Location Identification of High Impedance Faults Using Synchronized Harmonic Phasors

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***Abstract*—This paper proposes a novel method to identify the location of a high-impedance fault (HIF) in a power distribution system. The developed method uses *synchronized harmonic phasors* with focus on the third harmonic component. Such harmonic synchrophasors could be provided in practice, e.g., by distribution level phasor measurement units, a.k.a, μPMUs. In this regard, the location of the fault can be estimated based on the impedance that is calculated from the third harmonic voltage and current synchrophasors produced by the fault and captured by the μPMUs. In this method, both resistance and inductance are estimated, to allow fault location identification even in a network with multiple type conductors. Note that, the fault does not need to be fully observable. As few as two μPMUs would be sufficient to estimate the HIF location at least to certain accuracy. The effectiveness of the proposed method is demonstrated through simulating the IEEE 33 bus test system in PSCAD.**

I. Introduction

Most interruptions in electric power systems are due to fault occurrences at distribution level. Solving the challenging problems of fault detection and fault location identification are of great interest to utilities. These problems are particularly difficult to solve when it comes to high impedance faults (HIFs). The HIFs are typically caused by electrical contact between an energized conductor and a non-conducting object, such as fallen conductor on soil or contacting tree limb.

Unlike other faults that often lead to huge fault currents, the HIFs result in a very low fault current within a typical magnitude ranging from 40A to 100A. Therefore, the HIF fault current often does not exceed the predetermined distribution level protective devices settings, i.e., mostly pick-up current of overcurrent relays and blowing fusible link of fuses. That is why the HIF detection and localization is a challenging problem, since it imitate like a typical large load and may be energized for a long time. Therefore, utilities are interested in finding new ways to accelerate the HIF location process due to technical and economic issues, as well as for human safety. Note that, the voltage between the energized conductor and external object poses safety problems for human lives.

Due to the importance of problem, several methods have been proposed in literature for HIF detection in distribution systems. From time domain point of view, some algorithm based on ration ground relay [1], proportional relay [2], and feature extraction from smart relay [3] were employed for fault detection. Also, analyzing the transient behavior of a signal in time and frequency domains provides a solution to detect HIF through wavelet methods [4]. In the frequency domain, using Fourier transforms, several efforts have been conducted based on application of harmonic components in identifying the HIF [5], [6]. Among the proposed methods in literature, the third harmonic component are much more applicable to detect the HIF, since the third harmonic components in HIF current has key characteristic which distinguishes it from other harmonic sources existing in the system [7].

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Besides the mentioned efforts to detect the HIF, several methods based on impedance calculation through fundamental component is proposed to find the HIF location [8]–[10]. However, these methods are highly prone to error caused by impedance of fault. In [11] the authors propose a parameters estimation method to decrease the effect of fault impedance. Besides using the fundamental frequency component, some approaches are developed for HIF detection based on monitoring transient signals with high frequency components [12], [13]. Also, a hybrid method based on high frequency and impedance calculation is developed in [14]. However, the HIF location using fundamental frequency components is not reliable, since as mentioned before the HIF current magnitude and typical load current magnitude are similar.

To the best of our knowledge, the HIF location has been less investigated using higher harmonic impedances, due to the lack of high-resolution monitoring devices in distribution level. While in recent years, the high resolution measurement devices have been propagated in distribution level. Thus, this paper aims to propose a new approach for HIF location using distribution level phasor measurement units, a.k.a, μPMUs. Most of HIF are accompanied with arcing characteristic [15], which leads to nonlinear current injection into the system. Fault current contains harmonic components, so the HIF can be regarded as a current harmonic source. The proposed method analyzes the system with considering this harmonic source and try to calculate harmonic impedances to estimate the location of HIF. To such aim, it is assumed that the network is equipped with μPMUs which are capable of capturing synchronized harmonic phasors of voltage and current. As the main advantages of the method, the proposed method does not dependent to fault impedances and is able to calculate resistance and inductance separately, which is desirable for the network with multi-type conductors.

II. HIF Model and Characteristic

Because of the stochastic nature of the HIFs, it is not possible to represent every HIF by a single model; yet, we can take into

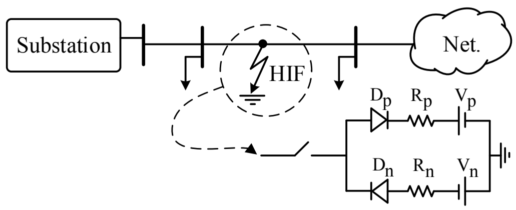

Fig. 1. Equivalent circuit model for HIF [17].

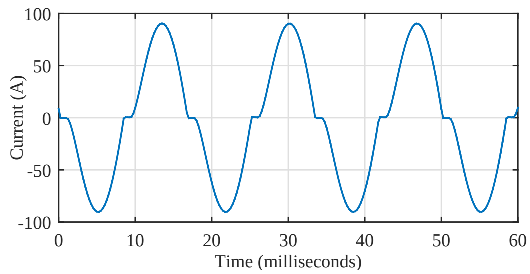

Fig. 2. HIF current derived from proposed model.

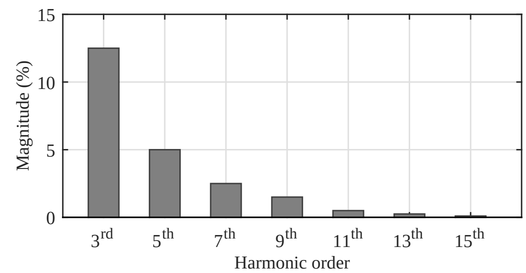

Fig. 3. High order harmonic component of HIF current.

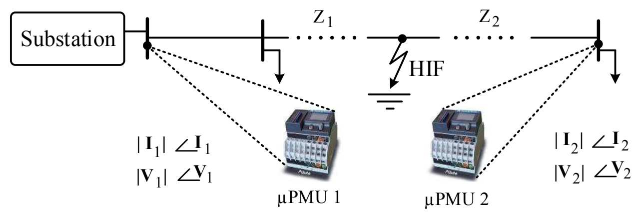

Fig. 4. High order harmonic component of HIF current.

consideration for the purposes of our analysis. Most studies on HIF are done using experimental [7], [8]. The most principle characterization of HIFs is identified as an electric arcing that is due to poor contact between the conductor cable and the earth or with an earthed object [16].

In this paper, we use an equivalent circuit model for HIF that was developed in [17], see Fig. 1. This model to a great extent is in line with the actual HIF feature and properly characterize HIF accompanied with arcing. As can be seen in Fig. 1, this model consists of two legs, each one includes a DC source, resistor, inductor, and a diode. The DC sources serves to represent the arcing voltage of air with earth or earthed object. The two resistances and inductances are considered as the impedance of contacting object. The two DC sources are placed with different polarity. In the upper leg, when the line voltage is greater than the DC voltage, the fault current flows through the ground. Otherwise, when the voltage is less than the DC source in the lower leg, the fault current reverses backward from the ground. However, once the line voltage is between the DC voltage sources, none of the legs provides a path to flow the fault current. By adjusting the value of the DC sources, inductances, and resistances in the two legs, the fundamental characteristics of the HIF current can be resembled.

The HIF current signal that is derived from the above model is depicted in Fig. 2. As shown in Fig. 2, HIFs have inherently non-linear and always result in distorted currents. Therefore, harmonic analysis is critical in the evaluation and determination of HIFs. In particular, it is documented, from several experiments, that the third harmonic is significant in the HIF current. Fig. 3 shows the high order harmonic component corresponding to the fault current in Fig. 2. As can be seen, among the high order harmonic components, the third harmonic is predominated. In this study, the proposed method for the HIF location is based on analysis of third harmonic pahsors.

III. Proposed Method

When a fault occurs in distribution feeder, the outage management process is initiated by fault detection and identification. In the case of HIF, the fault detection is a challenging problem since the fault current can *not* be distinguished from load current considering the fundamental frequency component. In this context, as mentioned in the literature, the third harmonic would be a reliable indication for HIF occurrence. This harmonic component also can be used for fault location procedure. The third harmonic produced by HIF can be capture via measurement devices installed across the network. Considering these measurements together leads to estimate the distance of fault from each one, thereby locating the HIF.

In order to clarify the proposed method, a simple feeder shown in Fig. 4 is used. The feeder is equipped with two μPMUs installed at the beginning and at the end of the feeder is shown in Fig. 4. Suppose an HIF occurrence in feeder, the installed measurements at the beginning and end of the feeder record the fault current. The HIF can be diagnosed using the third harmonic component of fault current. Beside this, the calculated impedances from each μPMUs to faulted-point can be used to find the exact location of HIF. Next, the step-by-step of the proposed method for HIF location will be described.

A. Harmonic Component Produced by HIF

Power systems have time-varying harmonics due to applications of non-linear loads, switching, and fault events. In order to carry out harmonic analysis of HIF, the harmonic component of voltage and current caused by HIF should be distinguish from those of produced by other sources of harmonic. In this regard, following diagnosing a disturbance as a HIF through analyzing third harmonic component of fault current captured by μPMUs, the change of measured voltage and current caused by HIF can be calculated through comparing pre-fault and post-fault measurements as:

$$V_{h,i} = V_{h,i}^{post} - V_{h,i}^{pre}, \tag{1}$$

$$I_{h,i} = I_{h,i}^{post} - I_{h,i}^{pre}, \tag{2}$$

where the subscript h stands for the order of the harmonics, of interest in this paper is $h = 3$. Also, the subscript i refers to the μPMU 1 and 2. In addition, the superscript *pre* and *post* represents the pre-fault and post-fault, respectively. As mentioned before, the HIF inject a significant amount of third harmonic current in the network. Accordingly, the HIF can be assumed as a third harmonic current source which inject current harmonic current [18]. Based on the superposition method, the third harmonic component of voltage and current caused by this harmonic current source can be obtained through subtracting the post-fault and pre-fault third harmonic voltage and current for each measurement.

B. Harmonic Impedance Calculation

In the previous step, the voltage and current produced by HIF, as a harmonic source, at measurements point of the system was obtained. Without loss of generality we assume that the injected third harmonic fault current flows through substations. This assumption derived from the fact that the impedance of the substation seen from fault point is much less than the loads impedance. Therefore, the current flow through the load points between the fault point and substation is negligible compared with the fault current flow through substations. The impedance between fault point and μPMU can be calculated as:

$$Z_{h,if} = \frac{V_{h,i} - V_{h,f}}{I_{h,i}}, \tag{3}$$

where subscribes i and f denotes the location of μPMUs and fault, receptively. In (3), the voltage at fault point is not measured by μPMUs. Considering both μPMUs, there is a set of two equations with three unknowns. By subtracting each two formulations related to two μPMUs and knowing the total impedance between two μPMUs, the impedances between fault point and measurement points can be calculated as:

$$Z_{h,if} \cdot I_{h,i} - Z_{h,jf} \cdot I_{h,j} = V_{h,i} - V_{h,j}, \tag{4}$$

$$Z_{ij} = Z_{h,if} + Z_{h,jf}, \tag{5}$$

where, the voltages and currents are related to the harmonic components obtained from post-fault and pre-fault measurements in superposition method. Among the harmonic component, the third harmonic is predominated in fault current. Accordingly, calculation based on the third harmonic would leads to more accurate results. It is also worth to mention that in these calculation measurements are assumed to be synchronized.

IV. Case Study

This section intends to apply the proposed framework to a test system to demonstrate the effectiveness of the proposed method for HIF location. To such aim, IEEE 33 bus test system is considered at test system. The single line diagram of the feeder is shown in Fig. 5. The technical data of this network can be found in [19]. It is assumed that the test system is equipped by two or three μPMUs, in different scenarios, while the HIF locations are marked in the Fig. 5. The proposed method is examined in two scenarios: 1) *first scenario* where we have access to the data of μPMU 1 and 2, and 2) *second scenario* where we have access to the data of μPMU 1, 2, and 3. The analysis is followed by conducting an under-contingency sensitivity analysis.

A. First Scenario

In this scenario, it is assumed that two μPMUs are deployed at bus number one and bus number 18 of the network. By employing the measurements of these μPMUs, the location of the HIF can be determined between bus number one and bus number 18. It means that the line connecting bus number one to bus number 18 is considered as main feeder and the distance of HIF on main feeder to each μPMUs is calculated. The results of HIF occurrence in three different points are reported in Table I.

As shown in Table I, for the first HIF event, i.e., *HIF 1*, the μPMUs capture third harmonic voltage and current phasors. Based on the obtained measurements, it is obvious that that the third harmonic current produced by HIF flow towards bus number one where the network originated from. In addition, the flow of current toward end of the feeder (μPMU 2) is negligible. The calculated impedance between HIF and μPMU 1 is $\bar{Z}_{h,f1}$, while the actual impedance is $Z_{h,f1}$. The different between the calculated and actual impedance derived from the fact that some leakage HIF currents flow towards loads, which the HIF current seen at μPMU 1 is not equal to the total HIF current produced at HIF point. Based on the calculated impedance between HIF point and μPMU 1 as well as μPMU 2, the location of HIF can be approximated somewhere near the bus number six.

Similarly, for $HIF2$ and $HIF3$, the calculated impedances between HIF point and μPMU 1 as well as μPMU 2 demonstrate the location of HIF at the main feeder and near the bus number nine. Unlike to $HIF1$ and $HIF2$, where located on main feeder, $HIF3$ occurs on lateral feeder. The calculated impedance for this case is roughly similar to $HIF1$. This fact shows that in case a fault occurs on lateral feeders, the two μPMUs located at the beginning and end of main feeder will estimated the fault location near the bus which lateral originated from. Therefore, based on the impedance calculation, if the location of HIF is near a bus connected to lateral, the bus and the related lateral will be counted for fault zone, and should be investigate for fault. This fact shows that the laterals are not observable through μPMUs installed at the beginning and end of the feeder. Table I provides the error of calculated impedance for each HIF events. Based on the results, the errors of calculated resistance and inductance are different. In some cases, the errors of these two parts are in opposite direction, thereby compensating each other and lead to reduction in error of calculated impedance magnitude.

B. Second Scenario

In this case, another μPMU is added to bus number 33, as end of the lateral connected bus number six. By doing so, $HIF3$ will be observable and unlike to first case, their locations on this lateral is specified. In this case, by considering μPMU 1 and μPMU 3, the distances of fault respect to μPMU 1 and μPMU 3 is estimated based on calculated impedance. The results of

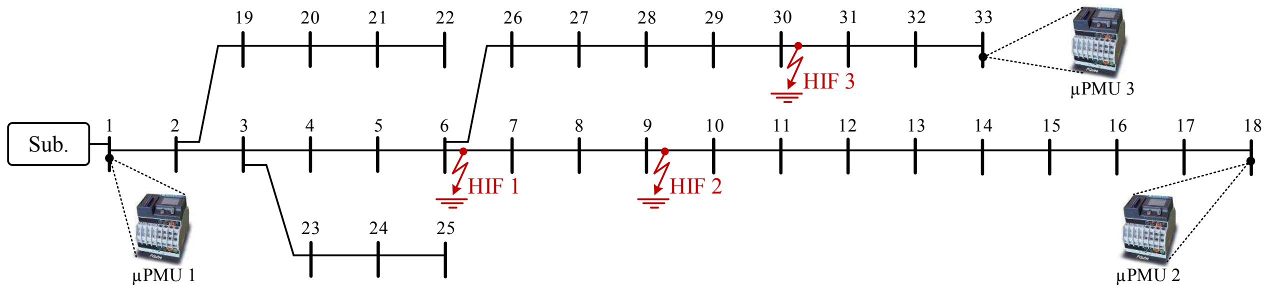

Fig. 5. Under-study feeder.

TABLE I
MEASURED THIRD HARMONIC IMPEDANCE AND CORRESPONDING ERRORS IN *First Scenario*

Location	$Z_{h,f1}$	$Z_{h,f1}$	$\Delta Z_{h,f1}$ %	$\lvert\Delta Z_{h,f1}\rvert$ %	$Z_{h,f2}$	$Z_{h,f2}$	$\Delta Z_{h,f2}$ %	$\lvert\Delta Z_{h,f2}\rvert$ %
HIF 1	2.51+j3.36	2.15+j4.18	16.7-j19.6	10	8.56+j24.12	8.92+j23.3	-4+j3.5	2.6
HIF 2	4.44+j9.14	4.08+j8.93	8.8+j2.3	3.4	6.63+j18.34	6.98+j18.55	-3.7-j1.1	1.6
HIF 3	2.63+j3.4	2.15+j4.18	22-j18	8.5	8.44+j24.08	8.92+j23.3	-5.3+j3.3	2

three HIF in different location of the network are provided in Table II.

According to results of Table II, the current phasors at μPMU 1 and μPMU 3 demonstrate that the HIF current flow towards the μPMU 1 and the current flow towards μPMU 3 is negligible. Based on the calculated impedance between the HIF and μPMU 1 as well as μPMU 3, the distance of HIF from μPMU 1 and μPMU 3 is determined. In case of $HIF1$, the calculated impedance release that the HIF location is somewhere near bus number six. Also, the results of $HIF1$ event is similar to $HIF2$ event. This fact shows that for the HIF occurs somewhere between bus number six and bus number 18, the location of HIF is estimated near bus number six. In other words, locations between $HIF2$ and μPMU 2 are blind spot for HIF location done by measurements of μPMU 1 and μPMU 3. Accordingly, in case $HIF1$, the area between $HIF1$ and μPMU 2 are also investigated for fault. $HIF3$ is located on the lateral. Based on the calculated impedances, the distances of HIF respect to μPMU 1 and $HIF3$ estimated HIF location near bus number 30. The error associated with the impedance calculation in this case is shown in Table II.

In the first case, it was obvious that the lateral connected to bus number six is unobservable for HIF location. However, by adding another μPMUs, i.e., μPMU3, the lateral become observable for HIF location. Table III presents all the impedance calculated via combination of μPMU 1 and μPMU 2 as well as μPMU 3 measurements. Based on these impedances, by comparing the estimated distances obtained from combination of measurements, the location of HIF can be estimation on main feeder or the lateral. More specifically, considering these combinations addresses the issue of blind spots for each two measurements combination.

C. Under-contingency Sensitivity Analysis

Most methods proposed for fault location are prone to a degree of error. The main error of the methods derived from the lack of information regarding fault parameters estimation. This issue is more critical for HIF, due to stochastic nature of fault parameters such as arcing. In this case, it is difficult to have an accurate estimation of the fault distance. However, our proposed method is independent of fault parameters and can estimate fault distance without knowing any information regarding fault parameters. Accordingly, this method to a great extent makes sure regarding the accuracy of estimated distance. Moreover, this method by separately estimating the resistance and inductance could be efficiently used in the network with multi-type conductors in order to estimate the fault distance. To have a better view with respect to the accuracy of the proposed methods, the error of estimated impedance for HIF along the main feeder is investigated through Fig. 6, where $|\Delta R_{h,fi}|$, $|\Delta X_{h,fi}|$, and $|\Delta Z_{h,fi}|$ denote the error of resistance, inductance, and impedance, respectively, all magnitudes.

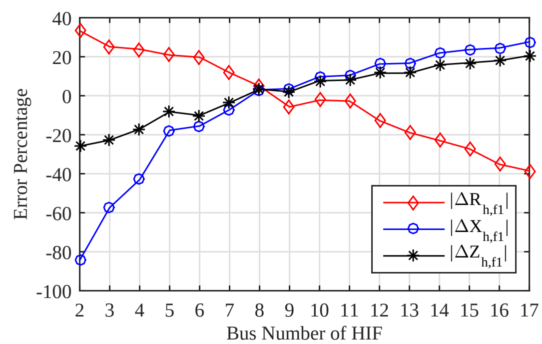

Fig. 6. Error variation in resistance, inductance, and impedance versus the location of HIF event.

As shown in Fig. 6 errors are provided with direction to have a meticulous analyzing of them. For HIF near the substation, the error of the calculated impedance is high, derived from the tiny amount of calculated impedance. However, this amount of error is not a big deal in fault location, because it just to an extent increase the fault zone. By getting away from substation, the error of estimated resistance and inductance will be decrease, such that for HIFs at middle of the feeder these amounts are at their minimum errors. However, by increasing distance, the resistance is estimated lower than the true resistance, while the inductance is estimated greater than

TABLE II
MEASURED THIRD HARMONIC IMPEDANCE AND CORRESPONDING ERRORS IN *First Scenario*

Location	$\bar{Z}_{h,f1}$	$Z_{h,f1}$	$\Delta Z_{h,f1}$ %	$\|\Delta Z_{h,f1}\|$ %	$\bar{Z}_{h,f3}$	$Z_{h,f3}$	$\Delta Z_{h,f3}$ %	$\|\Delta Z_{h,f3}\|$ %
HIF 1	2.28+j3.6	2.15+j4.18	6-j13.8	9.5	4.14+j12.46	4.27+j11.88	-3.1 +j4.9	3.8
HIF 2	2.42+j3.63	2.15+j4.18	12-j13.1	7.3	4+j12.43	4.27+j11.88	-12.5+j13	7.23
HIF 3	4.47+j12.21	5+j10.73	-11+j13.7	9.9	2.15+j4.17	1.62+j5.65	32.7-j28	20

TABLE III
MEASURED IMPEDANCE THROUGH THE COMBINATION OF μPMUS

Measurement	$\bar{Z}_{h,fi}$	HIF 1	HIF 2	HIF 3
μPMU 1 and 2	$\bar{Z}_{h,f1}$	2.51+j3.36	4.44+j9.14	2.63+j3.4
	$\bar{Z}_{h,f2}$	8.56+j24.12	6.63+j18.34	8.44+j24.08
μPMU 1 and 3	$\bar{Z}_{h,f1}$	2.28+j3.6	2.42+j3.63	4.47+j12.21
	$\bar{Z}_{h,f3}$	4.14+j12.46	4+j12.43	2.15+j4.17

its true values. The current measures at substation accounts for this phenomenon. As previously explained, there are some leakage currents which flow through the load points, causing the currents measured at substation to be different from total fault current. By increasing distance, the difference between these currents increase, causing the resistance and inductance errors to in-crease in the mentioned way. However, the error of impedance magnitude is always lower that both resistance and inductance error, which is due to error compensation of resistance and inductance in impedance magnitude. Considering errors of estimated distances provides an overview regarding the placement of μPMUs for fault location. In this regard, by increasing the number of μPMUs along the feeder, not only does the suspected area of fault decrease, but the error of estimated distance to fault in the fault area decreases as well.

V. CONCLUSIONS

This paper proposed a method to locate HIF in distribution systems. The method was developed based on third harmonic analysis of voltage and current synchrophasors that are measured in a network undergoing fault. In this regard, the HIF can be treated as a third harmonic source which injects current harmonic into the network. Synchronized voltage and current pahsors captured by μPMUs can be used to calculate impedances in order to estimate the distances to fault from each μPMU. Based on the results ant findings, just by having two μPMUs installed at the beginning and end of the feeder, the location of HIF can be determined on main feeder. However, the lateral points are blind spots for fault location, which can be addressed by installing μPMUs at the end of the laterals. The developed method is independent of fault parameters. In addition, by estimating resistance and inductance separately, the proposed method is desired for networks consisting of multiple types of conductors. The error of estimated impedances in this work is originated from leakage currents flowing to the load points. The number of μPMUs can be increased to enhance location accuracy.

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