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Detection, classification and fault location in HV lines using travelling waves

***Abstract**. The article describes the travelling wave algorithm of detection, classification and fault location based on wavelet transform, which precisely locates faults in HV lines. The automatic procedure of testing of the algorithm is presented, which enables to perform many simulations. The best version of algorithm is determined.*

***Streszczenie.** W artykule przedstawiono falowy algorytm detekcji, klasyfikacji i lokalizacji miejsca zwarcia wykorzystujący przekształcenia falkowe, który dokładnie lokalizuje miejsce zwarcia w liniach wysokiego napięcia. Przedstawiono automatyczną procedurę testowania algorytmu, która pozwala na przeanalizowanie licznych symulacji i określenie najlepszej wersji algorytmu. (**Detekcja, klasyfikacja i lokalizacja miejsca zwarcia w liniach WN wykorzystująca zjawiska falowe**).*

Keywords: HV line, fault location, travelling wave phenomenon, wavelet transform.
Słowa kluczowe: linia WN, miejsce zwarcia, zjawiska falowe, przekształcenie falkowe.

Introduction

Fault location in high voltage (HV) lines is one of the most important issues which is dealt by power staff. Accurate fault location enables to restore HV line to work in a short time, which improves the security and reliability of power system operation.

Nowadays, the most commonly used fault locators are impedance locators. These devices determine fault location with such an error that it is usually impossible for power staff to locate the fault efficiently. For this reason, researchers in many countries are working on developing methods and devices which can locate faults more accurately. In the literature the most common method which is described to improve fault location accuracy is a method based on travelling wave phenomenon [2], [3].

Traveling wave theory has been known for a long time. The first article in Europe on this subject was published in Elektrotechnische Zeitschrift in the 1931. The application of travelling waves to power system fault locators was firstly presented in [4]. Since then, much attention was paid to the usefulness of travelling wave phenomena in precise fault location in HV lines. However, the lack of appropriate technological tools to monitor the broadband transient signal and the limitations associated with digital signal processing methods, has considerably limited the possibility of use of the designed methods. This possibility emerged in the early 90's, thanks to advances in microprocessors technology, development of digital signal processing techniques (including wavelet transform) and the development of satellite-based synchronization devices.

Dommel and Michels proposed travelling wave method to detect faults in transmission lines in the article [13]. Transient voltages and currents are used together with correlation function similarly as is it done in fault localization in [14]. This method is accurate, when the width of time window which is needed to filter an electromagnetic wave is chosen properly. But the width is depending on the fault location, which is parameter which we are looking for, so the method which is based on correlation function is not feasible to implement on hardware platform [15]. There were some attempts to use narrow and wide time windows in order to solve this problem in [16].

The algorithms of travelling wave fault location between 80-ties and 90-ties of previous century are based on superposition of currents and voltages. Basing on the theory presented in [17] the ASEA company developed and installed its first travelling wave fault locator named RALDA in 1976 [18].

The issue of using travelling wave phenomenon in power system automation is popular nowadays. There are new published books [19], Ph.D. dissertations [20][21] and patents [22], which are associated with travelling wave phenomenon. Research work is undertaken to implement and improve wave criterion in power system protection devices:

- distance [23][24],
- differential [25][26][27],
- directional [28][27],
- HVDC lines [29][30][31].

As a result of research work undertaken over the past two decades, there are several travelling wave fault locators [5], [6], [7], which are operating in power systems. At the moment, travelling wave fault locators are used in many countries including USA, China, RPA, Scotland, Canada [8], [9], [10].

One of the travelling wave fault locator which is offered on the world market is the device developed by two companies Kehui Electric Co. (China) and Hathaway Systems Ltd. (Ireland) with cooperation with XiAn Communication University and Tsinghua University of China [6].

Although, there are quite a large range of travelling wave fault locators on the market, these devices are quite rarely used because of their costs. There is still a need to seek better and cheaper solutions.

Because of that, the detection, classification and fault location algorithm was developed. The algorithm is based on wavelet transform and it will be implemented on the hardware platform in future.

Travelling wave phenomenon

Of all the transients that occur in power systems, the transients associated with travelling wave phenomenon are one of the shortest - they last from microseconds to milliseconds. A sudden and significant change in voltage in at least one place in the HV line leads to generation of an electromagnetic wave, which propagates from that point in two opposite directions, toward the substation A and substation B (fig. 1.)

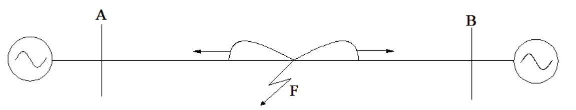

Fig. 1. Propagation of electromagnetic waves in HV line after a fault

Wave propagation in HV Line is defined by the equations, which for lossless line (*R*=0, *G*=0) are:

(1) $$-\frac{\partial u(x,t)}{\partial x} = L\frac{\partial i(x,t)}{\partial t}$$

(2) $$-\frac{\partial i(x,t)}{\partial x} = C\frac{\partial u(x,t)}{\partial t}$$

The solution of the above two equations in general case:

(3) $$u = u' + u'' = f_1(x - vt) + f_2(x + vt)$$

(4) $$i = i' + i'' = \frac{1}{Z} f_1(x - vt) - \frac{1}{Z} f_2(x + vt)$$

Electromagnetic wave can be divided into voltage wave *u(x,t)* and current wave *i(x,t)*, which represents the propagation of electric and magnetic fields respectively.

The interpretation of the equation (3) and (4) are two waves shown in Figure 2:

- voltage wave *u'(x,t)* and current wave *i'(x,t)* propagating with velocity *v* along the *x* axis (Figure 2a),
- voltage wave *u''(x,t)* and current wave *i''(x,t)* propagating with velocity *v* in opposite direction to *u'(x,t)* and *i'(x,t)* (Figure 2b).

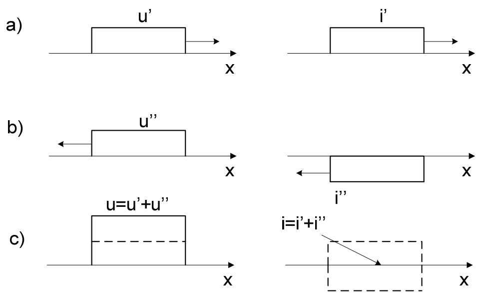

Fig. 2. Lossless line - propagation of voltage and current wave in the direction of: (a) increasing value of x, (b) decreasing value of x; (c) wave superposition.

The Figure 3 presents fault currents in substation A after a line-to-earth fault in the middle of HV line (line length 100 km). The waveforms presented in Figure 3, are obtained from the fault simulation in HV line presented in Figure 1. It is worth to mention that HV line is modeled as Frequency Dependent (Phase), generators are modeled as simple 3-phase voltage sources and substations (A and B) are modeled as earth-to-line capacitance. The rectangle in Figure 3 marks the area which is shown in Figure 4, which allows for more accurate observation of current waves reaching the substation. The fault occurred at t_f = 225 ms. The first wave reaches the substation at the time t_1 = 160 μs after t_f. Wave which propagates at a speed close to the speed of light ($v \approx$ 300 000 km/s), needs approximately 160 μs to travel distance of 50 km. The second wave which reaches the substation after next t_2 = 320 μs is the result of reflection of the first wave from the substation A, and successive reflection from the fault location. During the time interval t_2 the wave travels the distance of 100 km.

In the travelling wave fault location algorithm the most important issue is to precisely determine the moment when waves reach a substation. For this purpose, time-frequency transforms are used, mainly wavelet transforms.

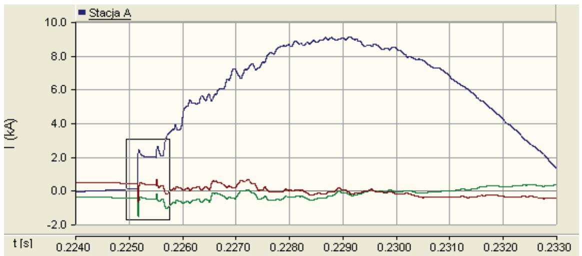

Fig. 3. Fault currents in substation after L1-E fault occurred in HV line

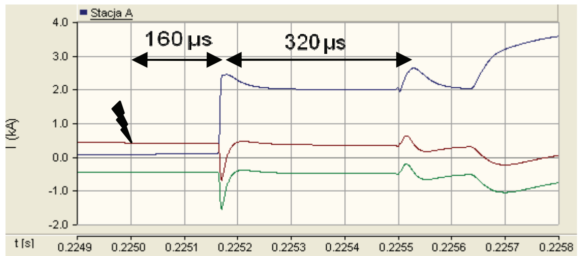

Fig. 4. Wave propagation after a fault in HV line (zoomed Figure 3)

Wavelet transform

In conventional power system automation devices the main quantity which is analyzed is a periodic component of currents and voltages. The frequency transforms are used (i.e. Fourier transform, Walsh, Kalman), which allow to accurately determine the frequency spectrum of the signal. But these frequency transforms can't determine the exact moments when the wanted frequency has occurred.

In the case of travelling wave fault locators precise information about frequency domain representation of the signal is not as important as getting the appropriate information when signal changes in the relevant frequency range. It is important to detect the exact moment of arrival of electromagnetic wave to a substation and to determine the moment of arrival of successive waves resulting from reflections from the nodes – points where the characteristic impedance is changing.

A wavelet transform is used for the analysis of non-stationary signals, whose frequency changes over time. The wavelet transform can be used in travelling wave fault location algorithm for analysis of non-stationary signals containing sine and impulse components, which are characteristic for transient signals.

Continuous wavelet transform is defined by equation:

(5) $$CWT(a,b) = \int_R s(t)\frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right)dt; \quad a \in R^+ - \{0\}, b \in R$$

In the algorithm (presented in Figure 6) the discrete wavelet transform is used, which can be defined as:

(6) $$\mathrm{DWT}[a,b,n] = \frac{1}{\sqrt{a}}\sum_n f[n]\cdot\psi[\frac{n-b}{a}]; \quad a = 2^j, b = k2^j, (j,k) \in Z^2$$

where: *f*[n] – input signal, *ψ* – wavelet function, *a* – scale coefficient, *b* – shift coefficient, j – decomposition level.

DWT*[a,b,n]* is a measure of similarity between the test signal *f[n]* and the wavelet function *ψ*. The input signal doesn't have to fulfill any conditions, but wavelet function *ψ* must vanish rapidly to zero at the ends of its range:

$$\int \left|\psi(t)\right|^2 dt = 1 \quad (7)$$

The wavelet function ψ has to be oscillatory and its average value must be equal to zero:

$\int \psi(t)\, dt = 0$ By changing *a* and *b* coefficients, which define a wavelet function ψ, it is possible to create wavelet family. The smaller the value of scale coefficient *a*, the wavelet function is narrower in time, and therefore it is characterized by higher frequencies. When the scale coefficient *a* increases, the wavelet is stretched and the amplitude increases, so that the wavelet energy is constant. By changing the coefficient *b* the wavelet is shifted in time.

The wavelet function must be selected in such a way that it will closely match the shape of signal component which is to be detected. Signal analysis using wavelets is realized by checking the local similarity between the signal and the wavelet. It is performed by convolution in time domain or multiplication of spectra in frequency domain.

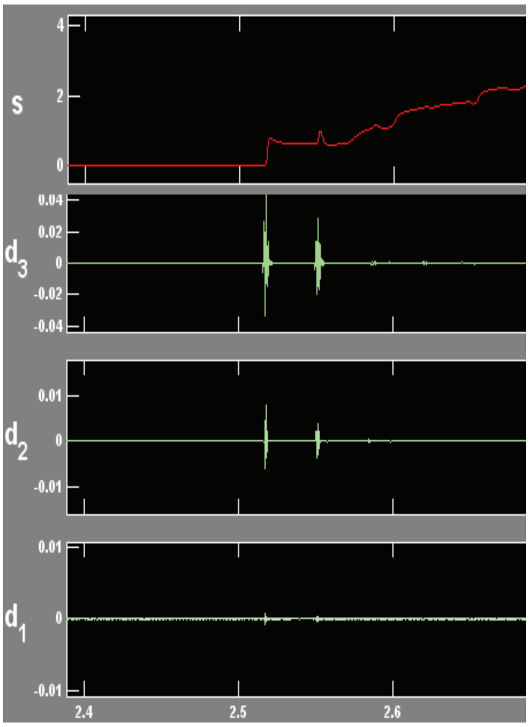

Fig. 5. The view of Wavelet Toolbox – wavelet db4; s – input signal, d1…d3 – detail coefficients on different decomposition levels

The wavelet transform enables to analyze signal for different frequency bands simultaneously. In multiresolution analysis using a wavelet transform, the signal is divided into two groups of decomposition coefficients: approximation and detail. Approximation coefficients are associated with low pass filtering of the input signal, and detail coefficients are associated with high pass filtering. The signal *s* and its wavelet detail coefficients on several decomposition levels are presented in Figure 5. When the sampling rate equals to 1 MHz, the detail coefficients on the first wavelet decomposition level corresponds to frequency range 250 – 500 kHz; second: 125 – 250 kHz; third: 67,5 - 125 kHz. Approximation coefficients are not presented in Figure 5, because they are not used in the travelling wave algorithm.

Travelling wave algorithm

The basic tasks of travelling wave fault locator are:

- current recording ,
- fault detection,
- fault classification,
- fault localization.

Currents are sampled and saved to the memory of microprocessor scheme with 1 MHz sampling rate. When the input signal exceeds a certain threshold the fault is detected. Fault classification is based on samples collected 1 ms before and 2 ms after a fault detection. After a fault is classified the localization algorithm is performed.

Detection algorithm

The traveling wave fault locator records phase currents and perform a 0, α, β transformation and wavelet transform. If the absolute value of detail coefficients is greater than the set threshold, then the fault occurred in the HV line. The detail coefficients are obtained by using certain wavelet function on specified wavelet decomposition level.

Figure 6 presents the block diagram of the detection algorithm. Phase currents I_{L1}, I_{L2} and I_{L3} are subjected to 0, α, β transformation which in result gives I_{α}, I_{β} and I_0 currents. Then these currents are subjected to the specified wavelet transform. Quantities $I_{\alpha d}$ and $I_{\beta d}$ are used to detect the fault, which correspond to currents I_{α}, I_{β} after a wavelet transform, which is performed on second decomposition level. If one of these values exceeds the set threshold, this means that in the HV line a fault has occurred.

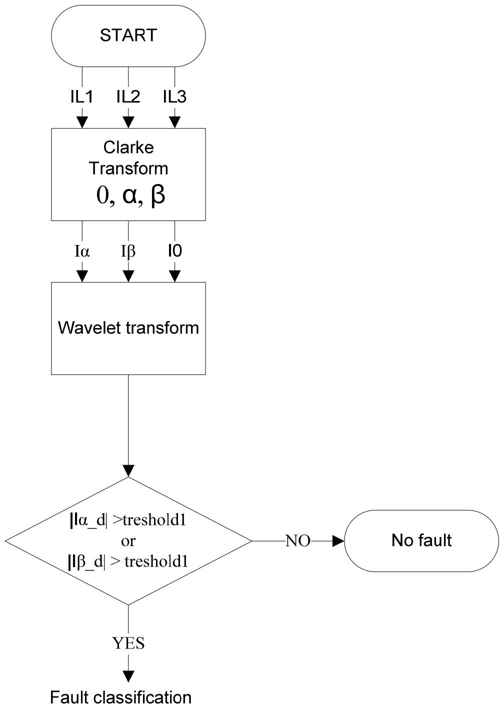

Fig. 6. Block diagram of detection algorithm

Classification algorithm

The classification algorithm is based on the algorithm presented in [11]. In the article the db8 wavelet transform on third decomposition level is used. The sampling rate equals to 12,5 kHz, so the frequency range 781 – 1562 Hz is analyzed.

The algorithm presented in this publication is based on wavelet bior3.3 and second decomposition level with 1 MHz sampling rate. So the frequency range, which is analyzed equals to 125 - 250 kHz. Samples which are used by the algorithm are collected between 1 ms before and 2 ms after fault detection. In the publication [11] the time frame which is used for the classification of fault is not specified. Moreover, the article assumes a different way to distinguish the switching operation from short-circuit and other values were set as thresholds, which are used for fault classification.

The classification algorithm enables to discriminate between:

- short-circuits:
  - single phase: L1-E, L2-E, L3-E,
  - two-phase: L1-L2, L1-L3, L2-L3, L1-L2-E, L1-L3,
  - three-phase: L1-L2-L3, L1-L2-L3-E,
- lightnings.

In Figure 7 the block diagram of classification algorithm is presented. At the beginning, the algorithm detects the type of disturbance occurring in HV line - lightning, short circuit or switching operation. If the value of $I_{\alpha d}$ and $I_{\beta d}$ will exceed a particular threshold, then a lightning occurred, otherwise a short circuit or a switching operation occurred in the line. The distinction between short-circuit and switching operation is based on the fact that the closing of the circuit breakers poles are not simultaneous. The time period from closing a circuit breaker pole L1 to closing pole L2 is approximately equal to 0,65 ms, and the time period between closing L2 pole and L3 pole is approximately equal to 0,75 ms. So if the time period between the appearance of a wave in phase L1 and the appearance of a wave in phase L2 is greater than 500 μs or the time period between the occurrence of a wave in phase L2 and the appearance of a wave in phase L3 is greater than 600 μs, then a switching operation occurred in HV line. The classification algorithm is based on S1, S2, S3 coefficients, which are the sum of wavelet detail coefficients on second decomposition level for the analyzed time range respectively for the phases L1, L2 and L3. It is possible to distinguish, all types of faults, by performing simple arithmetic operations (shown in Figure 7) using these coefficients.

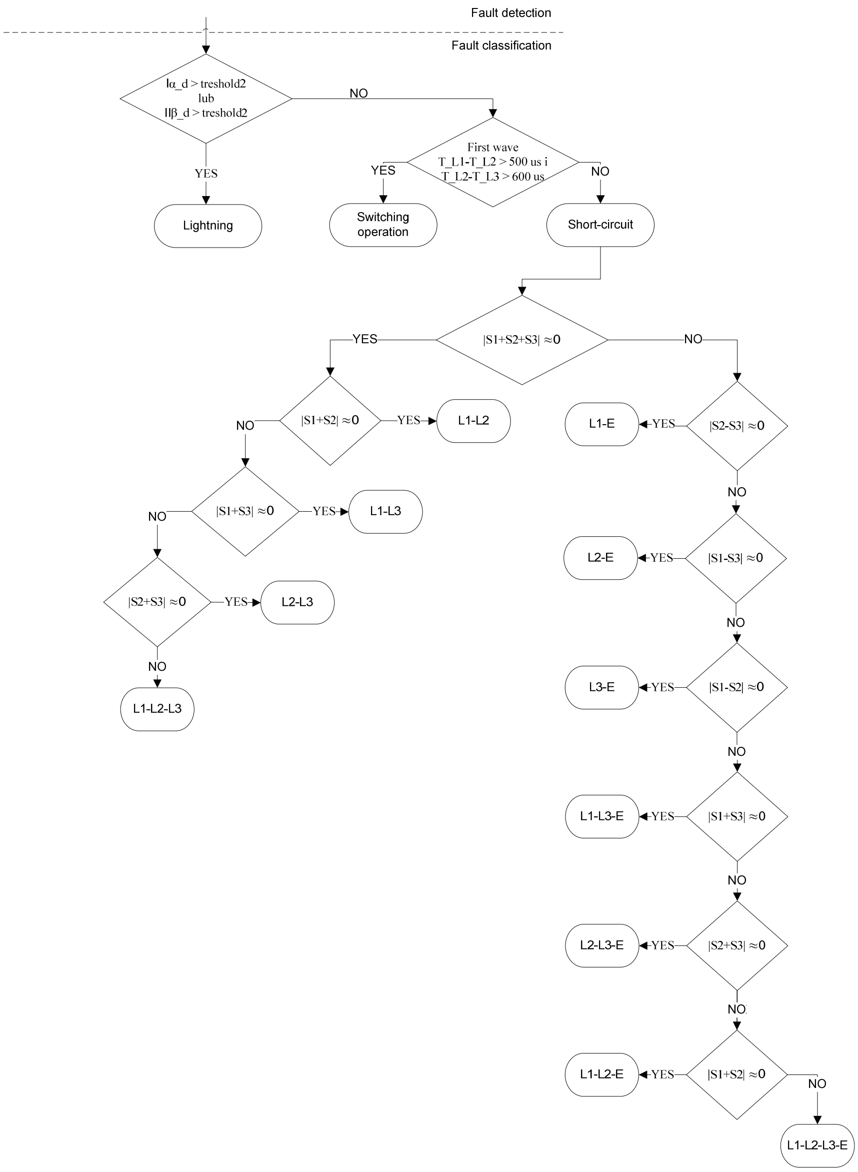

Fig. 7. The block diagram of classification algorithm

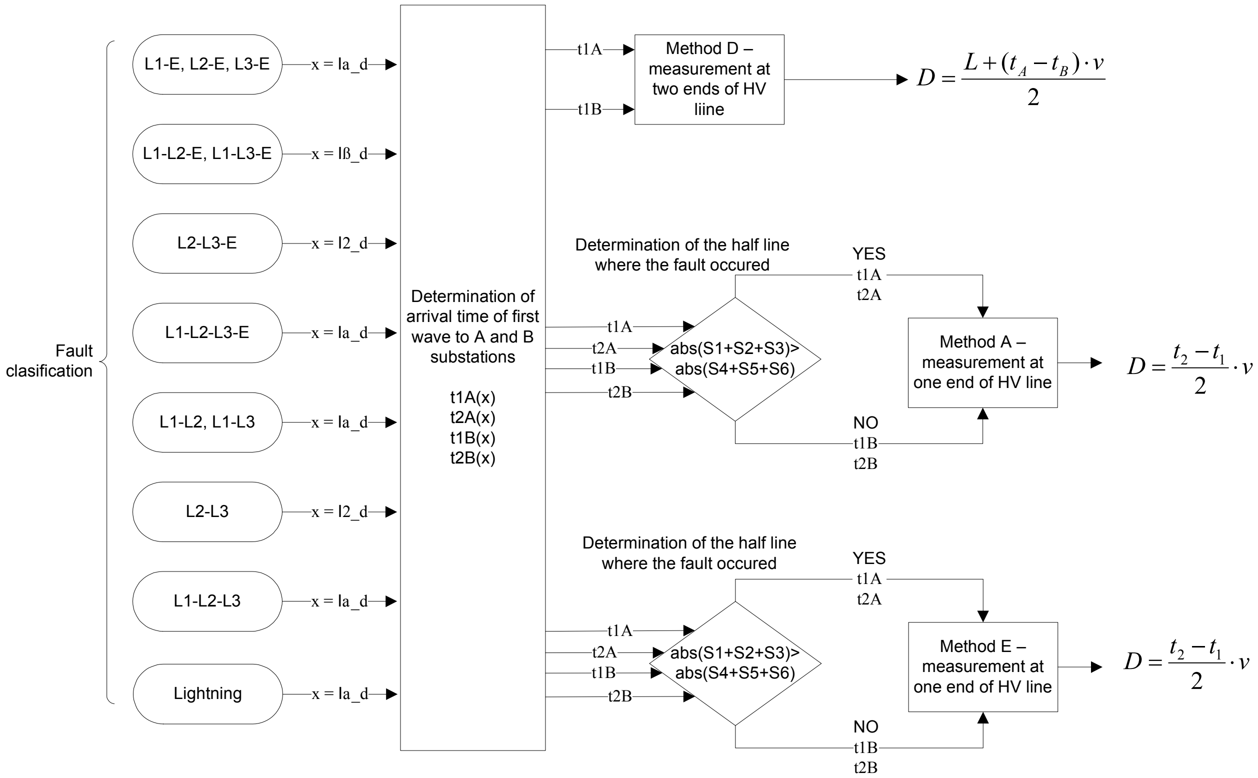

Fig. 8. The block diagram of localization algorithm

Location algorithm

After detection and classification of the fault, the location algorithm is performed. Depending on the fault type the algorithm uses different quantities to determine a fault location. The block diagram of location algorithm is presented in Figure 8, where *x* is assigned to the quantity which is used for determination of arrival time of waves to A and B substations. For example, a line-to-earth fault is localized using the detail coefficients I_{α_d} which are the result of wavelet transform performed on I_α current, which is obtained from Clarke transform.

After determining arrival time of the first and second wave to the substation A and B, corresponding values are transmitted to the blocks implementing different methods of measurement. The D method (measurement is performed at two ends of the line) uses only first wave from fault point which reach the substation A and B. The A method (measurement is performed at one end of the line) uses the first wave, which propagates from the fault location and the second wave, which is the result of reflection from the substation A (or B) and then from the fault location. In the algorithm, the A method requires the determination in which half of the line a fault occurred. If the absolute value of the sum of S1, S2 and S3 will be greater than the absolute value of the sum of S4, S5 and S6 than the fault occurred in the first half of the line. Otherwise, the fault occurred in the second half of the line.

The method E (measurement at one end of the line) similarly to method A requires the determination of half of the line, in which there was a switching operation. In the method E the source of the waves is not a fault, but a closing operation of circuit breaker.

Test model

The test model is composed of three 220 kV lines – Figure 9. Fault locators are placed in the substation A and B. The subsystem is placed in the middle of line, which allows for automatically carrying out many simulations for various parameters of the fault location, fault resistance, etc.

The algorithm of traveling wave fault locator needs only a few milliseconds to record all necessary waves. Therefore, when analyzing the electromagnetic wave propagation in HV lines the complex electromechanical phenomena of synchronous generator whose influence can be observed for a longer period of time, are not taken into account. So generators are modeled as simple voltage sources.

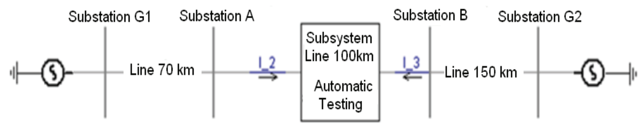

Fig. 9. The test model

In order to properly model a HV line the Frequency-Dependent (Phase) model of HV line was chosen in PSCAD/EMTDC which can be used for modeling a line with distributed parameters, where all line elements are frequency dependent (not only inductance L and capacitance C, but also resistance R).

When considering the frequency signals in the range kilohertz main element model of the substation busbar is the earth capacitance. This value depends on the power equipment (generators, transformers, etc.) which is connected to the busbar.

The current transformer is modeled as a low pass filter, which transfer signals up to 200 kHz [12]. The current transformer models built-in the PSCAD/EMTDC library were not used, because they do not model capacitor coupling which occurs for high frequencies. The saturation phenomenon was also not included. For short time which is needed to record all necessary travelling waves it is unlikely that the current transformer will saturate.

The procedure of automatic testing of the algorithm

The purpose of testing the algorithm was to verify the proper operation of the algorithm for different:
- fault types (short circuits - L1-E, L2-E, L3-E, L1-L2-E, L1-L3-E, L2-L3-E, L1-L2, L1-L3, L2-L3, L1-L2-L3 -E, L1-L2-L3, lightning, switching operations),
- distance from fault to substation (1 km, 2 km, 5 km, 10 km, 20 km, 30 km, 40 km, 50 km, 70 km, 85 km),
- fault angle (0° - 90° in steps of 2°),
- fault resistance.

Due to the large number of simulations that were performed and the need to test different versions of the algorithm, tests were carried out using an automatic testing procedure. Flowchart showing the procedure for the automatic testing is shown in Figure 10. The simulation model which was realized in PSCAD/EMTDC is shown in Figure 9.

In PSCAD/EMTDC there are approximately 4,000 different cases simulated, which are characterized by different fault type (L1-E, L1-L2 etc.) fault location and different fault angle.

As a result of the simulation ASCII COMTRADE 1999 files are obtained, which are assigned to each of the simulated cases. *File_nr.dat* contains the current waveforms of phase L1, L2, L3 at the substation A and B, sampled at 1 MHz. *File_nr.cfg* is a configuration file that is used to scale the values from data file. *File_nr.hdr* includes information concerning the date and time of simulation. File *Mrun.out* is generated by a block *Multiple Run* in the PSCAD / EMTDC program and contains information about the executed simulation (number of simulations, fault type, fault distance from the substation and the fault angle).

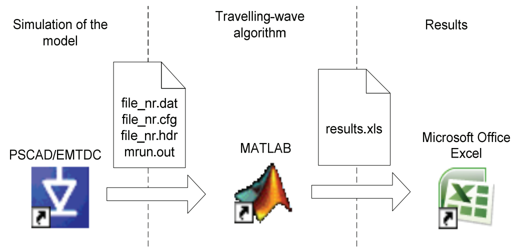

Fig. 10 Block diagram of automatic testing of the algorithm

COMTRADE files are then loaded to MATLAB where for each of the 4,000 files (which represent the phase currents waveforms in substations at the end of HV line) the travelling wave algorithm (detection, classification and location) is carried out. The output file *results.xls* contains the data associated with simulation and the results of the algorithm, such as: fault classification, fault location determined by A an D method.

Knowing the range of frequencies, which are necessary to determine the fault location and the frequency response of current transformers the type of wavelet function and decomposition level, which will be implemented in the fault locator was determined. The selection of the optimal wavelet was conducted using the signal received from the program PSCAD/EMTDC which is analyzed in Matlab using Wavelet Toolbox.

Two frequency ranges where selected 67,5 – 125 kHz and 125 – 250 kHz by taking into account the following factors:
- protection current transformer can transfer frequencies up to 200 kHz,
- with an increase in the frequency range, the accuracy of determining moment of change of the signal is increasing. For higher frequencies a wavelet transform is narrower.

In the work, the algorithm was tested at different levels of wavelet decomposition
- second decomposition level (frequency range 125-250 kHz),
- third decomposition level (frequency range 67,5 - 125 kHz).

And by using different wavelet functions:
- daubechies (db1-db12, db20),
- symlets (sym2, sym3, sym4, sym5, sym7),
- coiflets (coif1, coif2, coif3, coif4, coif5),
- biorthogonal (bior1.1, bior1.3, bior1.5, bior2.2, bior2.4, bior2.6, bior2.8, bior3.1, bior3.3, bior3.5, bior3.7, bior3.9, bior4.4, bior5.5, bior6.8),
- rbiorthogonal (rbior1.1, rbior2.6, rbior3.3, rbior4.4, rbior 6.8),
- dmey.

Best results

As a result of the tests described in the previous chapter the best version of the algorithm proved to be the D method (measurement at two ends of line), second decomposition level (frequency range 125 – 250 kHz), wavelet function – bior3.3. Results are presented in Table 1.

The best wavelet function, which gives most accurate fault location is a biorthogonal 3.3 wavelet. This is mainly due to the fact that the selection of the best wavelet for a given application is to select the wavelet which will be most similar to the wanted signal component, which in this case corresponds to the increase in current associated with the propagation of electromagnetic wave.

Table 1. The best version of the algorithm – test results,

Error	Number of simulations	Percentage
< 200 m	2772	71.63%
200 - 400 m	412	10.65%
400 - 600 m	187	4.83%
600 - 800 m	346	8.94%
800 - 1000 m	37	0.96%
1 - 2 km	86	2.22%
> 2 km	30	0.78%

Summary

The purpose of this study was to implement an algorithm for detection, classification and location of the fault based on travelling wave phenomena, which will be characterized by better accuracy compared to the widely used impedance methods for the location of fault. Developing such an algorithm will allow for improved stability of power system due to a more effective inspection of the line, which can be performed by the exact location of the fault. A refinement of the algorithm was made possible thanks to the automatic testing procedure based on PSCAD/EMTDC, Matlab and Excel. With the ability to analyze a large number of results it was possible to realize the algorithm which gives a satisfactory accuracy of the location of the fault.

Summarizing, the algorithm for detection, classification and location of the fault location based on the wavelet transform, allowing the exact location of faults in the HV lines was developed. This algorithm provides the location of fault with an average error of 250 m except in cases where fault occurs at voltage zero crossing (or near: ±2,5°).

This accuracy was achieved by:

- correct choice of wavelet functions,
- correct choice of frequency range,
- correct determination of electromagnetic wave propagation speed in HV line.

EMTP-type model was developed for the analysis of travelling wave phenomena in HV lines, enabling verification of the algorithm, by performing many simulations.

The program which automatically tests the algorithm using the PSCAD/EMTDC, Matlab and Excel, was developed. It was necessary because of the large number of variants which were needed to be verified – about 300 000 cases.

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