



PS1 – S3-02



Detection of High Impedance Fault in MV Distribution System

Sankara SUBRAMANIAN, Krishnakumar VENKATARAMAN
ALSTOM Grid
UK

sankara.subramanian@alstom.com;
krishnakumar.venkataraman@alstom.com

KEYWORDS

High Impedance Fault, Wavelet, Harmonic, Intermittent, EMTP.

1 INTRODUCTION

High impedance fault (HIF) is generally defined as unwanted contact of an electrical conductor on a nonconductive surface like road, tree limb, sod or some other surface or object which restricts the fault current to a level below that can be reliably detected by conventional relays [1]. Undetected HIFs such as downed conductors are rather dangerous for personal safety and property security. The primary objective of clearing a HIF is protection of personnel and property and not the power system. Therefore, HIF detection (HIFD) is of crucial importance for utilities and protection engineers.

Detection of HIF has long since been of great challenge as well as interest for industrial and academic research. Generally, ways to detect such kind of fault are mainly focusing on waveform features. Harmonics feature such as 3rd harmonic's amplitude and phase has been used by early researchers [2], [3]. However, harmonic should not be considered as a feature uniquely for HIF, moreover, the accuracy may be affected by the background harmonic source such as nonlinear loads.

Randomness such as intermittence is another straightforward feature [4], [5], yet randomness may not cover all HIF cases either. Due to the complexity of the problem, artificial intelligence such as Neural Network (NN) [6], [7] and expert system [4] becomes the focus of HIFD research, but these methods may need considerable training and setting with stage-tests, and the mechanism of these NN black-box style methods is not so clear either. Arc detection using high frequency component and wavelet is also a focus for HIFD [6], [8]. However, in the distribution system, measurement should be taken to discriminate HIF arc from other high frequency distortion. In a word, due to the complexity of system condition and fault cases, it is a truth that not all kinds of HIF can be fully securely detected [1] by any method.

These type of faults are predominant in MV networks in countries like USA, Brazil, Australia, Saudi Arabia, UAE, Thailand, Vietnam, etc., For example in Saudi Arabia, UAE, and Australia, high resistance faults occur due to the resistivity of the soil (desert sand dunes) and in other countries like USA, Brazil, Thailand, etc., where bare over-head conductors pass through dense forest trees and create chances of high resistance faults.

HIFs produce little or no fault current. Typical fault currents range from 10 to 50 amps, with a very erratic waveform. Here are typical results of staged faults at two different test sites for a typical 12.5 kV feeder [13].

TYPICAL FAULT CURRENTS ON VARIOUS SURFACES

Typical 12.5 kV Distribution Feeder	
Surface	Current (A) @ 7200 V L-G
=====	
Dry asphalt	0
Concrete (non-reinforced)	0
Dry sand	0
Wet sand	15
Dry sod	20
Dry grass	25
Wet sod	40
Wet grass	50
Concrete (reinforced)	75

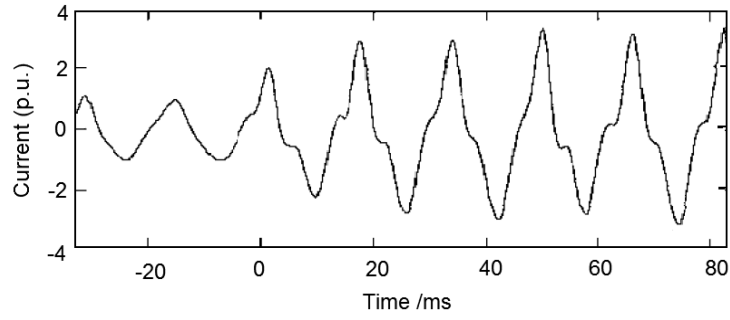
In order to improve the security and reliability of HIF detection, an integrated scheme is proposed in this paper, which takes advantages of the most significant features of HIF ranging from high frequency transient to fundamental component: 1) Arcing feature: the distortion of waveform by arc's quench and re-ignition at zero crossing point; 2) The lower order harmonics signature: the harmonic current caused by the fault impedance non-linearity. 3) Random feature: the randomly extinguishing and bursting of fault current. Wavelet time frequency localization [9] has been used to extract the high frequency features. Measurements such as average tracking have been taken to eliminate the background interference. Simulation result proves that the combination of these features cover most HIF cases and can also distinguish HIF from many other interferences.

This paper is organized as follows: the analysis of field recorded data and a HIF modeling method using ATP-EMTP MODELS are presented in section II. The wavelet based high frequency detection principle is section III. The harmonic principle for non-linearity and fundamental principle for intermittent are presented in section IV, and the integrated scheme of these principles is detailed and tested in section V.

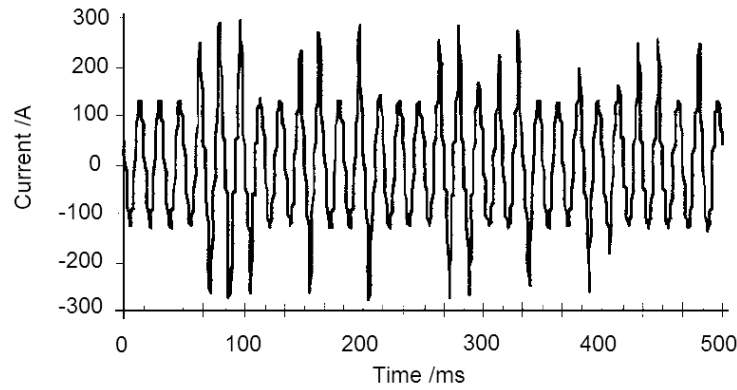
2 FIELD DATA AND MODELLING

Due to the lower steady state fault current, HIF features mostly come from the more detailed fault path characteristics. This is highly relying on the more unpredictable and complex fault conditions and environments. Various stage tests have been conducted to investigate these features of HIF. As a summary, these features can be classified as following:

- 1) The arcing features: HIF often burns with AC arcing at the fault point, due to the lower fault current, the arcing details features become phenomenal. Fig.1 (a) borrowed from Taiwan Power Co.' stage fault result shows a distinctive feature of the fault current at the crossing zero point, which can be regarded as an evident of the fault arc. The AC arc has a nature of crossing zero quenches and re-ignitions: every half cycle, when arc current cross zero, the injection power of arc goes down letting the arc path goes cooler, there will be a short time quench after current cross zero and then when voltage goes up the arc will be re-ignited. This contributes to the detail distortions around the fault current's zero-crossing points.
- 2) The harmonic features caused by the ground fault non-linearity. The path resistance is varying periodically according to the thermal condition of each cycle: when current increases, the heat of fault path accumulates, the conductance will increase as well. This will inject harmonics into the fault current. Also shown in Fig.1 (a), in a lower frequency scale, harmonics will be another distinctive feature of the HIF.
- 3) The random intermittent features as shown in Fig.1 (b) from Texas A&M University's stage fault result. Which can also be explained by a similar mechanism of arc/ground resistance: the HIF is often within free-air of better cooling conditions. Therefore, the arc/fault current is much easier to extinguish and remain quenching for many cycles. And it will re-ignite when the fault path condition randomly changes.



(a) Taiwan Power Co. 11kV feeder's test on grass [10]



(b) TAMU's data for erratic of HIF [5]

Fig. 1: HIF fault current with arcing distortions

In order to reconstruct these features, an HIF model has been developed based on arc thermal equation and ground resistance. Using MODEL of the ATP-EMTP program, this model is used to generate the fault current for further algorithm proposal and tests.

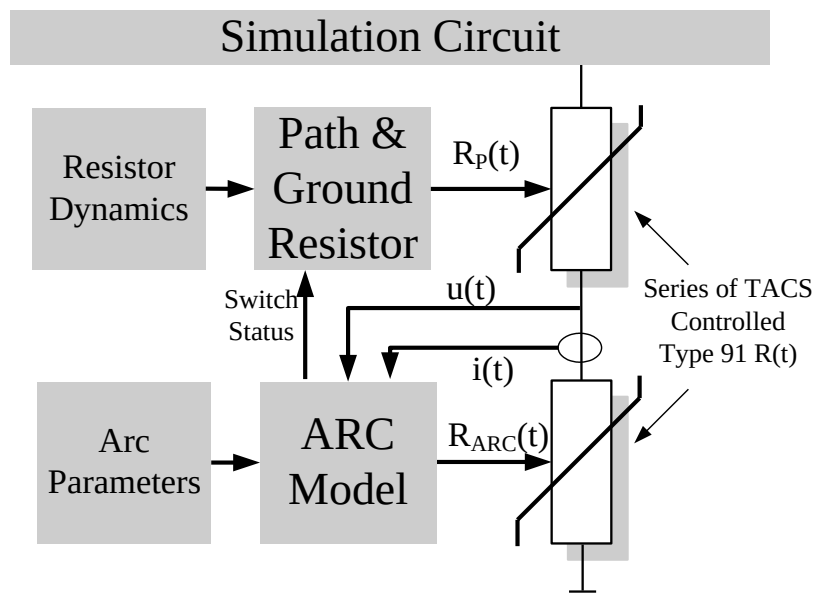


Fig. 2: HIF model in ATP-EMTP

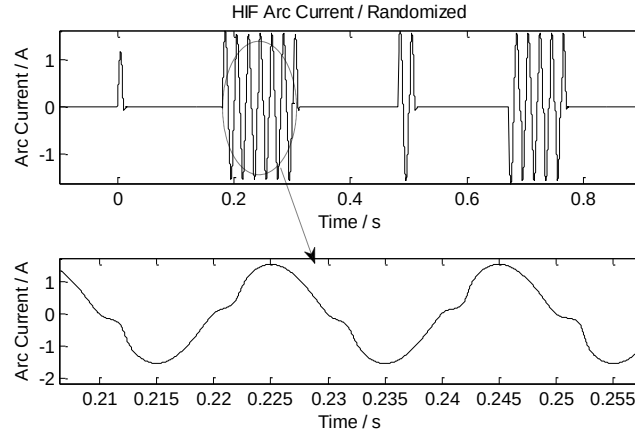


Fig. 3: Arc current of HIF model

The Mayr's equation with randomized parameters is used to construct the arc resistance R_{ARC} . The Mayr's equation is:

$$\frac{1}{g} \frac{dg}{dt} = \frac{d \ln g}{dt} = \frac{1}{\tau_m} \left(\frac{Ei}{P_m} - 1 \right) \quad (1)$$

Mayr's model has been proved suitable to depict the arc with lower current (less than 100A). In this equation, g is arc conductance per length; τ_m is time constant which represents the temperature inertia of the arc. P_m is the power loss of the arc per length; E is arc voltage per length. And i is arc current. Therefore, there are three pre-set parameters of the equation: the arc length, the power loss, P_m , and the time constant, τ_m . By introducing random factor into these parameters, the intermittent can be simulated.

The ground resistance R_P is a time variable resistance with a relative high value of non-conductive surface like coarse sand and shale, which is varying from 10k Ω to 5k Ω when fault conducted [11].

A simulation result is shown in Fig.3. Arc parameters are: time constant $\tau_m = 600\mu s \cdot (1 \pm 0.25 \cdot Rnd)$, Rnd is a uniform-distributed random number generated by EMTP and ranging from 0 to 1. $P_m = 9$ kW/m, arc length is 5 cm. Every half cycle after current crossed zero, a new τ_m will be generated preparing for the next-time current crossing zero. Arc is considered completely extinguished when $g < \exp(-300)$.

As shown in above Fig.3, HIF current is restricted by the higher path resistance R_P . HIF intermittent is simulated by varying the arc parameter every half cycle. HIF harmonic and detail waveform distortion is simulated through the thermal equation of Mayr's arc model. Therefore, this model reveals all these three distinctive features of HIF as summarized. Based on these features, individual principles have been proposed for detection and discrimination.

3 WAVELET BASED TRANSIENT DETECTION PRINCIPLE

3.1 Basic Principle

The distortion of the waveform caused by arc quenches and re-ignitions zero is one of the most significant features of HIF. These detailed distortions are relatively concentrated around the zero-crossing point. In order to capture this feature, there are two basic considerations: 1) to exact these high frequency distortions from its sinusoid carrier; 2) to locate these distortions around the zero-crossing point. In this paper, wavelet transform is used to achieve these two aspects. Particularly, dyadic wavelet transform is adopted for its feature of time shift invariance.

Dyadic wavelet transform is a suitable tool for the time-frequency localization. One major usage is to decompose and to describe a signal in both time and frequency domain used as a filter bank. This wavelet filter bank has many advantages comparing to traditional Fourier algorithm.

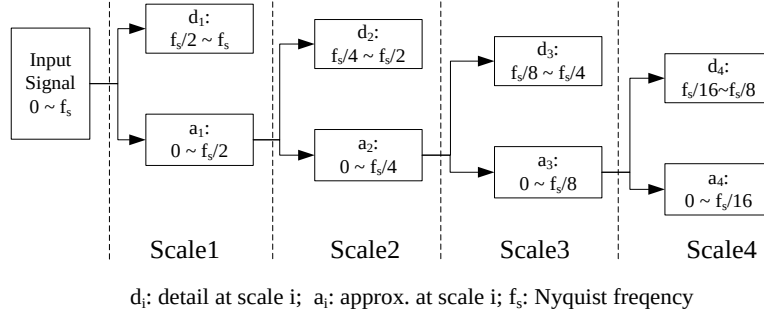


Fig. 4: Illustration of Wavelet Filter Bank

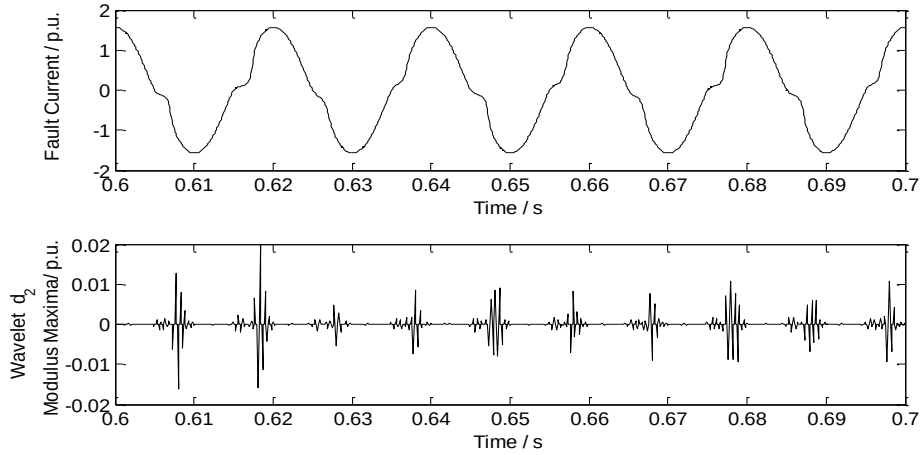


Fig. 5: Illustration of Wavelet decomposition

Wavelet filter bank has adaptive resolution corresponding to different decomposition scale. As shown in above figure, take the lower scale, like scale1 for example. It has the widest equivalent frequency bandwidth: $f_s/2 \sim f_s$ located at the higher upper half within the Nyquist frequency limit to depict the detail component d_1 . As a matter of fact, a wider window in frequency domain has a more accuracy equivalent window (a narrower window) in time domain. Therefore, higher frequency component can get a more accurate decomposition result in time domain. Also with the time shift invariance feature, dyadic wavelet transform is suitable to locate these high frequency distortion in particular time point with more accuracy. Moreover, this filter bank is a perfect recovery system that preserves most information of the input signal at each scale, and the modulus maxima (local extreme point) of each scale's detail component can represent the waveform distortion. A db4 wavelet is adopted to construct the wavelet filter bank and the sampling rate is set at 10 kHz. Following figure is an example of the processing of the wavelet filter bank on the fault neutral current. The modulus maxima of the d_2 component are used to represent the detail distortion:

The distortion is extracted by the wavelet detail component; moreover, these modulus maxima concentrate around the current crossing zero points. These form the detection criterion:

- 1) The total distortion level should be above a threshold.
- 2) The distortions should be concentrated around zero crossing points in each cycle.

3.2 Algorithm Design

In order to capture this particular HIF feature, a procedure has been designed to realize the above criterion. Firstly, a mechanism is applied to check the zero crossing points Z_p . Then a window is located around these Z_p . In every two cycles: two symbols are calculated:

$$SumIn = \sum |M_{d2}(t_i)| \quad t_i \in (Z_p - \delta_1, Z_p + \delta_2)$$

$$SumAll = \sum |M_{d2}(t_i)|$$

$$SumRatio = SumIn / SumAll$$

$Md2(t_i)$ is the modulus maxima of $d2$ in every two cycle. $SumIn$ is the absolute sum of the $d2$'s modulus maxima within this window at crossing zero. $SumAll$ is the absolute sum of all these detail components' modulus maxima of these two cycles. The $SumRatio$ is used to check if there are intensive distortions around the cross zero point: the criterion can be written as:

- 1) $SumAll > \text{Threshold}$ indicates distortions is above a setting level.
- 2) If 1) is true, and $SumRatio > 1-\delta$, indicates distortions are located around zero crossing point.

In the following Fig.6, the time window length is set as $1/4$ of a whole cycle and start from a crossing zero point. When fault randomly conducts, $SumRatio$ is above $1-\delta$ threshold. The distortion is around the crossing zero points, and an HIF suspicion will be issued.

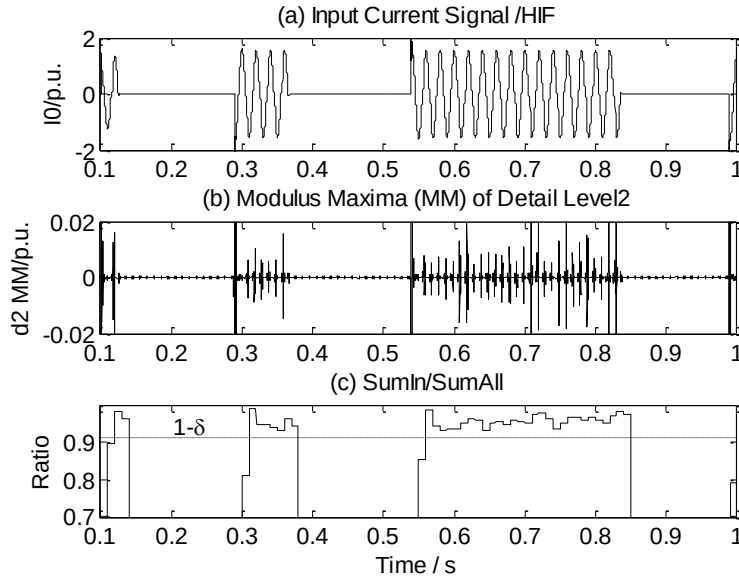


Fig. 6: Hi-frequency feature extraction. $1-\delta = 0.91$; time window = $1/4$ cycle

HIF can be captured by this zero-crossing feature in high frequency scope. However, high frequency feature cannot cover all HIF cases due to the complex fault situation. Also high frequency component may be vulnerable to transducer extenuation and noise interference. In order to improve reliability, harmonic and fundamental principles in lower frequency scope are integrated into this scheme as backup.

4 HARMONIC AND FUNDAMENTAL PRINCIPLES

4.1 Harmonic Principle

Harmonic is another important feature of HIF, as explained in section II, in an AC cycle, the resistance near zero will be greater than the resistance near peak. Therefore, harmonics can be a representation of this non-linearity. In this paper, third harmonic current with a phase difference around 180° comparing to fundamental current is used to represent this non-linear feature.

The detection criterion of harmonic principle is as following:

- 1) The fundamental amplitude is above a threshold.
- 2) Phase difference between 3rd harmonic and fundamental is within a range around 180° .
- 3) Amplitude ratio between 3rd harmonic and fundamental is above a threshold.
- 4) Above three requirements last for non-trivial time duration.

In order to eliminate the interferences of background harmonics such as saturations, non-linear loads, an average-samples based increment value (ASI) is used to extract the HIF fault feature. A one-cycle array of sampled points keep updating in the memory to tracking the average shape of current

waveform. If the amplitude of the newly sampled cycle is greater than the average samples array, the ASI array will be calculated by subtracting the average samples array from the newly sampled array, otherwise, if the newly sampled array is lower than average samples, the average samples array will be reset to the newly sampled array. This ASI array then will be used in the harmonic feature extraction.

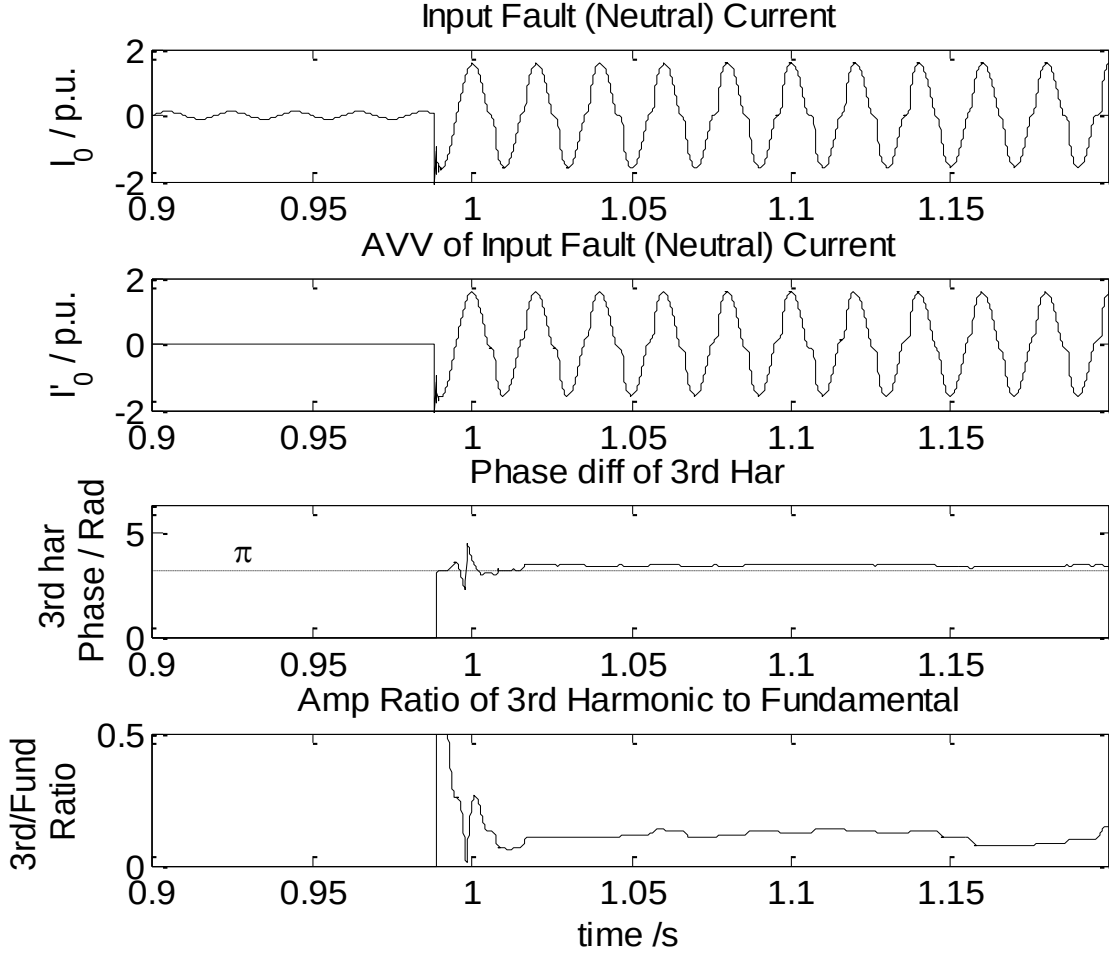


Fig. 7: Illustration of feature extraction of harmonic principle

Once the criterion has been satisfied for a pre-set duration, the HIF suspicion flag will be issued.

4.2 Fundamental Principle

The erratic increases and decreases of the amplitude in the scale of cycles is another focus for HIF detection. For normal loads and operations, the changes of waveform will be normally predictable: there will be no such lasting-randomly changes from cycle to cycle. In order to capture such HIFs features and to discriminate from normal operation, following aspects should be considered:

HIF fault burst current is the superimposed component mainly determined by the fault path resistance. Therefore, the increment amplitude should be used. An average-amplitude based increment value (AAI) is calculated and used for the fault detection. An adjustable tracking low-pass filter is used to track the average amplitude in the scale of the normal load change rate. The AAI will be calculated by subtracting the average amplitude from the newly-sampled current amplitude.

Fault evaluation is based on identifying the status of burst-or-extinguish by comparing the AAI to a sensitive threshold. Fault will be captured by counting the changes of burst-or-extinguish status of AAI within pre-set time duration.

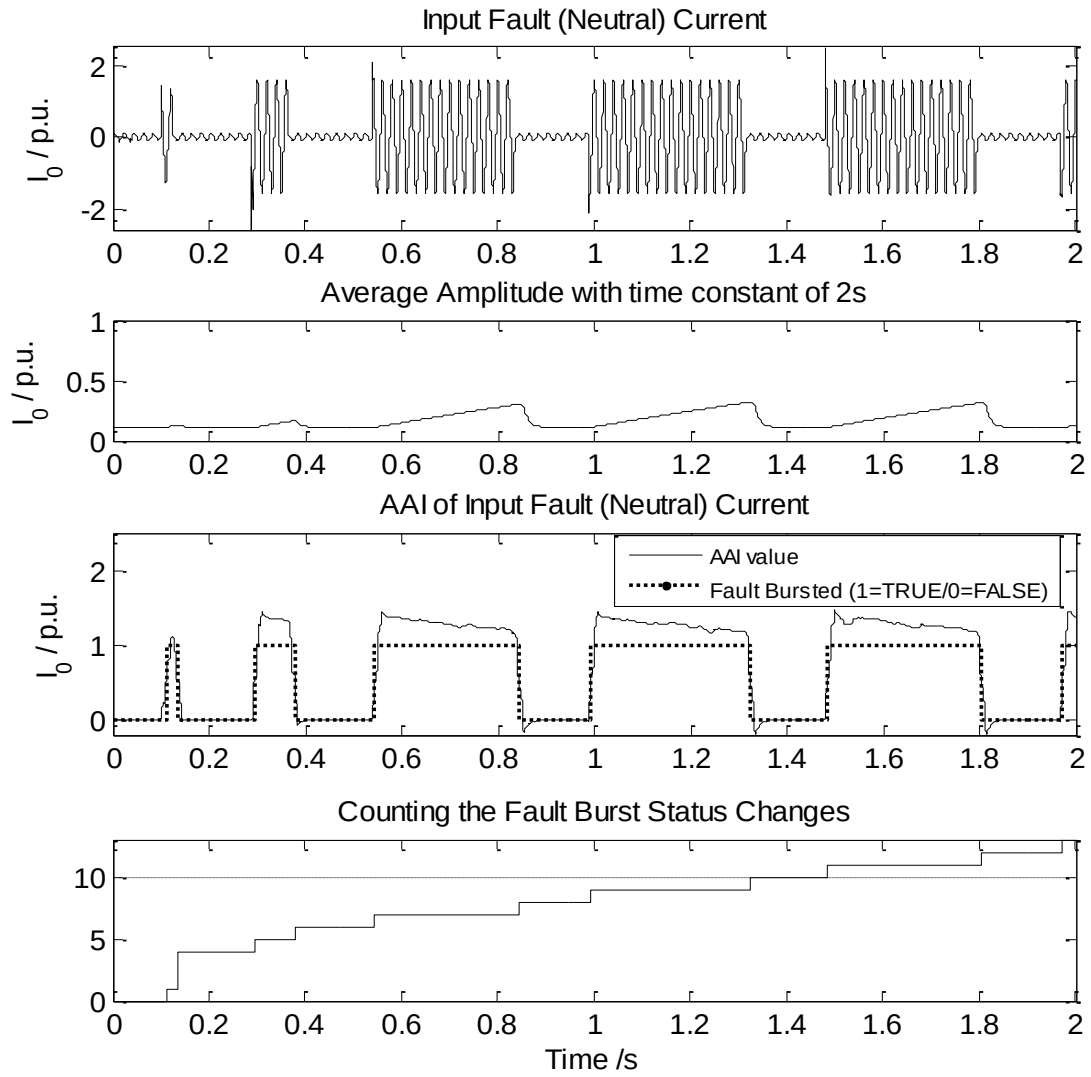


Fig. 8: Illustration of feature extraction of fundamental principle

To avoid mistaken the decrease as an increment, the tracking filter adjust its time constant when the AAI value is below zero, therefore, this AAI value can be a better representation of the increase of amplitude. Thus it is suitable for the detection of the HIF's intermittent conducting feature.

In above, the setting is configured as: if 10 times of state changes within 2 seconds presents, the HIF suspicion flag will be issued.

Following table is a summary of the performances of proposed principles under different situations:

Table 1: Summary of Performances of Proposed Principles

Principles:	Hi-frequency	Harmonic	Fundamental
HIF	Y	Y	Y/D
Non-linear load	N	N	N
Capacity Transient	N	N	N
CT saturation	D	Y/D	N

Y= Operates, N= Restrains, D= Depend on situations.

5 CONCLUSION

In this paper, following aspect has been discussed:

1. The HIF is studied according to the field recorded data. Some of the most significant feature of HIF has been summarized: the arcing feature, the harmonic feature, and the intermittent feature.
2. An HIF model has been developed based on arc thermal equation. Using this model in ATP-EMTP, the three most significant features have been reconstructed.
3. Three detection principles aiming at these significant features have been proposed: The high frequency principle is designated for arc detail distortion; the harmonic principle using the increment samples based on average is designated for earth fault non-linearity detection. Fundamental principle based on increment amplitude is designated for the detection of intermittent burst-extinguish of HIF current.
4. These three principles have been tested individually under different fault situation, the EMTP results shows that with the integration of these three principles' results, the integrated scheme can cover a wider range of the HIF situations and can significantly improve the sensitivity as well as the security of the HIF detection.

REFERENCES

- [1] PSERC_WorkingGroup_D15, "High Impedance Fault Detection Technology," Report of PSRC (www.pserc.org). March 1, 1996.
- [2] D. I. Jeerings and J. R. Linders, "Unique aspects of distribution system harmonics due to high impedance ground faults," *Power Delivery, IEEE Transactions on*, vol. 5, pp. 1086-1094, 1990.
- [3] A. E. Emanuel, D. Cyganski, J. A. Orr, S. Shiller, and E. M. Gulachenski, "High impedance fault arcing on sandy soil in 15 kV distribution feeders: contributions to the evaluation of the low frequency spectrum," *Power Delivery, IEEE Transactions on*, vol. 5, pp. 676-686, 1990.
- [4] R. Patterson, W. Tyska, B. D. Russell, and B. M. Aucoin, "A Microprocessor-Based Digital Feeder Monitor with High-Impedance Fault Detection," in *Forty-Seventh Annual Conference for Protective Relay Engineers Texas A&M University, College Station, Texas, USA*, 1994.
- [5] C. L. Benner and B. D. Russell, "Practical high-impedance fault detection on distribution feeders," *Industry Applications, IEEE Transactions on*, vol. 33, pp. 635-640, 1997.
- [6] M. Michalik, W. Rebizant, M. Lukowicz, L. Seung-Jae, and K. Sang-Hee, "High-impedance fault detection in distribution networks with use of wavelet-based algorithm," *Power Delivery, IEEE Transactions on*, vol. 21, pp. 1793-1802, 2006.
- [7] M. Al-Dabbagh and L. Al-Dabbagh, "Neural networks based algorithm for detecting high impedance faults on power distribution lines," 1999, pp. 3386-3390. Vol. 5.
- [8] N. I. Elkalashy, M. Lehtonen, H. A. Darwish, M. A. Izzularab, and A.-M. I. Taalab, "DWT-Based Investigation of phase currents for Detecting High Impedance Faults Due to Leaning Trees in Unearthed MV Networks," in *Power Engineering Society General Meeting, 2007. IEEE, 2007*, pp. 1-7.
- [9] Y. Li, X. Dong, Z. Q. Bo, N. F. Chin, and Y. Ge, "Adaptive reclosure using high frequency fault transients," in *Developments in Power System Protection, 2001, Seventh International Conference on (IEE)*, 2001, pp. 375-378.
- [10] H. Shyh-Jier and H. Cheng-Tao, "High-impedance fault detection utilizing a Morlet wavelet transform approach," *Power Delivery, IEEE Transactions on*, vol. 14, pp. 1401-1410, 1999.
- [11] "IEEE guide for measuring earth resistivity, ground impedance, and earth surface potentials of a ground system of a ground system," *IEEE Std 81-1983*, 1983.
- [12] S. Mallat and W. L. Hwang, "Singularity Detection and Processing with Wavelets," *IEEE Transactions on Information Theory*, vol. 32, pp. 617- 643, March 1992.
- [13] B.M. Aucoin and R.H. Jones, "High Impedance Fault implementation issues," *IEEE Transactions on Power Delivery*, vol. 11, Number 1, pp. 139- 148, January 1996.