore, waveform distortions will show various offsets relative to zero-crossings, especially in Fig. 2(e)–(f) (see the relative position between the zero-crossing point and the midpoint of the distortion interval). Neglect of distortion offsets could cause malfunctions of detection algorithms. For example, [23] proposes a voltage-current characteristic profile (VCCP) to describe the distortions of HIFs. For HIFs with small distortion offsets, the VCCPs typically exhibit good hysteresis loops, no matter for obvious or weak air arcs, as shown in Fig. 4(a). They are with large slopes near the origin and much smaller ones near extremums. However, for HIFs with large distortion offsets, VCCPs cannot present the above phenomena (Fig. 4(b)) but show two vastly different trajectories.

3) Ineffective Distortions: Different from the distortions of the ‘zero-off phenomenon’, ineffective distortions are usually caused by intermittent arcing processes or background noises. Many large ineffective distortions cannot be eliminated by simple filters. Fig. 4(c) illustrates this characteristic also with VCCPs, which show more complicated trajectories than typical conditions.

B. Classification of HIFs According to Distortions

According to the above discussions, distortion of a HIF generally possesses one or several of the following features:

i) with obvious arcs and severe distortions, like HIFs in Fig. 2(a), (b), (f), (h) and (i);

ii) with weak arcs and slight distortions, like Fig. 2(c)–(e) and (g);

iii) with large distortion offsets, like Fig. 2(e)–(g) and (i);

iv) with ineffective distortions, such as the impulse caused by intermittent arcing process, like Fig. 2(h) and (i).
With the summarized features, a classification is made as follows to better assess the validities of algorithms in detecting different types of HIFs:

Type A is with feature i) but without feature ii)-iv);
Type B is with feature ii) but without feature i), iii) and iv);
Type C1 is with feature i), iii) but without feature ii), iv);
Type C2 is with feature ii), iii) but without feature i), iv);
Type D is with feature iv).

III. DETECTION OF HIF

A. Description of the Interval Slope

In most countries, the zero-sequence network of the medium-voltage (MV) distribution system is isolated from loads at the low-voltage (LV) side due to the ungrounded wirings of step-down transformers [23], [31]. As a result, zero-sequence current is widely used for fault protection in European countries and China. However, zero-sequence current in a HIF is much smaller than rated value and thereby more interfered with by noises. As a result, a detection algorithm with good anti-noise ability, as well as the capability of detecting diverse distortions, is primary for feature descriptions.

Firstly, zero-sequence currents need the preprocessing by a wavelet filter (WF) or low-pass filter (LPF). The WF carries out de-noise in various frequency bands, while the LPF eliminates noises over the cut-off frequency.

Secondly, the distortions of zero-sequence current can be reflected by derivative. To restrain the derivative fluctuation caused by background noises, we define an interval slope to describe the waveform shape by linear least-square fit (LLSF) and Grubbs-criterion-based robust local regression smoothing (Grubbs-RLRS). It is introduced in detail as follows.

For a zero-sequence current $i_0(n)$, its interval slope at the sampling point $n_s$ is denoted as $IS_{i_0}(n_s)$, which is described with the LLSF. Each point of $i_0(n)$ corresponds to a point of $IS_{i_0}(n)$. For $n_s$, its absolute value of interval slope $|IS_{i_0}(n_s)|$ is expressed as:

$$|IS_{i_0}(n_s)| = \frac{l \sum_{n \in INT_{n_s}} |n_0(n)| - \sum_{n \in INT_{n_s}} n \sum_{n \in INT_{n_s}} i_0(n)}{l \sum_{n \in INT_{n_s}} n^2 - (\sum_{n \in INT_{n_s}} n)^2}$$

(2)

where, the interval $INT_{n_s}$ is with the length of $l$ and lets $n_s$ as the midpoint; $l$ is suggested as $N_T/8$ and $N_T$ represents the number of sampling points in a power frequency cycle. In the following paper, the interval slopes all represent the absolute value $|IS_{i_0}(n_s)|$ unless specially indicated.

For a sinusoidal waveform (Fig. 5(a)), the interval slope decreases to the minimum only near the minimal or maximal instantaneous currents, which presents the shape of a ‘double M’ in a cycle. However, for a distorted waveform in Fig. 5(b), the instantaneous currents, which presents the shape of a ‘double M shape’ in a cycle. Therefore, features of interval slopes can be used to identify HIFs and distinguish from the non-fault conditions.

However, to eliminate the impacts of ineffective distortions, especially the impulse noises caused by intermittent arcs like Fig. 2(i), a method of Grubbs-RLRS is used to filter the zero-sequence current before calculating interval slopes.

Denote the $i_0(n)$ that belongs to the interval $INT_{n_s}$ as $i_0^{INT_{n_s}}(n)$. It represents the interval of current (with length of $l$) that is for the calculation of $|IS_{i_0}(n_s)|$. Then, RLRS is used by firstly building an $m$-order polynomial $f_m^{INT_{n_s}}(n) = a_0 + a_1 n + \cdots + a_m n^m = \sum_{j=0}^{m} a_j n_j$ to fit $i_0^{INT_{n_s}}(n)$. The fitting error is expressed as:

$$\xi = \sum_{i=1}^{l} \varepsilon_i = \sum_{i=1}^{l} \left[ IS_{i_0}^{INT_{n_s}}(n_i) - \sum_{j=0}^{m} a_j n_j \right]^2 \cdot w_i$$

(3)
where, \( w_i \) is the weight coefficient and initiated as 1. The purpose of RLRS is to find out an \( \alpha = \{\alpha_j, j = 0, 1, \ldots, m\} \) that makes \( \xi \) become the minimum. Let \( \xi' = 0 \) and the \( \alpha \) can be calculated as follows [29]:

\[
\alpha = (N^TWN)^{-1}N^TWI
\]  

(4)

where, \( N \in \mathbb{R}^{l \times (m+1)} \) and \( N_{i,j} = n_i^j; W \in \mathbb{R}^{l \times l} \), which is a diagonal matrix and \( W_{i,i} = w_i \); \( I \in \mathbb{R}^{l \times l} \) and \( I_{1,1} = \frac{1}{i_0^{\text{INT}_{n_i}}(n_i)} \).

Ineffective distortions like the impulse signals show fast variation compared to the distortions of the ‘zero-off phenomenon’. To eliminate the impacts of the ineffective distortions, \( w_i \) and \( \alpha \) are updated based on the Grubbs-criterion [30]. It excludes the abnormal values with the idea of iterative screening, which is suitable for the continuous anomalies of impulse signals.

A definition of ‘normalized residual’ of Grubbs-criterion is expressed as:

\[
G_i = \frac{\varepsilon_i - \bar{\varepsilon}}{\text{STD}(\varepsilon)}
\]  

(5)

where, only the \( \varepsilon_i \) with \( w_i = 1 \) is considered in the calculation, i.e., \( \varepsilon = \{\varepsilon_i \mid w_i = 1 \text{ and } i = 0, 1, \ldots, m\} \). \( \bar{\varepsilon} \) represents the average value of \( \varepsilon \), and \( \text{STD}(\varepsilon) \) represents its standard deviation. Update the \( w_i \) as follows:

\[
\begin{align*}
\{ w_i = 1, & \quad G_i < G_{p,N} \\
\{ w_i = 0, & \quad G_i \geq G_{p,N}
\end{align*}
\]  

(6)

where, \( G_{p,N} \) represents the Grubbs threshold with confidence probability of \( p \) that generally range in 90%~99.5%. \( p \) is set as 90% in the paper. The value of \( G_{p,N} \) with different \( p \) and \( N \) can be referred to Table V in the Appendix A. After the update of \( w_i \), (3)–(6) are conducted circularly until no \( w_i \) is updated from 1 to 0 anymore. Then, \( |IS_{i_0}(n_s)| \) is calculated by replacing the original interval in \( i_0(n) \) with the \( i^{\text{INT}_{n_s}}(n) \).

Finally, a curve of the interval slope can be achieved by calculating the \( |IS_{i_0}(n)| \) point by point. However, \( |IS_{i_0}(n)| \) can also be calculated every a few points and then uses the interpolation to accelerate the calculation. The effectiveness of the Grubbs-RLRS is illustrated in Fig. 6(a)–(c). In Fig. 6(a), it shows that the impulse noise cannot be eliminated by a preprocessing of traditional LPF. The ineffective distortion can even be enlarged if the cut-off frequency \( f_c \) is too low, making the impact of the ineffective distortion more difficult to be eliminated. Therefore, we suggest using a LPF with \( f_c \) around 1500 Hz.

Fig. 6(b) shows that directly using derivative of current is useless. Comparatively speaking, the interval slope described by LLSF in Fig. 6(c) (bottom right of Fig. 6) can better restrain the fluctuations. Moreover, Fig. 6(c) also demonstrates the advantages of the Grubbs-RLRS method (red line) in eliminating the interference of impulse noise, which guarantees the correct presentation of ‘double M shape’.

## B. Judgment

After the description of interval slopes, the judgment that whether a HIF happens is made by implementing the following procedures. The main idea is to judge whether the interval slope \( |IS_{i_0}(n)| \) can present the “double M shape” like Fig. 6(d), and last for some successive cycles.

Step 1: In each cycle, find out the positions of the maximal and minimal zero-sequence currents by fast Fourier transform (FFT). The abscissas of the two positions are denoted as \( N_1 \) and \( N_2 \) as shown in Fig. 6(d). Considering the deviation of FFT, \( N_1 \) and \( N_2 \) are further calibrated as the minimal interval
slopes in the vicinity. \( N_0 \) represents the minimal interval slope in the vicinity of \( N_1 - N_T/2 \). Then, pursue Step 2.

Step 2: For the half-cycle \([N_0, N_1]\), \( n_{\min} \) is a minimal point in \([N_0 + d, N_1 - d]\), i.e., satisfying \(|I_{S_0}(n_{\min} - 1)| \leq |I_{S_0}(n_{\min})| \leq |I_{S_0}(n_{\min} + 1)|\). The short zone \( d \) in the vicinity of \( N_0 \) and \( N_1 \) is to neglect the \( n_{\min} \) near the maximal or minimal currents. Make a judgment that whether the following two conditions are both met. If so, pursue Step 3, otherwise, skip to the next cycle and return to Step 1.

Condition 1): The first \( n_{\min} \) in \([N_0 + d, N_1 - d]\) is denoted as \( n_{\min,0} \) and it should satisfy three criteria:

\[
\begin{align*}
|I_{S_0}(n_{\min,0})| & \leq K_{set1} |I_{S_0}(n_{\max,1})| + |I_{S_0}(n_{\max,2})| \\
N_{num,1} & = N_{num,2} = 2 \\
n_{\max,1} & < \frac{N_0 + N_1}{2} < n_{\max,2}
\end{align*}
\]

(7)

where, \(|I_{S_0}(n_{\max,1})|, |I_{S_0}(n_{\max,2})|\) are two maximums respectively in the interval of \((N_0, n_{\min})\) and \((n_{\min}, N_1)\); \( K_{set1} \) represents the sensitivity coefficient and is generally set as \(0.80 \sim 0.85\) (the statistical basis of this threshold is shown in Fig. 19 of Appendix B); \( N_{num,1} \) and \( N_{num,2} \) in Criterion (2) are the numbers of the sampling points that satisfy (8) and (9), respectively. The Criterion (2) is to confirm that the curve crosses up and down only twice on each side of the \( n_{\min} \), so that a ‘M shape’ in the half-cycle can be guaranteed. Criterion (3) is to confirm that \( n_{\max,1} \) and \( n_{\max,2} \) do not concentrate on one side of each half-cycle, which is not in accordance with the characteristic of the ‘zero-off phenomenon’.

\[
|I_{S_0}(n_{c1})| = \frac{|I_{S_0}(n_{\min})| + |I_{S_0}(n_{\max,1})|}{2}, \\
n_{c1} \in (N_0, n_{\min})
\]

(8)

\[
|I_{S_0}(n_{c2})| = \frac{|I_{S_0}(n_{\min})| + |I_{S_0}(n_{\max,2})|}{2}, \\
n_{c2} \in (n_{\min}, N_1)
\]

(9)

Condition 2): If there exist more than one \( n_{\min} \) in \([N_0 + d, N_1 - d]\), all \( n_{\min} \) (except \( n_{\min,0} \)) should satisfy:

\[
\begin{align*}
& \left\{ n_{\min} \in (n_{\max,1}, n_{\max,2}) \\
& \frac{|I_{S_0}(n_{\max,1})| - |I_{S_0}(n_{\min})|}{|I_{S_0}(n_{\max,2})| - |I_{S_0}(n_{\min})|} \in [1 - K_{set2}, 1 + K_{set2}]
\end{align*}
\]

(10)

where, \( K_{set2} \) also presents the sensitivity coefficient. \( K_{set2} \) is set as \(0.05 \sim 0.25\) (also based on the analyses in Fig. 19).

Step 3: Implement the same procedure for the half-cycle \([N_1, N_2]\) as for \([N_0, N_1]\). If the two half-cycles are both identified as ‘M shape’, this cycle is recorded as a ‘fauty cycle’ and thereby exhibit ‘double M shape’. Then, pursue Step 4.

Step 4: Pursue Step 1-3 cycle by cycle. If there are a few successive cycles recorded as ‘fauty cycles’, the HIF is detected. Empirically, the number of the successive cycles to confirm a HIF is set as 4~6. On the one hand, this setting is to avoid mistakes due to coincidental judgment. On the other hand, low impedance arc faults can be fast eliminated by overcurrent relays before being detected by the algorithm.

IV. CASE STUDY

In this section, we systematically analyze the reliability and security of the algorithm. Herein, reliability represents the ability to successfully detect HIFs under various scenarios and interferences, whereas security represents the ability to correctly distinguish from non-fault conditions so as to avoid unnecessary outage. Finally, comparisons with some advanced algorithms are also carried out in the section.

A. Reliability

To verify the reliability of algorithm, effects of distortion diversity, unbalanced loads, DGs, topology changes, neutral types, fault/measuring positions, and noise interferences are analyzed, respectively.

1) Diversity of Distortions: As discussed in Section II, the distortion of current is affected by different fault scenarios, especially by ground material and humidity. Therefore, it’s necessary for an algorithm to be able to detect diverse distortions of HIFs.

Twenty-eight real-world HIFs experimented in the 10 kV distribution system are achieved by grounding the conductors to different materials, including soil, cement, reinforced concrete, grass, pole, and asphalt concrete. The humidity of ground material is simply classified as wet and dry. Besides, three neutrals are selected for the experiments, including 9 for isolated neutral, 12 for resonant neutral, and 7 for low-resistor-earthed neutral.

Firstly, detailed detection result of a real-world HIF, which is grounded to dry cement pole at a network with resonant neutral, is illustrated in Fig. 7. Set \( K_{set1} = 0.83 \) and \( K_{set2} = 0.1 \). The HIF happens around 0.19 s as in Fig. 7(a). Fig. 7(c) presents the judgment of whether a cycle is detected as a ‘fauty cycle’. When there are successively 4 cycles being detected, a trigger signal is sent out. During 0.19 s~0.29 s, the distortions are mainly produced by the ionization of solid dielectric. At about 0.29 s, the arc ignition occurs and exerts dominating influences on the waveform distortions after that. In the two processes, the ‘double M shape’ of interval slopes can be both reliably identified as shown in Fig. 7(b). In addition, before fault happens, distortions also exist due to the severe background noises caused by measuring errors. However, it can be correctly distinguished by the proposed criteria.

Fig. 8 presents the interval slopes of 9 HIFs, whose current have been shown in Fig. 2 and include all the 5 types of HIFs that have been classified in Section II.B. Compared to their descriptions by VCCP in Fig. 4, the proposed algorithm can uniform the features of all types of HIFs, which all present interval slopes with pure ‘double M shape’ in a cycle.

2) Operation of Unbalanced Load: In most countries, like Europe and China, lines of the three phases at MV distribution networks (3 kV~35 kV) are intact. Meanwhile, the loads and DGs connect to MV distribution network through a transformer with wiring of Delta/Y, Delta/Yg (Yg means grounded Y wiring), Y/Y, Y/Yg or Y/Delta, etc. For these wirings, three phase currents are neutralized at the primary side of transformer.
therefore, behaviors at the load side or DG side don’t affect the zero-sequence current at the MV network. The above conclusions are well-known and also indicated by many literatures like [23], [31] and [33].

IEEE 34-bus system is used for illustration, where lines and transformer wirings are modified accordingly. A large unbalanced load connected to Bus-854 is emphasized and marked in Fig. 9. Three DGs are considered, including a solar DG connected to Bus-848, and two wind DGs connected to Bus-840, Bus-890, respectively. Output of three DGs are initialized as 0.5 MW. The transformers connecting DGs and MV distribution networks are with Delta/Yg wirings according to [33]. Then, the zero-sequence network of the IEEE 34-bus system is shown in Fig. 10 (a HIF happens at k1).

As shown in Fig. 10(a) and (b), the unbalanced load and DGs are not included in the zero-sequence network because of the isolation of transformers. In Fig. 10, zero-sequence impedances of feeder lines can be neglected compared to line-to-ground capacitances [10]. Zero-sequence network is known to be energized by a virtual voltage source (marked as $u_f$), which has the same magnitude with and the opposite phase to the pre-fault phase-to-ground voltage at the fault point. $R_{HIF}$ represents equivalent fault zero-sequence resistance, equaling three times of fault resistance. According to the HIF model in [34], fault resistance is the series connection of a constant resistor $R_T$ and a nonlinear resistor $R_{arc}$. Besides, the circuits when selecting three different types of neutrals are also shown in Fig. 10, where the $R_N$ and $L_N$ represent the equivalent neutral zero-sequence resistance and inductance.

For the large unbalanced load at Bus-854, powers of phase A, B, and C are 228 kW + 120 kVar, 45 kW + 22 kVar, and 1.3 MW + 0.6 MVar, respectively. The load connects to the network, which is with isolated neutral, at time of $T_1$. Then, the measurements at M2 are shown in Fig. 11(a). Obviously, although the imbalance and variation of loads make significant influences on phase currents, the zero-sequence current are nearly unaffected due to the isolation of transformer. However, some transient disturbances that happens closely after $T_1$ are caused by unbalanced leakage magnetic flux of transformer after the sudden connection of loads.

Then, with the unbalanced load happening at $T_1$, a HIF ($R_T = 2k$), $R_{arc} \in [0, 6] k$) happens at $T_0$ ($T_0 < T_1$) and the fault position is k1. The zero-sequence current measured at M2 and its interval slope ($|IS_{0n}(n)|$ and $|IS'_{0n}(n)|$) are shown in Fig. 11(b). As is shown, most interferences of the transient disturbances can be eliminated by the proposed LLSF-Grubbs-RLRS method, so that the ‘double M shape’ of interval slope can still be reliably shown in each cycle.

3) Operation of Distributed Generator (DG) and Island: Similarly, due to the isolation of transformers, behaviors of DGs do not directly affect zero-sequence currents at the MV network. However, operations of DGs can effectively raise the voltage level, especially at the far end of feeder line.

Configurations of DGs are the same as in Part 2). If a HIF happens under the same ground condition ($R_{HIF}$ is unchanged), the zero-sequence currents will mainly be affected by the change of $u_f$ according to Fig. 10(b). Change the outputs of three DGs to make the voltage at Bus-834 raise from 22.51 kV to 23.33 kV and 24.29 kV, when the proportions of DG output are 39.04% and 83.61%, respectively. Fig. 12 shows the zero-sequence currents measured at M3, where DGs connect to the network at $T_1$ and the HIF happens at $T_2$ ($T_2 > T_1$, fault position is still at k1). Further, when a breaker cuts off the line between Bus-858 and Bus-834 at time of $T_0$ ($T_0 < T_1$), the right network marked in Fig. 9 becomes an island. At this time, voltage level of Bus-834 sags to 16.59 kV, and the zero-sequence current is exhibited as a ‘blue’ line in Fig. 12. As is shown, operation of DGs, including island, can effectively change the voltage of system and thereby affect the phase and amplitude of zero-sequence currents. However, distortions are little affected when $R_{HIF}$ is unchanged. In practice, variation of voltage level can make some changes on $R_{HIF}$ as the activity of plasma in air will be affected. This effect will still come down to the diversity of waveform distortions, and thereby does not invalidate the proposed algorithm as discussed in Part 1).

4) Changes of Network Topology, Neutral Type, Fault Position, and Measuring Position: A more complicated network, IEEE 123-bus system (Fig. 13) is used to figure out how the changes of network topology, neutral type, fault position and
measuring position affect the waveform of zero-sequence current. PSCAD model of this system refers to the resource in [35]. Lines and transformers are modified to be in accordance with Europe or China MV distribution networks. Missing phase lines at the MV network side are supplemented. The transformers connecting network to loads are set as Y-Yg or Y-Delta wirings.

For the IEEE 123-bus system, there are two primary differences from IEEE 34-bus system. On the one hand, the voltage

![Fig. 8. Interval slopes of 5 types of HIFs (illustrated by the HIFs in Fig. 2), including the HIFs of (a) Type A and B, (b) Type C1 and C2, and (c) Type D.](image)

![Fig. 9. Topology of IEEE 34-bus system.](image)

![Fig. 10. (a) Zero-sequence network of the IEEE 34-bus system with DGs; (b) Equivalent zero-sequence network.](image)

![Fig. 11. Effects of unbalanced loads on (a) phase currents and zero-sequence current (measured at M2) at the MV distribution network without HIF, and on (b) zero-sequence current with HIF.](image)

![Fig. 12. Effects of DGs on zero-sequence current (measured at M3) at the MV distribution network.](image)
level significantly decreases from 24.9 kV to 4.16 kV. If \( R_{HIF} \) is set to be the same as in Part 2) and 3), the zero-sequence current would be only several hundred micro-amperes or even less. In practice, a lower voltage level makes it more difficult to break down the air gap insulation, whereas a lower current level makes it easier to be disturbed and extinguished. That explains why HIFs mostly happen at the MV distribution network rather than the LV level (below 1 kV) [31].

On the other hand, the zero-sequence network of the IEEE 123-bus system will significantly change and the distribution of zero-sequence currents will be much more complicated.

In this part, we use the same \( R_{HIF} \) as Part 2) and 3). In a practical 4.16 kV power system, the HIF with this level of \( R_{HIF} \) is difficult to be detected because the fault current is beyond the measuring range. We make this setting just for comparison and to explain the phenomenon. Fig. 14(a)~(c) present the zero-sequence currents under three different neutrals. For each neutral, there are three lines of figures respectively representing the situations when HIF happens at three positions \( k_1 \sim k_3 \) in Fig. 13. In each figure, zero-sequence currents measured at M1~M4 are presented (fault time is \( T_f \)). As is shown, although the IEEE 123-bus system is with considerable unbalanced loads, the zero-sequence current at normal state is low due to the isolation of transformers.

Combined with the zero-sequence network, just like that of the IEEE 34-bus system in Fig. 10, the amplitude, phase and distortion of currents in three neutral networks are summarized as follows.

**i) Isolated neutral, Fig. 14(a):**
- Amplitudes of zero-sequence currents at different measuring positions are various. They depend on the total zero-sequence line-to-ground capacitances at the ‘back’ network of a measuring point. The ‘back’ here means the opposite direction to where the fault is. Therefore, it can be understood that the zero-sequence current at M1 should be close to zero.
- The positive direction of zero-sequence current is set to be from substation to the end of feeder. Then, the phases of currents are opposite at two sides of fault.
- Distortions of currents measured in different positions are similar.

**ii) Resonant neutral, Fig. 14(b):**
- The zero-sequence current through Petersen coil is to neutralize line-to-ground capacitance currents of the whole network. Therefore, current amplitudes measured ‘before’ fault positions are larger. The ‘before’ here means the measuring position is in the path from the fault to substation, and otherwise, is ‘behind’. Therefore, the current at M1 should be the largest.
- Phases of currents at the overall network are similar.
- More detectable distortions, i.e., the ‘double M shape’ of interval slope, can be measured ‘before’ the fault position than the ‘behind’, as shown in Fig. 14(b). It is also observed that currents at the beginning of main branches (M2 or M3) show more detectable distortions than at the substation (M1), because the current of non-fault branch will neutralize fault distortions at M1.

**iii) Low-resistor-earthed neutral, Fig. 14(c):**
- Generally, the equivalent neutral zero-sequence resistor \( R_N \) is much smaller than the total zero-sequence line-to-ground capacitive reactance of the network, so current amplitude ‘before’ the fault position is commonly much larger than the ‘behind’. However, if line distance or imbalance of the network increases to enlarge the zero-sequence line-to-ground capacitances, the amplitude difference can be reduced.
- Phases of currents ‘before’ the fault position are similar to each other, which lags about \( \pi/2 \) comparing to that of the current ‘behind’ the fault position.
- Detectable distortions, i.e., with ‘double M shape’ of interval slope, are mainly presented in the current ‘before’ the fault position.

In conclusion, differences of current amplitudes and phases, as well as diversity of waveform distortions, can be caused when the discussed fault conditions change. Theoretically, detectable distortions for the proposed algorithm always exist when measuring positions are set at the beginning of each major branch (not load branch or substation), like M2 and M3 in Fig. 13. However, when the feeder line is long, considering the attenuation of current amplitude at the isolated neutral network and the distortion neutralization of healthy feeders at the resonant neutral network, more deployment of measuring device will certainly improve the detection reliability.

5) *Anti-Noise Ability:* The anti-noise ability is also significant for the algorithm reliability. Noises that exist in zero-sequence currents are mainly generated by intrinsic measurement errors and electromagnetic background noises.

Bad data is one type of measurement error, which shows up as significant differences of a few sampling points from their normal values. Bad data only sporadically occurs, so it can be eliminated by the LLSF-Grubbs-RLRS method just like impulse signals in Fig. 6.

Another primary measuring error is generated when a signal is beyond the measuring range, which is reflected just like electromagnetic background noises. For a HIF with extremely low current, this type of measuring error usually makes significant influences on the current waveform.

A real-world HIF is used for illustration as shown in Fig. 15. The zero-sequence current shown in Fig. 15(a) is obtained by
Fig. 14. Distortions of zero-sequence current when neutral type, fault position and measuring position are different: (a) isolated neutral; (b) resonant neutral; (c) low-resistor-earthed neutral. For each neutral, there are three lines of figures, respectively representing the situations when HIFs happen at $k_1 \sim k_3$.

a practical measuring device. The HIF is tested at a resonant network and grounded to the dry cement. Dry cement is with high-level and low-degraded insulation so that the fault current is extremely low and increases slowly. Before 0.35 s, the zero-sequence current of fault (Fig. 15(a)) is so small that nearly equals the pre-fault value. Therefore, the current is significantly interfered with by measurement errors, and the proposed algorithm is hardly effective. As the increase of current, noises caused by measuring errors can be eliminated by LLSF-Grubbs-RLRS, and ‘double M shape’ of interval slope in each cycle can be successively described (Fig. 15(b)).

More discussions about the anti-noise ability are carried out also with the 28 real-world HIFs in Section IV.C.

B. Security

The security of a detection algorithm is equally essential for practical applications, which requires the algorithm not to send out the tripping signal during non-fault disturbances.

The non-fault events that can cause distortions of zero-sequence currents mainly include: switching of a capacitor, operation of unbalanced arc furnace load, inrush current of zero-sequence current transformer (CT), and saturation of zero-sequence CT. The zero-sequence currents and corresponding interval slopes of these events are shown in Fig. 16(a)–(d), respectively. They are detailedly analyzed in the following.

1) Switching in/out of Capacitor: According to IEEE standard C37.99-2012 (Section 6.2) [36], shunt capacitors mostly connect to the network in $Y$ or Delta wiring. However, when the network is with effectively grounded neutral, a $Y_g$ wiring can be selected to reduce the transient voltage during the switch, especially for the system above 121 kV. Under this circumstance, the behavior of a capacitor will affect the zero-sequence current most.

A shunt capacitor bank with $Y_g$ wiring is connected to the Bus-854 of IEEE 34-bus system, where low-resistor-earthed neutral is selected. Suppose that the capacitor bank switches in at 0s and switches out at 0.1s. Then, the zero-sequence current measured at M2 is presented in Fig. 16(a).

According to Section III.B, two requirements should be met before a HIF is detected. Firstly, the interval slope in a cycle should be extracted as a ‘double M shape’, i.e., a ‘faulty cycle’ is
judged. Secondly, at least 4 successive cycles should be extracted as ‘faulty cycle’.

The figure (iii) of Fig. 16(a) presents the judgment of ‘faulty cycle’. As is shown, both the transient switching process and the stable state cannot be extracted as ‘double M shape’, so the capacitor switching won’t be wrongly detected.

2) Operation of Single-Phase Arc Furnace: According to IEEE standard C57.17-2012 (Section 7) [37], the wiring of the transformer at the arc furnace side should always be Delta. Therefore, harmonics at the arc furnace side are self-neutralized and cannot be transmitted to the zero-sequence current at the MV network.

For example, a single-phase arc furnace is also connected to Bus-854 of the IEEE 34-bus system. The zero-sequence current and three-phase currents measured at M2 are all shown in Fig. 16(b). Although the phase currents exhibit variance, harmonics and imbalance, the amplitude and distortion of zero-sequence current is unaffected due to the isolation of transformer. However, caused by arcing intermittence, some transient harmonic components are produced on zero-sequence currents, which are caused by the leakage magnetic flux of transformer. These transient components are irregular and cannot be extracted as ‘double M shape’ in each cycle, so the unbalanced arc furnace load will not be wrongly detected by the proposed algorithm.

3) Inrush Current of Zero-Sequence CT: When the CT for zero-sequence current is suddenly connected to the network by a breaker, inrush current could occur and cause waveform distortions. Fig. 16(c) presents the inrush current happening at the M2 of Fig. 9, which shows a decayed and distorted waveform of current. The inrush current is severely asymmetry. As shown in the figure (ii) of Fig. 16(c), although the interval slope sometimes shows the shape like ‘double M’, the two ‘M’ are concentrated in the middle of each cycle, because the distortion happens near the maximum of current. As a result, positions of $n_{\text{max}1}$ and $n_{\text{max}2}$...
do not satisfy the criterion (3) in Eq. (7). This event thereby won’t be wrongly detected.

4) Saturation of Zero-Sequence CT: When magnetism in a transformer accumulates beyond capacity, the transformer becomes saturated. Voltage is limited when it rises to a certain amplitude, while current increases rapidly at the same time and is exhibited as ‘spike wave’. Waveform distortions are thereby generated. Let the saturation happen at the secondary side of a zero-sequence CT (at M2 in Fig. 9, a ratio of 1:1 is used for example). Measured waveforms on both sides of the transformer are shown in Fig. 16(d), where the ‘black’ and ‘blue’ lines represent the currents at the primary and secondary sides, respectively.

As shown in Fig. 16(d), the ‘spike wave’ caused by transformer saturation makes the interval slope at the maximum and minimum of current increase, so as to be extracted as ‘double M shape’, which could be wrongly detected by the algorithm.

Actually, transformer saturation is a significant problem in the area of transformer protection. It has been concluded that distortion caused by saturation only happens at the saturated side of transformer, but not affect other sides [38], [39]. This conclusion is also verified by the case in Fig. 16(d), and has been utilized in many protection approaches to identify the transformer saturation. If both sides of the transformer are saturated, a wavelet-based approach is also proposed in [39] to identify the saturation event according to the distortion relationship between the two sides. With these auxiliary criteria, mistakes caused by CT saturation can be avoided.

In addition to the four events, it is also illustrated in Fig. 15 and Fig. 19(b), (d) that severe background noises during non-fault conditions do not lead to misjudgments.

In conclusion, the security of HIF detection can be guaranteed by the proposed algorithm in most cases.

C. Comparison With Other Advanced Algorithms

In this section, the reliability and security of the algorithm are both compared with four advanced algorithms. One proposed in [20] is based on high-frequency components, which have been popularly researched in recent years. Another three, including [23]–[25], detect HIFs also based on distortions.

1) Introduction to Algorithms: Specifically, in [20], the discrete wavelet transform (DWT) is used to describe the high-frequency harmonics of currents by a group of energies (denoted as $\xi_d$ and $\xi_c$). Then, a HIF is detected when the energies change reach their respective thresholds and last for a certain time. The algorithm in [23] describes the distortions of HIFs with VCCPs introduced in Fig. 4. A HIF is detected when the slope of VCCP near zero (denoted as $k_1$) is larger than 1 and the slope near extremum (denoted as $k_2$) is lower than 1. In [24], distortion of current $i_0(n)$ is described by concave and convex characteristic (CCC), which is quantified by the sign of second derivative (denoted as $D_2(n)$). It is known that the curve is concave when $D_2(n) < 0$, whereas is convex when $D_2(n) > 0$. In [25], an advanced distortion (AD) based approach is proposed, which detects HIF according to anomalies of current derivative (denoted as $D(n)$) during different periods in a cycle. Signals are all preprocessed by LPFs before utilizing the algorithms in [23]–[25]. As is claimed, the algorithms in [20] and [25] use phase currents, whereas those in [23] and [24] use zero sequence currents. The simplified principles and criteria of the above four algorithms are set in Table I.

2) Reliability Comparison: Reliability is compared firstly by using real-world HIFs. According to the classification standard in Section II.B, these 28 HIFs can be categorized as 5 Type A, 8 Type B, 3 Type C1, 6 Type C2, and 6 Type D. Detection results of different algorithms are shown in Table II.

As shown in Table II, all the algorithms show perfect behaviors for the Type A HIFs, which are with severe distortions and without distortion offsets or ineffective distortions. When the distortion becomes slight and smooth, like Type B and C2 HIFs, the algorithms of DWT and AD will gradually lose their reliability. When distortion offset exists, like Type C1 and C2 HIFs, algorithms of CCC and VCCP cannot perform well. Especially for Type C2, the entire distortion area will shift away from zero-crossing due to slight distortions. For Type D HIFs, which are interfered with by ineffective distortions, the LPFs used in VCCP and CCC cannot be effective enough so as to be invalid in some scenarios. In contrast, with the processing of the LLSF and Grubbs-RLRS, as well as the effective criteria, the proposed algorithm can correctly detect all of these samples. With the
above comparisons, it can be recognized that it’s necessary for an algorithm to be able to detect diverse distortions of HIFs in the practical application.

Anti-noise ability is also compared by the 28 real-world HIFs. Fig. 17 shows the detected rate of the above five algorithms under different noise levels. The noise is composed of practical noise and complementary simulated white noise. It demonstrates that the proposed algorithm has a stronger capability of noise immunity, as well as algorithm VCCP. They can both guarantee the reliability when the signal-to-noise ratio (SNR, the severer the noise, the smaller the SNR) is above 16 dB and becomes invalid when SNR is below 5 dB. However, for algorithm DWT, it can be significantly interfered with by noises and is completely invalid when the SNR is below 30 dB. In addition, although the algorithm of AD shows a higher detected rate under the low SNR condition, the detected rate decreases as SNR increases. This phenomenon indicates that the algorithm AD has a higher possibility of causing misjudgments under noisy environments.

Besides, a total of 495 HIFs are simulated in the IEEE 34-bus system (with DGs) and the IEEE 123-bus system by PSCAD to evaluate the performance of these algorithms under different scenarios. The automatic control of PSCAD by Python [34] supports the simulation batching of numerous HIF cases. The simulated scenarios are summarized in Table III. Suppose that a HIF is detected when the signal measured at any position satisfies the criteria. Then, the detected rates of five algorithms in the two systems are presented in Fig. 18.

As shown in Fig. 18, the detection results of simulated HIFs show some differences from that of the real-world HIFs in Table II as the real-world HIFs just happen near the measuring position. For the DWT and AD algorithms that claim to use phase currents, the detected rate closely depends on the relative positions between measuring device and fault. For example, when HIF happens at k1 in the IEEE 34-bus system, the load currents measured by M1 and M2 will be much higher than fault currents, and the current measured by M3 doesn’t include fault current. Therefore, the detected rate of DWT and AD in IEEE 34-bus system is low. It is shown in Fig. 18 that detected rates of these two algorithms are significantly improved if using zero-sequence current instead.

Simulated results also show that the distortion of zero sequence current will be weakened in a resonant neutral network when the length of a faulty branch becomes longer. Therefore, in the IEEE 123-bus system, detected rates of distortion-based algorithms will decrease, like VCCP, CCC, AD, and the proposed approach. This is because the slight distortions of some Type B and C2 HIFs will be further neutralized by the currents of healthy feeders. More installations of measuring devices in a long feeder can help improve the reliability.

3) Security Comparison: Four events introduced in Section IV.B are simulated for comparisons in the IEEE 34-bus system and the IEEE 123-bus system, respectively. Any measuring device wrongly detecting these non-fault events will be recorded as a misjudgment. Different parameters and positions of these events are set to obtain more samples. For example, a total of 36 capacitor switching events are simulated with a combination of two systems, three neutrals, two positions, and three capacitance values. There are also 36 cases for each of the other three events, where the change of capacitance

![Fig. 17. Comparisons of anti-noise ability between different algorithms.](image-url)

![Fig. 18. Detected rate of different algorithms in two systems.](image-url)
TABLE IV
MISJUDGMENT RATE OF VARIOUS ALGORITHMS

| Event Method | Capacitor Switching | Single-Phase Arc Furnace | Inrush Current of CT | Saturation of CT |
|--------------|---------------------|--------------------------|---------------------|------------------|
| DWT          | 16.67%              | 58.33%                   | 100%                | 47.22%           |
| VCCP         | 0%                  | 0%                       | 0%                  | 27.78%           |
| CCC          | 0%                  | 0%                       | 0%                  | 22.22%           |
| AD           | 0%                  | 100%                     | 100%                | 72.22%           |
| Ours         | 0%                  | 0%                       | 0%                  | 44.44%           |

value is replaced by the change of equivalent impedance of arc furnace, switching angle for transformer inrush current, and knee voltage for CT saturation. Then, misjudgment rates of five algorithms, which all use zero-sequence currents, are presented in Table IV.

As is shown, all the algorithms, including our proposed one, make misjudgments for CT saturation. However, CT saturation can be distinguished by some auxiliary criteria as introduced in Section IV.B.4). Except for that, VCCP, CCC, and our proposed algorithms perform the best in security, while the DWT and AD algorithms cannot guarantee it well.

With systematic and contrastive analyses, features of HIFs can be affected by many factors. As is shown, some algorithms cannot achieve high reliability mainly because they are infeasible for various HIF features, use unsuitable signals, or have poor immunity to noises. Some algorithms achieve high reliability by giving up a part of security. Taken together, the proposed algorithm performs better in improving the reliability on the premise of security. It is realized owing to the universal feature description by the LLSF-Grubbs-RLRS method and reasonable criteria.

V. CONCLUSION

HIF detection in the distribution system is a challenging and significant subject. To better understand the diversity presented by the waveform distortions of HIFs, this paper classifies HIFs into five types. For many existing algorithms, only two to three types can be effectively detected. Therefore, this classification can help better assess the reliability of an algorithm when the diversity of fault distortion is under consideration. A distortion-based algorithm is proposed in the paper, describing the waveform shape with the defined interval slopes, which are extracted by the methods of LLSF and Grubbs-RLRS. Their combination shows good effectiveness in correctly and uniformly presenting the ‘double M shape’ of interval slopes for all types of HIFs. This paper makes a systematic verification to clarify the influences of various factors on the effectiveness of algorithm. Compared to a high-frequency-harmonic based algorithm and three distortion based algorithms, the proposed algorithm shows its comprehensive superiorities in reliability and security.

The proposed algorithm is invalid at the multi-grounded neutral distribution system, which is with the configuration of three-phase-four-wire, like in the North America. This is because the variation, imbalance and harmonic from the load side will significantly interfere with zero sequence current, and phase currents as well. Distortions of faults will thereby be covered.

Appendix A

TABLE V
GRUBBS THRESHOLD $G_{p,N}$

| N  | P  | $G_{p,N}$ |
|----|----|----------|
| 5  | 0.0% | 1.602    |
| 6  | 0.0% | 1.729    |
| 7  | 0.0% | 1.828    |
| 8  | 0.0% | 1.909    |
| 9  | 0.0% | 1.977    |
| 10 | 0.0% | 2.036    |
| 11 | 0.0% | 2.088    |
| 12 | 0.0% | 2.134    |
| 13 | 0.0% | 2.175    |
| 14 | 0.0% | 2.213    |
| 15 | 0.0% | 2.247    |
| 16 | 0.0% | 2.279    |

$p$ represents confidence probability and reflects the strict degree of abnormality screening. Abnormalities are more easily to be eliminated as $p$ decreases. $N$ represents the number of samples in the sequence for screening. The sampling frequencies of the field and simulated HIF in the paper are both 6.4 kHz, i.e. $N \leq 80$ when the length of interval slope is set as $l = N_r / 8$.

Appendix B

Fig. 19 presents the statistical accordance of $K_{set1}$ in Eq. (7), by using the real-world experiment data achieved in the 10 kV distribution system. How the $K_{set1}$ affects reliability (detected rate) and security (misjudgment rate) of algorithm are considered. A HIF is detected when the criteria in Section III.B is satisfied. A misjudgment is recorded when the pre-fault normal state is wrongly detected as fault.

Fig. 19(a) and (b) respectively represents the detected and misjudgment rate of 28 HIF cases when $K_{set1}$ and $K_{set2}$ are different. It shows that the reliability is mainly affected by $K_{set1}$, while $K_{set2}$ affects a little. However, considering the security, the thresholds should be approximately set as $K_{set1} \in [0.78, 0.86]$ and $K_{set2} \in [0, 0.33]$. Fig. 19(c) and (d) shows the effects of $K_{set1}$ and noise level (signal to noise ratio, SNR). The noise is composed of practical noises and the noises complemented by simulation. Due to the page limitation, only the situation when $K_{set2} = 0.1$ is shown. With more statistical analyses, we suggest that $K_{set1} \in [0.80, 0.85]$ and $K_{set2} \in [0.05, 0.25]$ in order to guarantee the reliability and security when noise is over 15 dB.

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Fig. 19. Statistical analysis of the threshold $K_{set1}$ and $K_{set2}$ by using 28 real-world HIFs. (a) Detected rate and (b) misjudgment rate affected by $K_{set1}$ and $K_{set2}$. (c) Detected rate and (d) misjudgment rate affected by $K_{set1}$ and noise level (SNR).

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