

## Application of wavelet transform for identification of single phase-to-ground fault in compensated networks

**Abstract.** In a number of EU countries medium voltage networks operate in the compensated neutral mode. In that case an arc suppression coil is commonly shunted with a resistor. The most common type of damage to such networks is a single phase-to-ground fault. The paper presents the method for two stage identification of a line where the fault has occurred. The first stage is based on the analysis of high frequency components arising under transients. At the first stage a continuous wavelet transform is used to find frequencies. The second stage involves an analysis of the steady-state mode of a single phase-to-ground fault. Based on the energy spectrum of higher harmonics a damaged line is detected. To determine the energy spectrum at the second stage of the work a wavelet packet transform is applied. Wavelet transform has a number of advantages compared with short-time Fourier transform (STFT), particularly when analyzing non-stationary modes. The proposed method can be implemented to organize digital protection against ground faults.

**Streszczeni.** Sieci średniego napięcia w wielu krajach UE działają w skompensowanym trybie neutralnym. W takim przypadku cewka gasząca łuk jest zwykle bocznikowana przez rezystor. Najczęstszym rodzajem uszkodzeń w takich sieciach jest zwarcie jednofazowe do ziemi. W artykule przedstawiono technikę dwuetapowej identyfikacji linii, na której nastąpiło uszkodzenie. Pierwszy etap opiera się na analizie składowych wysokiej częstotliwości powstających pod wpływem stanów nieustalonych. W pierwszym etapie do znalezienia częstotliwości używana jest ciągła transformata falkowa. Drugi etap obejmuje analizę stanu ustalonego pojedynczego zwarcia międzyfazowego. Na podstawie widma energii wyższych harmonicznyc wykrywana jest uszkodzona linia. Do wyznaczenia widma energii w drugim etapie pracy stosuje się transformację pakietu falkowego. Transformacja falkowa ma wiele zalet w porównaniu z krótkotrwałą transformatą Fouriera, szczególnie w przypadku analizy modów niestacjonarnych. Zaproponowaną metodę można zaimplementować do organizacji cyfrowej ochrony przed zvarciami doziemnymi. (Zastosowanie transformaty falkowej do wykrywania błędów doziemnych w jednofazowej linii przesyłowej)

**Keywords:** fault detection, industrial power systems, power system simulation, power system harmonics, wavelet transform.

**Słowa kluczowe:** wykrywanie uszkodzeń, przemysłowe systemy elektroenergetyczne, symulacja systemu elektroenergetycznego,.

### Introduction

Modes of neutral grounding in industrial power systems are defined by standards [1] and application of electric networks. Neutral grounding via an arc suppression coil with a shunt resistor is widely used in medium voltage networks of 3-69 kV in several European Union countries (Poland, Germany, the Czech Republic and Romania etc.). This engineering solution has the following advantages: no need for an immediate disconnection of single phase-to-ground fault, and, accordingly, consumers; small residual current at the fault location; fault self-neutralisation (particularly in overhead lines), etc. Timely determination of the line where there was a single phase-to-ground fault is required to ensure reliability and safe operation of electrical plants.

Traveling wave method or its updating can be used to secure medium voltage systems from ground faults [2]. One of the ways to protect from single-phase-to-ground fault (SPGF) protection, using magnitudes of zero-phase-sequence and a set mode is securing at currents of higher harmonics of the current  $3i_0$  and voltage  $3u_0$ . Fourier transformation is conventionally used to analyze the harmonic composition of current or voltage. However, the mathematical tool of wavelet transform has been applied more during the last decades to analyze and describe the dynamics of complex non-linear processes in electric power engineering. Wavelets are used as a hierarchical basis to analyze indignations across a broad spectrum in conditions of non-stable studied processes. Literature review has shown that the instrument of wavelet transform is used to study the voltage quality in no-break power sources [3], transient analysis in electric power systems [4], fault locations [5], protection relay logic design, electrical equipment diagnostics, load forecasting, and electrical measurements and so on.

The article [6] has suggested application of wavelet transform to identify and classify short circuits power systems 230 kV. Wavelet transform is applied for fault

detection including the lines of high voltage direct current (HVDC) [7].

### Basic concept of wavelet transform

Wavelet transform is a modern mathematical apparatus which is widely used for frequency analysis of electric power system operation modes. A distinction should be drawn between continuous (CWT), discrete (DWT) and packet (PWT) wavelet transform.

Regular signal wavelet transform means its representation in the form of generalized series or Fourier integral for the system of basis functions:

$$(1) \quad \psi_{ab}(t) = \frac{1}{\sqrt{a}} \psi\left(\frac{t-b}{a}\right)$$

Basis functions are constructed from the mother (source) wavelet  $\psi(t)$ . Mother wavelet possesses certain characteristics due to time-shift operations ( $b$ ) and scale change ( $a$ ). The multiplier  $1/\sqrt{a}$  ensures the norm independence of these functions from the scaling number  $a$ .

The authors used continuous wavelet transform [8] to analyze high-frequency components in the low-voltage network. For this a laboratory test unit with a dividing transformer has been made. The work [9] introduces a method to locate a line-to-ground fault in the network with the resonant earth bounding. The method suggests introduction of the additional source with the frequency 25 Hz.

Large computing costs are required for wavelet spectrum calculation with continuous change of parameters  $a$  and  $b$ . The set of functions  $\psi_{ab}(t)$  is redundant. In this case discretization of a signal takes place on retention of recovery capability. Discretization is usually carried out through powers of two:

$$a = 2^m, \quad b = k \cdot 2^m$$

$$(2) \quad \psi_{mk}(t) = \frac{1}{\sqrt{2^m}} \psi(2^{-m}t - k),$$

where,  $m$  and  $k$  are integers. In this case the plane  $a$ ,  $b$  is converted into the corresponding mesh  $m$ ,  $k$ . Transformation in this case is called a discrete one.

The discrete wavelet transform is used in [10] to determine the power of independent current indexes for line-to-ground faults. The presented model uses a method of artificial neural networks to analyze a short circuit in the chain generator-transformer [10].

A discrete wavelet transform of the specified current signal  $i(t)$  corresponds to the convolution of this signal with an impulse filter response

$$(3) \quad \begin{cases} i_j^A = \sum_k h_0(2t-k) i_{j-1}^A \\ i_j^D = \sum_k h_1(2t-k) i_{j-1}^A \end{cases}$$

The current signal  $i(t)$  is passed through a digital low pass filter  $h_0$  and a digital high pass filter  $h_1$  (Fig. 1). The symbol  $\downarrow 2$  means the operation of decimation.

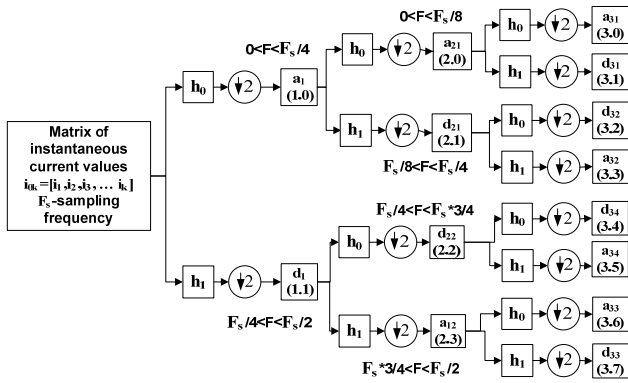


Fig. 1. Simplistic view of a wavelet decomposition

### Power system model for identifying ground fault

Basing on the wavelet transform in [11] the author identifies line-to-ground fault in the compensated network 15 kV. Herewith, the author denotes the presence of natural imbalance and high content of high harmonics. Bytes number is used as a basis model in [11] relation to detailing wavelet numbers.

This paper considers the problem of analyzing the zero sequence current at SPGF in mixed neutral ground systems.

Overvoltage ratio in the networks in the single-phase-to-ground fault protection depends on the ratio of the active current, flowing through the resistor  $R$  (fig. 2), to the resultant reactive current in single-phase-to ground fault protection.

Using a symmetrical component method from the diagram in Fig. 2 zero sequence current can be defined as:

$$(4) \quad \begin{aligned} 3i_0 &= -3C_1 du_0/dt = \\ &= 3C_0 \sum U_m \cos(\omega t + \varphi) + I_{md} e^{-\delta_d t} \cos(\omega_d t + \theta_d) + \\ &+ I_{mc} e^{-\delta_c t} \cos(\omega_c t + \theta_c). \end{aligned}$$

where  $\omega_d$  is the frequency of discharge oscillations;  $\omega_c$  is the frequency of charge oscillations;  $\delta_d$  is the attenuation constant of discharge oscillations;  $\delta_c$  is the attenuation constant of charge oscillations;  $U_m$  is the voltage component amplitude of the power frequency on the faulty phase.

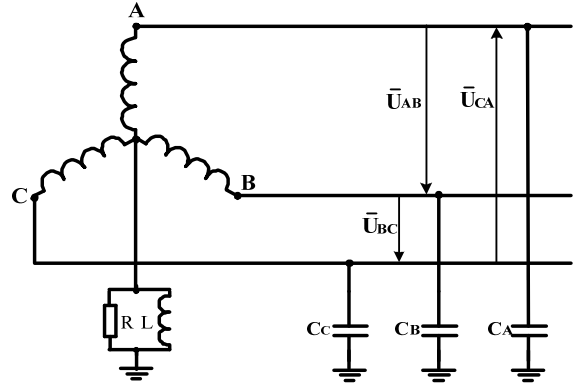


Fig. 2. Simplistic equivalent circuit system with mixed neutral grounding

Frequency of a discharge component depends on the distance between the point of fault and buses of the protected object as well as on the length and type of the PTL.

Frequency of a charge component depends on the power source inductance and total capacitive current of the network.

$$(5) \quad f_d = \frac{\omega_d}{2\pi}$$

$$(6) \quad f_c = \frac{\omega_c}{2\pi}$$

where  $f_d$ ,  $\omega_d$  are frequency and an angular rate of the discharge component,  $f_c$ ,  $\omega_c$  are frequency and angular rate of the charging component.

In long cable networks (main feed, for example, for magisterial lines in city networks is 6-10 kV), frequencies of charging and discharging fluctuations (5-6) can be comparable. It can condition significant errors when estimating ground current. It is necessary to filter frequencies higher than 1.5-2 kHz to sensitize admittance protection. Digital filtration of these frequencies can be done with wavelet transform.

This implies that it is possible to identify SPGF on the harmonic composition of the zero sequence currents.

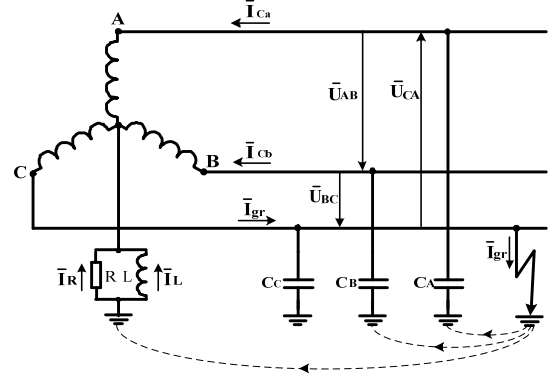


Fig. 3. Current flow paths at SPGF in the mixed neutral network

For a numerical experiment a power system simulation of network 10 kV was created in MATLAB / Simulink power system toolbox. Modeling in Matlab allows importing

received signals in the integrated block of Matlab wavelet toolbox, this block being successfully applied for a wavelet transform. The circuit parameters are presented in Tables 1, 2.

Table 1. Parameters of transformers

Block name	Transformer brand	Rt, $\Omega$	Xt, $\Omega$	Rm, k $\Omega$	Xm, k $\Omega$
Three-Phase Transformer0	TM-6300/110	16.09	219.77	1149.78	272.98
Three-Phase Transformer 1-3	TM-1600/10	0.71	3.41	30.31	4.91

Distributed Parameters Line1-3: 15 km. The phase fault C took place 5 km away from the bus-bar section.

Table 2. Parameters of electric power lines

sequence	R, $\Omega$ /km	L, mH/km	C, nF/km
Positive sequence	0.429	1.116	0.104
zero-sequence	0.573	4.896	4.233

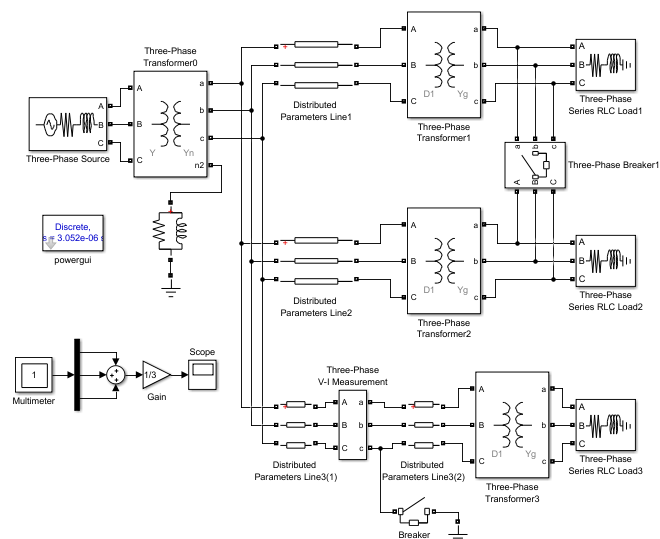


Fig. 4. Simulation model of the studied network

The ground fault is modeled at the time  $t=0.015$  s. The resulting oscillogram of the SPGF current is shown in Fig. 5.

A comparison of the current oscillogram of SPGF (Fig.5.) with the research results in [12] and their qualitative coincidence allows saying about the reliability of the accomplished modeling.

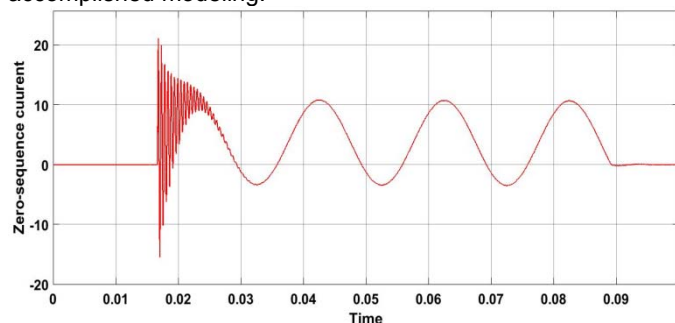


Fig. 5. Oscillogram of zero sequence current

In the analysis of stationary (steady-state) modes, wavelet analysis and the Fourier transform give qualitative agreement of the results. As the tests have shown, the error in defining currents and voltages is less than 1%. But

in the analysis of non-stationary modes (under the phase-to-ground fault the transient occurs), if the Fourier transform is used, spectral leakages occur (fig. 6).

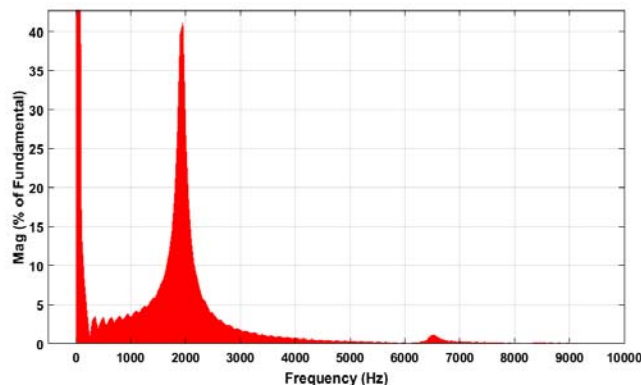


Fig. 6. The Fourier spectrum of the zero sequence current

To reduce the effect of spectral leakages different window functions are used, or the wavelet transform can also be applied.

The proposed algorithm can be represented in two stages.

**Stage 1.** Definition of frequency characteristics of the transient on the basis of the continuous wavelet transform.

In this paper, at the first stage a continuous wavelet transform was applied for analyzing the zero sequence current curve. Morse wavelet was used as a wavelet function. The results of the analysis are shown in Fig. 7. The continuous wavelet transform allows one to identify the most significant frequency components in terms of spectrum energy at an early stage.

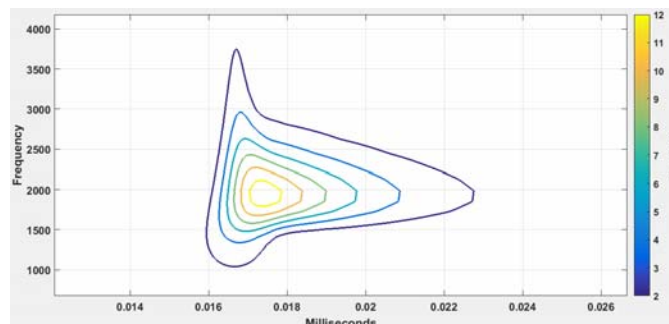


Fig. 7. Morse wavelet transform

As a result of the wavelet analysis of zero-sequence current, two frequency components of the transient were identified. As is clear from the scalogram (Fig. 7) two additional frequencies of 1 kHz and 5 kHz occur at the time of SPGF in the zero sequence current.

**Stage 2. Definition of higher harmonics spectrum energy of the steady state based on the packet wavelet transform.**

After frequency components having been identified, for more accurate calculation of the spectrum energy we can use the algorithm of the packet wavelet transform (Fig. 1). Based on recommendations presented in the paper [13] wavelet Daubechies (db10) was chosen as the basic wavelet.

Wavelet function is a digital filter, with amplitude frequency increase, which is determined by the wavelet type and the depth of wavelet decompositions when solving a certain problem. Wavelet function can be introduced by the pass land and the rejection land.

A criterion for choosing the best type of wavelet function has been formulated in the present work. Mean root square deviation  $\sigma$  of the values of the pickup signal  $i_k$  must be minimal comparing with the signal restored by wavelet indexes  $\hat{i}_k$  and the local energy of the spectrum for a selected harmonic group, with the target depth of decomposition should be seen to the fullest extent within the limits of the frequency range under study (7).

$$(7) \quad \left\{ \begin{array}{l} \sigma = \sqrt{\frac{\sum_{k=1}^n (i_k - \hat{i}_k)^2}{\sum_{k=1}^n i_k^2}} \rightarrow \min; \\ \Delta_{E_n} = \frac{E_n \sum_{k=n} |i_{j,k}^A|^2 + \sum_{k=n} |i_{j,k}^D|^2}{E_\Sigma \sum_{k=-\infty} |i_{j,k}^A|^2 + \sum_{j=J} \sum_{k=-\infty} |i_{j,k}^D|^2} \rightarrow \max. \end{array} \right.$$

where  $E_n$  is the spectrum power of the frequency range under study;  $E_\Sigma$  is gross energy of the wavelet spectrum;  $i_{j,k}^A$ ,  $i_{j,k}^D$  are approximating and detailizing wavelet coefficients of the decomposition level  $j$ , of the node  $k$  correspondingly.

Parseval equality analog is valid for wavelet transform. It states that the total energy of the voltage function  $u$  under study (current  $i$ , instantaneous power  $p$ ) can be determined via the peak value of wavelet coefficients:

$$(8) \quad E_u = \int i^2(t) dt = C_\psi^{-1} \iint V^2(a, b) \frac{dadb}{a^2}.$$

Calculation of the energy spectrum of wavelet coefficients makes it possible to identify a line in which there was SPGF. To eliminate the boundary effect, it is advisable to use "a one-cycle sliding window". The authors use this approach to detect transients in real-time by the energy of the wavelet coefficients.

The sum of the squares of the wavelet coefficients determines the energy of the specified frequency range

$$(9) \quad \sum_{n=1}^N [i_0(t)]^2 = \sum_{n=1}^N (i_n^A)^2 + \sum_{j=1}^J \sum_{n=1}^N (i_n^D)^2$$

where  $i_0(t)$  is the investigated zero sequence current;  $N$  is the number of wavelet coefficients at a given level of decomposition  $j$ ;  $i_n^A$ ,  $i_n^D$  are the approximation and detail coefficients.

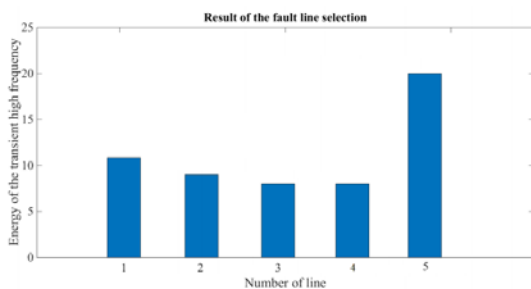


Fig. 8. Result of the fault line selection

Spectrum energy of each frequency band is calculated for each line. The obtained values of the energy of high frequency components are compared with reference ones (energy spectrum in the normal operating mode of the line). If there is an energy excess, the SPGF is identified. The fault in the examined network occurred in line 5 as is clear from Fig. 8.

High power in the spectrum of higher harmonics indicates the line with the single line to ground fault. The suggested algorithm allows continuous monitoring energy levels of the higher harmonics spectrum.

## Conclusion

The analysis of the mixed neutral ground system using the wavelet transform was performed. This method has some advantages over the widely used methods based on the short-time Fourier transform. The advantage relates to no necessary of choosing the STFT duration. Also, the wavelet transform allows one to decompose zero sequence current to frequency ranges giving the possibility of more detailed analysis of the charge and discharge frequencies. Wavelet transform allows better determining the line with single-phase-to ground fault protection comparing to STFT due to eliminating the spectrum flow. Wavelet transform represents an opportunity to perform digital filtration (at software level) of frequencies higher than 1.5-2 kHz. That increases sensitivity of admittance ground fault protection. The method proposed in this work, is based on the definition of the signal spectrum energy, and makes it possible to accurately determine the line where SPGF took place.

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