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Power line fault location using the Complex Space-Phasor and Hilbert-Huang Transform

***Abstract**. Fault location finding in power system is very important problem in power system monitoring. Moreover, demand for high grid availability are crucial for TSO's contracts. Many scientific papers are published on mentioned theme, along with efforts in transmission and distribution system operators about improving fault location accuracy. Recently, signal processing methods like Wavelets and Hilbert-Huang Transform are introduced in fault location procedure. In this paper, a new approach to power system fault signal processing is proposed. Three-phase fault voltages are converted to the vector of absolute values of its complex-space phasor. This vector represents fault traveling wave and it is further processed for fault location finding with Hilbert-Huang transform. The simulation results show that proposed method allows better accuracy in comparison to earlier procedures.*

***Streszczenie.** Lokalizacja zwarć w liniach przesyłowych jest ważna z punktu widzenia prawidłowego funkcjonowania linii przesyłowych. W ostatnim czasie zaproponowano wiele metod lokalizacji zwarć za pomocą falek czy transformaty Hilberta-Huanga. W tym artykule proponujemy przekształcenie trójfazowych sygnałów napięciowych za pomocą wektora przestrzennego. Rezultaty symulacji wykazują poprawę dokładności lokalizacji zwarć tą metodą w porównaniu z wcześniej opisanymi algorytmami (**Lokalizacja zwarć w liniach elektroenergetycznych za pomocą wektora przestrzennego i transformaty Hilberta-Huanga**)*

Keywords: Fault Location, Complex-Space Phasor, Empirical Mode Decomposition, Hilbert-Huang Transform

Słowa kluczowe: lokalizacja zwarć, zespolony wektor przestrzenny, rozkład na mody empiryczne, transformata Hilberta-Huanga.

Introduction

Fault location in electric power system has become very important with deregulation of electricity market and consequently drastically increased demands for grid availability. Historically, many authors and researchers published various ideas and solutions on this subject. In mathematical sense the leading idea was firstly to decouple measured power system quantities (three-phase voltage and currents). In that way, influence of mutual inductance, reactance and capacitance in observed part of power system is lost. As a result, the set of decoupled, physically independent equations are obtained. Those equations in different transformations are usually called *modes*, and those modes usually become input signals for further processing. The method of symmetric components is also a decoupling transformation and it is widely used for analysis and visualization of the three–phase electric circuits. This method has strong limitations, e.g. it allows the analysis of the stationary waveforms only [1]. However, power system fault location issue is improved in last few years with introducing a signal processing methods in power systems studies and analysis. Those methods usually demand one-dimensional signal as input. There exist many possible ways of description of three–phase quantities which aim to simplify the analysis or modeling of electric systems. One of them is the complex space–phasor [1].

In recent years many new methods in power system fault location using signal processing methods like Wavelets and Hilbert-Huang transform are published [7], [8]. Novel methods use traveling wave nature of fault transient voltages and currents in power systems. For obtaining of input signal for processing mathematical transform as Karrenbauer and Clarke's transform are used. As a result of mentioned transform applied on three-phase signal of measured i.e. busbar voltages, three *modes* are obtained (two aerial and one ground mode in Clarke's and two line-modes and one landline mode in Karrenbauer's transform). Every of those modes are carrier of some physical characteristics of measured three-phase quantities. In these procedures only one mode is used as input for processing, which means that some of physical information from real power system is lost. This is especially important for single phase to ground (SLG) faults, where ground mode contains important information - (usually aerial mode is used for processing in case of Clarke transformation and line mode for processing in case of Karrenbauer transformation of measured quantities). On the other hand, complex-space phasor is a one-dimensional signal which is a carrier of all physical characteristic of measured quantities and is more convenient as preprocessing stage to the the state-of-art signal processing methods like Hilbert-Huang transform. In this article we apply the complex-space phasor in combination with Hilbert-Huang transform which leads to higher accuracy of fault location.

Complex-space phasor

Complex-space phasor $\underline{f_P} = f_\alpha + j \cdot f_\beta$ of a three-phase system f_R, f_S, f_T is given by [1]:

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \sqrt{\frac{3}{2}} & -\sqrt{\frac{3}{2}} \end{bmatrix} \cdot \begin{bmatrix} f_R \\ f_S \\ f_T \end{bmatrix} \tag{1}$$

It describes, in addition to the positive-sequence component, an existing negative-sequence component, including all harmonic and non-harmonic frequency components of the signal. The point is that in one-dimensional signal all physical characteristics and information about measured electrical quantities are comprised. There is not any information dissipating in different modes. The absolute value of the complex-space phasor of measured voltages is processed with Hilbert-Huang transformation.

Since HHT method is described in detail in [9], here we present a short reference.

The Hilbert Huang transform

The development of the HHT was motivated by the need to describe nonlinear distorted waves in detail, along with the variations of these signals that naturally occur in nonstationary processes [8]. This method was recently applied in power system studies for analyzing non-stationary and nonlinear signals (see, for example, [2-7]). Its application to the transient signals from faulted power system is particularly advantageous. HHT is composed of empirical mode decomposition (EMD) and the Hilbert transform (HT).

Empirical mode decomposition (EMD)

The central part of HHT is EMD - a sifting process which results in signal decomposed into a number of intrinsic modes. The original signal S(t) in a that way, can be expressed as:

(2) $$S(t)=\sum_{i=1}^{n}c_i(t)+r_n(t)$$

In fact, EMD is similar to Wavelet decomposition (Figure 1).

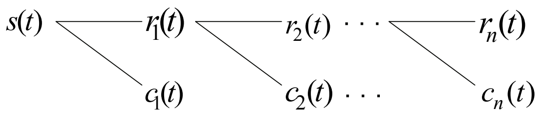

Fig.1. Decomposition of s(t) signal with EMD

Important is that first IMF $c_1(t)$ contains the highest frequency component of processed signal and this IMF is usually used as input for further processing with Hilbert Transform [9].

Hilbert Transform

The Hilbert transform of a real-valued time domain signal $X(t)$ is $Y(t)$, such that

(3) $$Y(t)=H[x(t)]=\int_{-\infty}^{\infty}\frac{x(\tau)}{\pi(t-\tau)}d\tau$$

$X(t)$ and $Y(t)$ form an analytical signal:

(4) $$Z(t)=X(t)+Y(t)=A(t)e^{j\theta(t)}$$

with

(5) $$A(t)=\sqrt{X^2(t)+Y^2(t)}$$

and

(6) $$\theta(t)=\tan^{-1}\left[\frac{Y(t)}{X(t)}\right]$$

where $A(t)$ and $\theta(t)$ are instantaneous amplitude and instantaneous phase, respectively. Instantaneous frequency is given by:

(7) $$f(t)=\frac{1}{2\pi}\frac{d\vartheta(t)}{dt}$$

Calculated instantaneous quantities reveal the traveling wave nature of voltages and currents in power system only when HHT is applied on signal pre-processed with EMD [7].

Traveling wave fault location using HHT

After fault in power system occurs, a non-linear signal of transient traveling wave is generated and runs along faulted transmission line to both ends of the line. Those traveling waves contain information about fault nature. The fault initial traveling wave has a wide frequency spectrum - from DC component to high frequencies. When such fault traveling wave arrives at the substation busbar, it will change incisively, i.e. traveling wave head will present the sudden change in the time-frequency diagram. In that way, traveling wave arrival to the measuring point (usually the busbar voltage transformers) is exactly a moment of sudden change recorded on measuring substation equipment.

As a result of the mutual coupling between adjacent transmission lines or underground cables, the head of fault travelling wave will be deformed and increase error in signal detection. Problem of mutual coupling has been tried to be solved with decoupling transformations. Karrenbauer's and Clarke's are the most often used as tool for signal pre-processing in recent signal processing analysis of power system fault signals [10]. This transformations decouple measured three-phase fault voltages or currents before analysis with wavelets, HHT or FFT [6,7]. After decoupling, three independent signals - *modes* are obtained. In Karrenbauer's transformation those are two line-line modes and one landline mode. In Clarke's transformation those are two aerial modes and one ground mode. Usually, just one of modes is used for further processing. Furthermore, ground modes are usually omitted in this analysis.

When line-line or aerial component mode of traveling wave arrives to the measuring point, the sharp singularity of signal can be detected. Then it is possible to determine the fault traveling wave arriving time to the busbars.

Then fault signal is decomposed into series of IMF's by empirical mode decomposition (EMD). Researchers showed that the singularity of the fault transient signal is mainly reflected in IMF1, consequently, the IMF1 is selected for further processing and analysis. Omitting of ground modes definitely means that some of important information about fault is lost, especially if single phase faults to ground are considered. This is reason why complex-space phasor is proposed as new pre-processing method. In such a way, all three measured quantities i.e. fault voltages are combined into one-dimensional signal of complex-space phasor. As already mentioned, complex-space phasor describe, among others, the negative sequence component which is very important for faults to ground.

Fault location calculations

Detailed derivation of formula for fault location is presented in [6], [7]. Here we present the reference to most important relations.

We assume the GPS time synchronization in two substations at both ends of faulted transmission line or underground power cable. Both measuring instruments (fault locators) can measure the time when traveling wave arrives. With L is denoted considered faulted transmission line. In Figure 2 is presented the considered case.

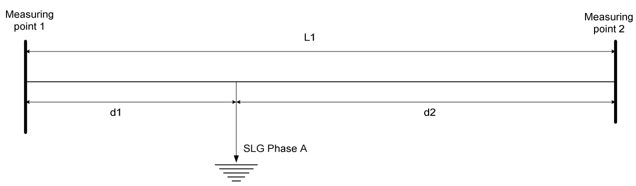

Fig.2. Illustration of faulted transmission line and measuring points in both ends

If we denoted traveling wave arriving times to the both ends with t_1 and t_2, and with *v* the speed of traveling wave, the final formula for fault location is [6]:

(8) $$d_1=\frac{v(t_1-t_2)}{2}+\frac{L}{2}$$

From (7) it is visible that if we can determine the time when fault traveling waves arrive the two substation busbars, it is possible to calculate fault distance from any of installed fault locators (measuring terminals).

Experimental test cases

For experimental testing of the proposed algorithm, we used a synthesized signal realized in MATLAB (SimPowerSystems), able to generate single phase to ground fault in observed part of power system. Measured voltages can be recorded on workspace and prepared for pre-processing.

In the first stage we converted recorded measured three-phase fault voltages from busbar B1 and B2 into signal of absolute values of complex-space phasor. Simulated part of power system is presented in Fig. 3.

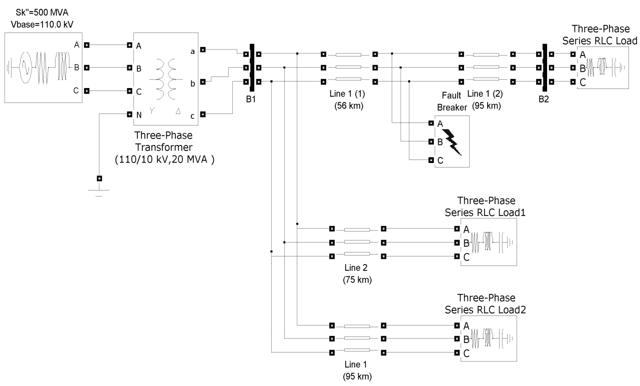

Fig.3. Simulation setup in MATLAB/SimPowerSystems used for numerical verification of proposed algorithm

Special attention is dedicated to single phase to ground faults in power system. Statistically, those faults are the most frequent by occurrences. In order to simplify the fault location procedure the distributed parameter model of transmission lines is chosen. For simulation the following power system parameters are taken: short-circuit power of external 110 kV grid is $S_k'' = 500 MVA$, network transformer rated with 20 MVA, 110/10 kV, YΔ. Faulted feeder is 151 km long with the following parameters: Positive phase sequence resistance R is 0.1256 Ω/km, XL inductive reactance of positive sequence is 0.1366 mH/km, XC inductive reactance is 0.1207 μF/km. Zero phase quantities are R_0=0.0187 Ω/km, XL_0=5.112 mH/km and XC_0=0.1286 μF/km. From quoted parameters velocity of traveling wave is calculated from

$$v = \frac{1}{\sqrt{LC}} \tag{9}$$

and the velocity of v= 2.463x10^5 km/s is obtained. There are also two healthy 10 kV feeders going from busbars B1 with lengths 75 km and 95 km. All feeders have symmetrical three-phase loads. Entire time of observed transient phenomenon is *t*=0.035 s, and single line to earth fault is simulated in phase A at t_0=0.025 s. Fault resistance value is R_{fault}=150 Ω.

HHT procedure for complex-space phasor of the fault transient signal

When the fault occurs on transmission line or underground cable, a traveling wave will be generated and runs along the line to the both ends. Existing pre-processing methods like Karrenbauer's or Clarke's transforms convert the three-phase measured quantities of fault voltages or currents usually in modes. Usual is that just one of the obtained modes was chosen for further processing as one-dimensional signal.

In this work, the absolute values of complex-space phasor are chosen for pre-processing of measured three-phase fault voltages. In Figure 4 the absolute value of complex-space phasor synthesized from measuring fault voltages at busbar B1 is presented. (fault inception t_0=0.025 sec).

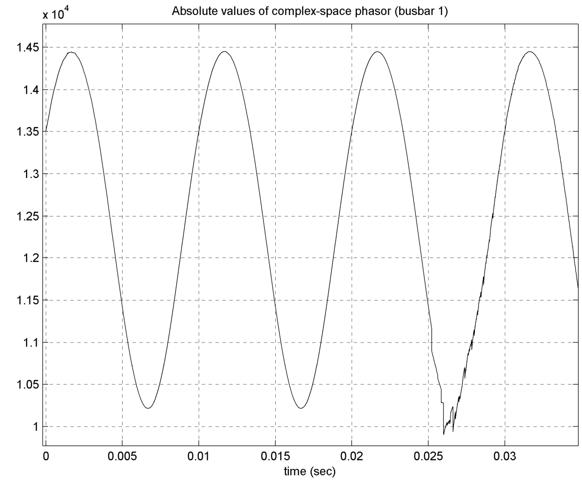

Fig.4. Signal of complex-space phasor absolute values (synthesized from measured voltages at B1).

In the moment of fault inception, singularity in complex-space phasor will be detected on fault locators installed on both ends. IMF components of fault traveling wave will be extracted by means of empirical mode decomposition (EMD). Earlier works showed that volatility and singularity of the transient signal is mainly reflected in IMF1 component. From that reason, IMF1 component is selected for further processing. With Hilbert-Huang transform we extract instantaneous amplitude and instantaneous frequency of processed signal and fault location can be determined from (8). In [6] is shown that instantaneous amplitude is sufficient for fault location calculation.

Calculation procedure and results

Fault is simulated at 56th kilometer of faulted transmission line measured from busbar one (B1), with fault resistance R_{ground} = 150 Ω. The following figures represent the instantaneous amplitude of traveling wave which are recorded at both ends at fault locators.

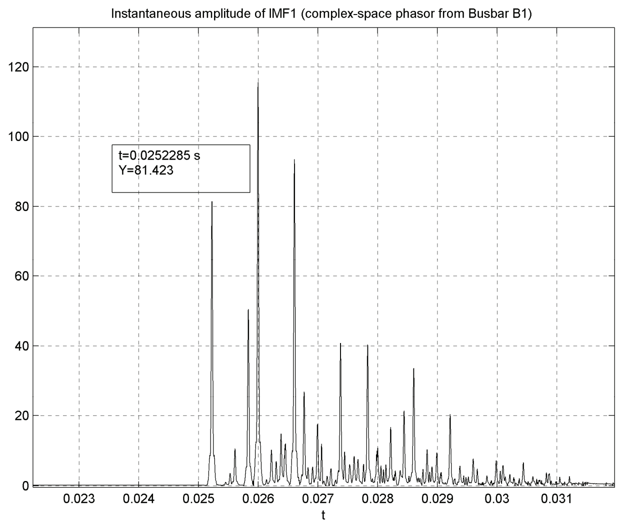

Fig.5. Instantaneous amplitude of IMF1 component of complex-space phasor synthesized from measured voltages at B1.

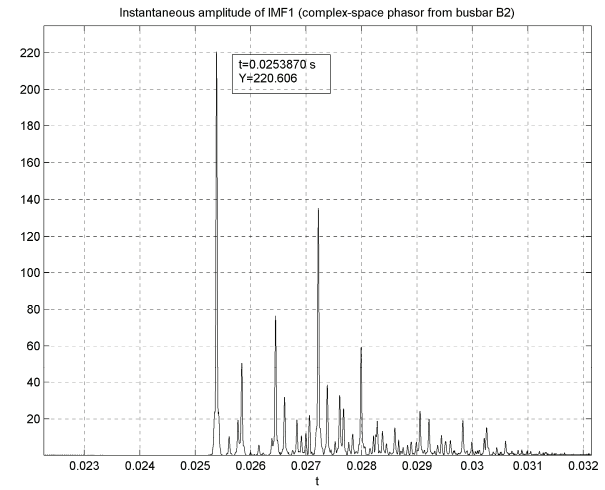

Fig.6. Instantaneous amplitude of IMF1 component of complex-space phasor synthesized from measured voltages at B2.

Before the fault occurrence, the instantaneous amplitude is flat. When the head of traveling wave reaches the measuring instrument, the instantaneous amplitude clearly change, i.e. singularity can be easily detected (Fig.5 and Fig. 6). From the first singularity point the travelling wave arriving time is computed. From obtained measurements the distance of d=55.98 km is calculated using (8). The error is 17.33 meters. For the same fault configuration at 56th kilometer using 500 kHz to 1 MHz measuring frequency, the error of 44.24 meters is obtained. Errors for 500 kHz- 1MHz differs only in some insignificant decimals. Practically - we have the same results in this range of measuring frequency.

Fault location procedure is also carried out with faulted line of 120 km length with simulated single line to ground fault at 40th kilometer from busbar B1. Calculated fault location is d1=39.99 km, i.e. the error is 9.88 meters for 2MHz fault voltage measuring resolution. For the same fault configuration at the 40th kilometer using 500 kHz to 1 MHz measuring frequency, the error of 51.7 meters is obtained.

The Table 1 represents results of measurements carried out on varying power system configurations and with varying characteristics of measuring equipment (varying measuring frequency from 0.25MHz to 2 MHz).

Table 1. Fault location results with different power system configuration

Real fault location (km)	Resolution of measuring instruments (MHz)	Fault Resistance (Ω)	Error (m)
56 km	2	150	17.33
56 km	0.5 & 1	150	44.24
56 km	0.25	150	202.03
40 km	2	150	9.88
40 km	0.5, 1	150	51.70
40 km	0.25	150	194.58

As shown, the application of complex-space phasor leads to the increased accuracy of fault location calculation procedure. Furthermore, the fault location accuracy is better using lower measuring frequency then in the results reported in [6], [7]. Better accuracy is due to the fact that complex-space phasor contains complete information about fault signal, without omitting important ground parameters from processing. For most frequent kind of fault in power system (single line-to-ground faults), this is of critical importance.

Conclusions and further work

In this paper, a new approach to power system fault signal processing is proposed. Three-phase fault voltages are converted to the vector of absolute values of its complex-space phasor. This vector represents fault traveling wave and it is further processed for fault location finding with Hilbert-Huang transform. Firstly, traveling wave is decomposed into IMF components. Then instantaneous amplitude of IMF1 is extracted with Hilbert transform for finding exact times when the heads of traveling wave arrive to the fault locators.

The results show that usage of complex-space phasor allows better accuracy in comparison with earlier decoupling procedures as Karrenabauer's and Clarke's transformations. Furthermore, lower measuring frequency at fault locator measuring instruments is used. That means considerable measuring instruments cost saving.

In further work we intend to apply presented method on more complex power networks.

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