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Application of signal wavelet decomposition for identification of arc earth faults

***Abstract**. This paper presents a novel criterion for identification of arc earth faults in medium voltage (MV) networks. This criterion is based on the discrete wavelet transform (DWT). The product of zero sequence current and voltage details is used to detect and to discriminate the internal faults from the external ones. New criterion was tested in a MV network. The test results show that the new criterion is very selective, accurate and effective, especially during arc intermittent short-circuits in compensated networks.*

***Streszczenie.** W artykule przedstawiono nowe kryterium do identyfikacji zwarć doziemnych łukowych w sieciach średnich napięć (SN), oparte na dyskretnej transformacie falkowej. Do identyfikacji I rozróżniania zwarć wewnętrznych od zewnętrznych wykorzystano sygnały będące iloczynem detali z dekompozycji falkowej prądu I napięcia zerowego. Nowe kryterium przetestowano w sieciach SN. Wyniki badań pokazują, że nowe kryterium jest bardzo selektywne, dokładne i efektywne zwłaszcza podczas identyfikacji zwarć łukowych przerywanych w sieciach kompensowanych. (**Zastosowanie transformaty falkowej do identyfikacji zwarć doziemnych**)*

Keywords: arc earth fault, wavelet decomposition, identification, modelling and simulation.
Słowa kluczowe: zwarcia doziemne łukowe, dekompozycja falkowa, identyfikacja, modelowanie i symulacja.

Introduction

In Polish medium-voltage (MV) networks about 70÷90% of total disturbances are single phase-earth short-circuits. Most of these disturbances occur with accompanying short-circuit arc and nonlinear transfer resistance. During such disturbances, earth currents and zero sequence voltages are highly distorted, irregular and non-stationary. Conventional earth short-circuit protection systems (directional and admittance-based ones) use fundamental harmonics of these quantities for short-circuit identification.

In the case of nonstationary arc short-circuits, the parameters of fundamental harmonics (amplitude, phase offset) change with time, thus their filtration becomes ineffective. Therefore, the estimates of criterion quantities (zero sequence voltage, zero sequence current and its components, admittance and its components) possess high pulsations and discontinuities, which make it impossible for the protection systems to operate properly.

It is assessed that the percentage of malfunctions of earth short-circuit protection systems, caused mainly by intermittent arc short circuits is about 5÷15%, most of the malfunctions occur in compensated MV networks. Therefore, attempts to develop new criteria of operation of protection systems are made, in order for them to be suited more accurately to specific signal conditions during arc to earth short circuits. Judging on the basis of the research results presented so far [1÷3], a break-through could be attained by the use of wavelet signal analysis. It is particularly useful for the purposes of non-stationary processes and it allows to focus on characteristic features of the examined signals: discontinuity, nonlinearity, abrupt changes.

The present paper offers a novel proposal of a criterion for identification of nonstationary earth short circuits based on the application of high frequency details of zero sequence voltages and currents and relationships among them. As it follows from the presented results, the proposed criterion is sharply outlined and it could be an alternative for solutions based on low frequency signal approximation [1÷3].

Wavelet signal decomposition

Discrete wavelet transformation and related multi-resolution wavelet signal decomposition are based on signal decomposition into components using basis selective functions in the time and frequency domains [4÷6]. The fundamental dependency of multi-resolution analysis assumes, that the signal $x(t)$ may be presented at different *m* detail levels as a linear combination of orthogonal basis functions: wavelets $\psi(t)$ and scaling functions $\varphi(t)$

(1) $$x(t)=\sum_n c_{m_k,n}\varphi(2^{-m_k}t-n)+\sum_{m=m_0}^{m_k}\sum_n d_{m,n}\psi(2^{-m}t-n)$$

where: $c_{m_k,n}$ - coefficients of signal approximation at k-th level, $d_{m,n}$ – details from successive decomposition levels, n – numbers of coefficients, $m=m_0,...m_k$ – numbers of decomposition levels.

Approximation coefficients $c_{m.n}$ of the lower level are obtained in practice by applying filtration of coefficients $c_{m-1,n}$ from the upper level with a low-pass (LP) filter associated with the wavelet and subsequent downsampling, i.e. elimination of every second sample. The details $d_{m.n}$ are obtained as the result of filtration of the same coefficients $c_{m-1,n}$ with the use of a high-pass (HP) filter and analogous downsampling (Fig. 1). These processes may described with the relationships:

(2) $$c_{m,n}=\sum_k h(k)c_{m-1}(n-2k)$$

(3) $$d_{m,n}=\sum_k g(k)c_{m-1}(n-2k)$$

where: $h(k)$, $g(k)$ – LP and HP filter coefficients.

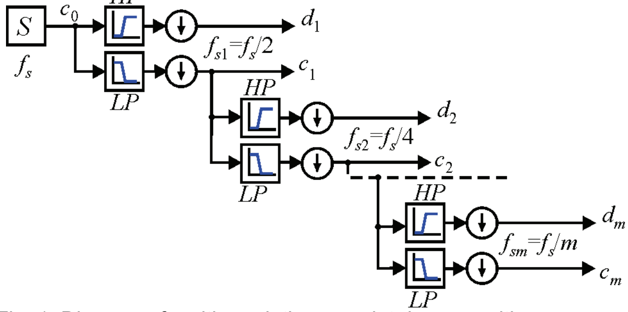

Fig. 1. Diagram of multi-resolution wavelet decomposition

The filters associated with wavelets should possess the following features:

- they have to possess a finite impulse response FIR (a compact carrier);
- they have to offer an accurate signal reconstruction;
- they should have a linear phase (optionally).

For direct and inverse discrete wavelet signal transformation the so-called quadrature mirror filters (QMF) are designed [9]. They are made up of a system of four filters directly integrated with each other, one low- and high-pass (*h and g*) pair is used for analysis, the other one (*h'*, *g'*) is used for synthesis.

Wavelet decomposition of earth short circuit signals

The process of search and examination of new criteria for identification of earth short circuits has been based on simulation studies with the use of PSCAD software [8]. In this software, a model of typical mixed MV (15 kV) network was developed. The general diagram of the aforementioned network is depicted in Figure 2. It consists of six lines (four overhead and two cable ones), of total capacitance current 46,79 A. It can operate with isolated neutral point, grounded with a Petersen coil or a resistor. In this network a series of intermittent arc short circuits was simulated, zero sequence voltages in the station and earth currents at the beginning of every line were recorded. The transients were next subjected to three-stage wavelet decomposition, in accordance to the general scheme given in Figure 1.

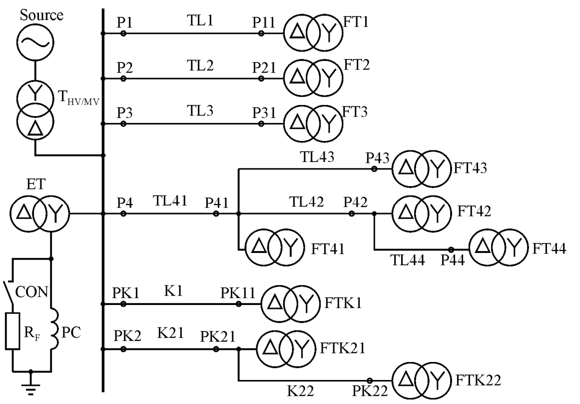

Fig. 2. General diagram of the modelled MV network

The research has been focused on high frequency details. For decomposition quadrature filters associated with wavelets of different kind were used. It was stated, that the wavelet, which is best correlated with short circuit signals, is the reverse biorthogonal wavelet, denoted with the nickname rbio3.5 [9]. In Figure 3 its shape, scaling function as well as impulse responses and amplitude spectra of analysis filters associated with this wavelet are presented. This wavelet emphasizes the signal details. The short circuits currents and voltages are also quite well correlated with rbio3.3 and Daubechies db3, db5 wavelets.

The usefulness to short circuits identification of signals created from a product of instantaneous values of details (wavelets) of earth current dI and zero sequence voltage dU delayed by one sample for different detailedness levels m was examined

(4) $$dp_m(n) = dI_m(n)\cdot dU_m(n-1)$$

and averaged signals

(5) $$dp_{ms}(n) = \sum_{k=0}^{K-1} p_m(n-k)h_{LP}(k)$$

where: dp – the product of details (proportional to the instantaneous power of details), dp_s – instantaneous smoothed-out power, h_{LP} – impulse response of smoothing filter, K – number of filter coefficients.

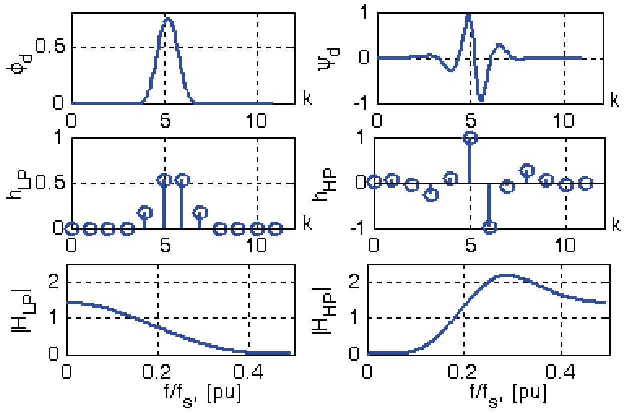

Fig. 3. Wavelet of rbio3.5 type ψ_d, its scaling function φ_d, impulse responses and amplitude spectra of filters LP and HP for decompositions associated with this wavelet

Summing up the research results it was stated, that the signals dp during intermittent arc short circuit are practically monopolar, on the line with the short circuit they have the positive sign, whereas on the 'healthy' lines they have the negative sign. Smoothing of these signals with the Hanning filter possessing no more than 10 coefficients allows to obtain practically monopolar impulses. This can be corroborated with results depicted in Fig. 4, which reveals the transients of zero sequence voltage, earth current in line TL4, earth current in line K2 and instantaneous power of details during an arc short circuit in the point P41 of the line TL4. This short circuit was simulated in a compensated network with compensation detuning s = 0,05. The signals pertaining to instantaneous power were depicted using relative units referred to zero sequence power of the network $S_E = U_0 I_E$ = 405 kVA. These correspond to the stage of forcing the active component of earth current.

The afore-described regularity occurs in different detail levels, but is best fulfilled at the second level (it gives the highest signal levels there). The details from this level, under the assumption, that the initial sampling frequency was equal to 2000 Hz, correspond to the frequency level 250÷500 Hz. Such details may be excreted using single stage decomposition, assuming the sampling frequency equal to 1000 Hz. Further considerations were thus limited to this decomposition.

The clearly outlined difference of polarity of instantaneous power impulses in the damaged and the 'healthy' lines allows to formulate a wavelet identification criterion for earth arc short circuits. The short circuit is recognized (operation signal Op = 1), if the sum of impulses I_{pul} corresponding to the positive instantaneous power of details attains the preset value N_s, i.e.

(6) $$Op = \left(\sum I_{pul} \ge N_s\right)$$

The impulses are counted if the logical condition is fulfilled:

(7) $$I_{pul} = (dp_s > p_s)\,\&\,(t_{dp} \ge t_{min})\,\&\,(\Delta t < T_{ret})$$

where: p_s – start-up power value, t_{dp}, t_{min} – actual and minimal time of impulse duration; Δt – time between individual impulses; T_{ret} – holding up time of memory counter (retriggeration) after subsequent impulses.

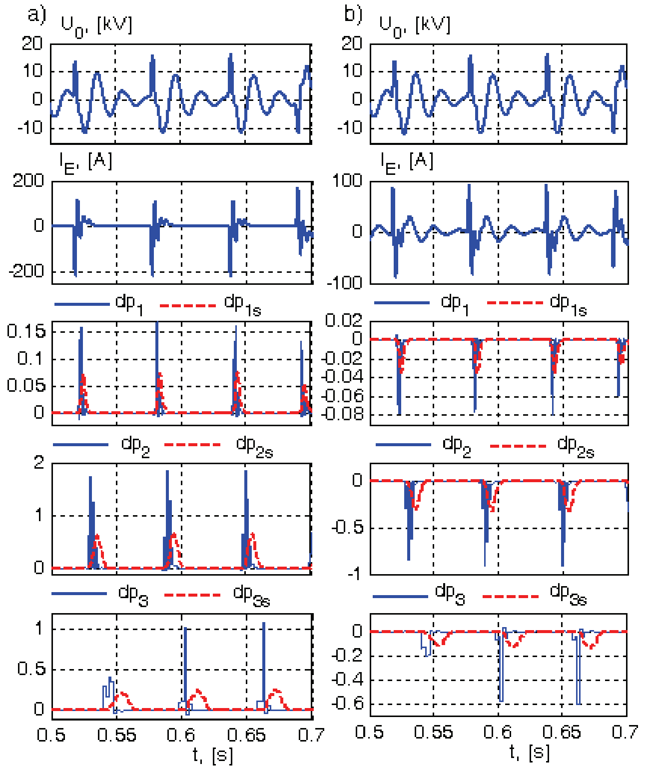

Fig. 4. Zero sequence voltage and currents and signals of instantaneous power of details at three levels of decomposition: a) on the line TL4 with earth short circuit; b) on the 'healthy' line K2

The criterion conditions (6) and (7) determine the way of implementation of the protection system. In Figure 5 a simplified model of such protection developed using PSCAD software is presented.

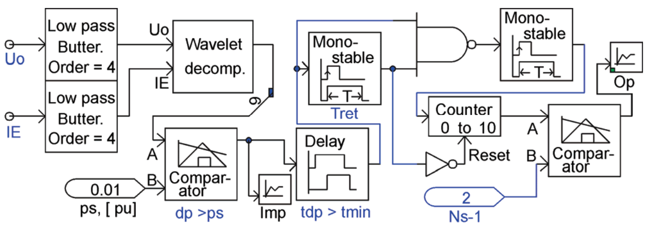

Fig. 5. A simplified model of protection system using the wavelet criterion

The voltage and current signals in the protection are subjected to initial low-pass filtering, then in the block *Wavelet dekomp* their digitization and wavelet decomposition are carried out. The instantaneous power of wavelets dp and dp_s are also calculated. The signal dp_s after a comparison with the preset value p_s is transformed into a logical impulse *Imp* and, if it fulfills the logical-time conditions (7), it is added to the counter content. After the condition (6) is fulfilled, the operation comparator changes the output state (signal Op) from zero into logical unity, what corresponds to the detection of the short circuit.

An important problem for the proposed protection is the choice of setting values. The initial research results have shown that if smoothing filter with window length 0,01 s (ten coefficients) is used it allows to preset the power value in the range of p_s = 0,002÷0,01P_E, what ensures obtaining a sufficient detuning from noise and accidental disturbances. Smaller values can be set for overhead lines and greater - for cable lines. The number of counted impulses should be chosen from the condition $N_s \geq 2$. The minimal impulse length may be chosen from the range $2T_s \leq t_{min} < 5T_s$ (T_s = 0,001 s – sampling period). Time T_{ret} depends on maximal expected time intervals between subsequent arc ignitions. In compensated networks the value of this parameter should be chosen above 0,2 s.

The model depicted in Figure 5 has been used for examination of efficiency to detect short circuits with the developed criterion. The tests have been performed for the following preset values: p_s = 0,01P_E, N_s = 3, t_{min} = 0,002 s, T_{ret} = 0,3 s. The short circuits in different points of the network depicted in Figure 1 in the case, when the network operates with neutral point: isolated, grounded with the compensation (Peterson) coil and grounded with a resistor R_N = 58 Ohm, which forces the active earth current up to 150 A. For simulation of intermittent arc short circuits a model of dynamic arc with an exponent dependency [7] was used. The short circuits with high voltage ignitions occurring seldom were focused on.

In Figures 6÷8 the exemplary decompositions of short circuit signals and the actions of the protection system are depicted. In all three cases a proper action of the protection system in the grounded line and lack of action in 'healthy' lines are observed. The efficiency measure of this protection is its sensitivity, equal to the ratio of maximal instantaneous power to the preset value $k_c = dp_{smax}/p_s$. For the presented cases k_c > 15, what means, that the condition $dp_s > p_s$ is fulfilled with a sufficient spare margin. The highest k_c values, of the order of 50, occur in compensated networks during short circuits with seldom arc ignitions. The lowest sensitivity occurs during short circuits in the network with neutral point grounded with a resistor.

The protection based on counting the impulses of instantaneous power of wavelets obtained from a single step decomposition of sampled signals, whose sampling frequency is f_s = 1000 Hz, is able to detect correctly arc short circuits with arc ignitions occurring once per period of the network frequency or more seldom. In the case of more frequent arc ignitions, the power impulses may superimpose due to too low resolution of details in time domain and impulse counting becomes ineffective. Of course, also in this case it is possible to detect the short circuits with the proposed approach, if one uses a higher sampling frequency, e.g. 2000 Hz and obtains current and voltage details with higher resolution in the time domain.

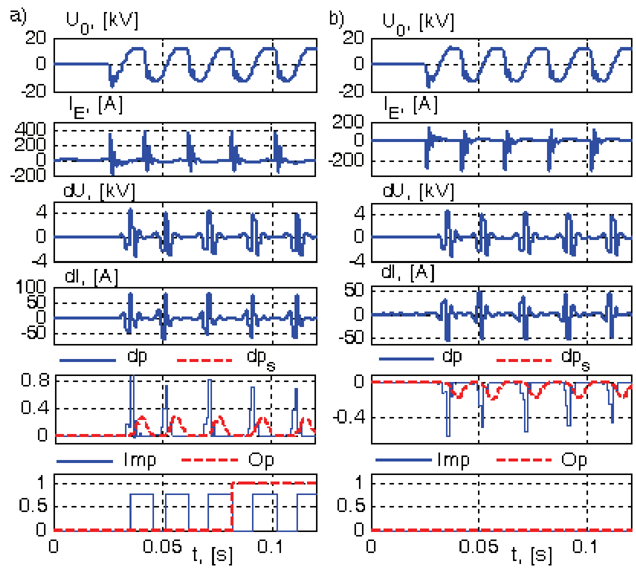

Fig. 6. The protection signals in a damaged K2 line (a) and a 'healthy' K1 line (b) during a short circuit at the point PK2 in a network with isolated neutral point

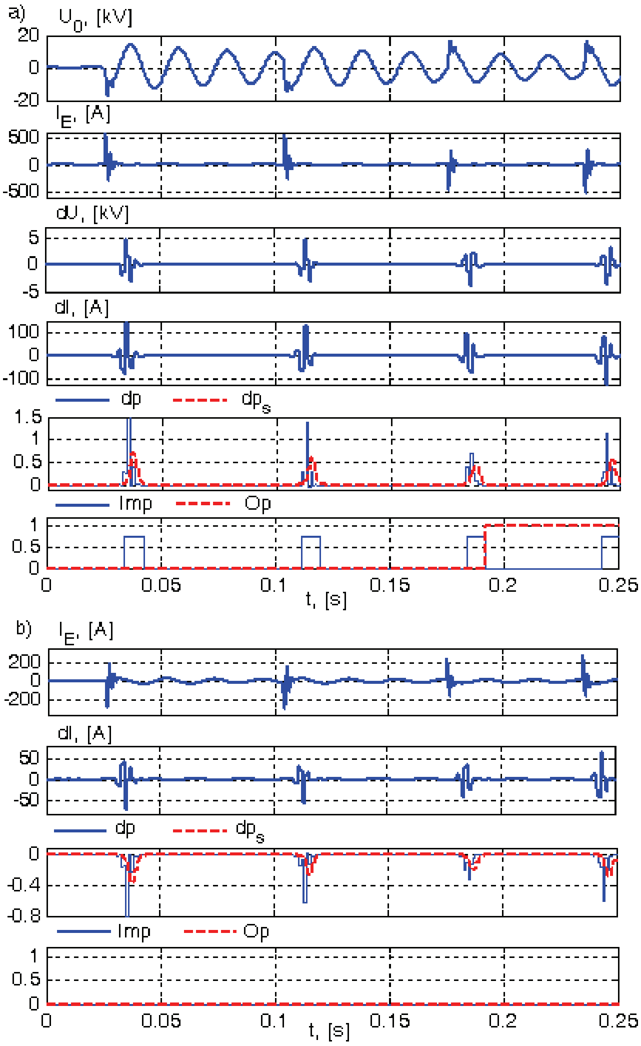

Fig. 7. The protection signals in a damaged TL4 line (a) and a 'healthy' K2 line (b) during a short circuit at the point P41 in a compensated network (s = - 0,1)

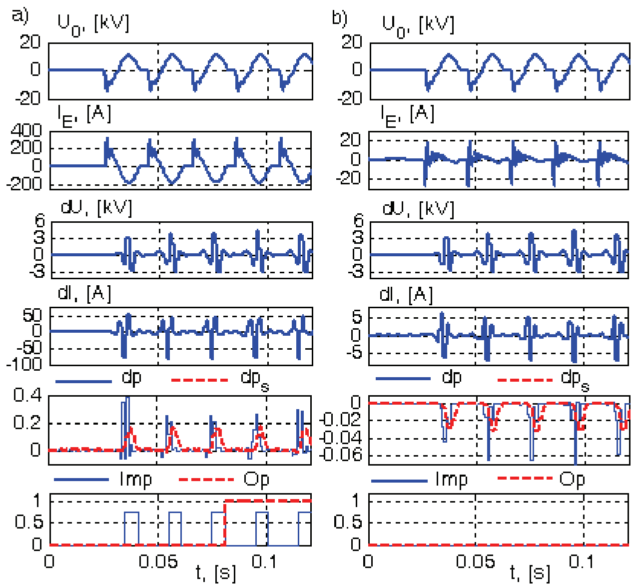

Fig. 8. The protection signals in a damaged K2 line (a) and a 'healthy' TL3 line (b) during a short circuit at the point PK21 in a network whose neutral point is grounded with a resistor R_N = 58 Ohm (150 A)

For identification of short circuits with frequent arc ignitions another criterion may be applied. It is based on the approximate integration of unity impulses, which correspond to the logical condition $Imp = (dp_s > p_s)$, and on a comparison of the integral with the setting value.

Conclusions

A new criterion for identification of earth arc short circuits was proposed, based on counting positive impulses of instantaneous power of zero sequence voltage and earth current details, which are obtained in the process of single stage (or multi-stage) wavelet decomposition.

A model of protection system using the new criterion of short circuit identification was presented. It was shown, that such protection, with filters for decomposition associated with reverse biorthogonal wavelet rbio3.5 and signal sampling at f_s = 1000 Hz is able to detect selectively arc short circuits occurring less frequently than once per period (or once per half of period if f_s = 2000 Hz). It reveals a very high sensitivity $k_c > 10$ during intermittent short circuits. It means that it is able to operate during arc short circuits with simultaneous action of high to-earth resistance. It is also sufficiently resistant to angle errors introduced by measuring transformers – it retains a high sensitivity and selectivity at f_s = 1000 Hz, when the angle error does not exceed ±4,5 degrees (what corresponds to an offset of current and voltage signals by $\pm 0{,}25 T_s$).

The protection is particularly useful in compensated networks for detection of short circuits occurring from time to time. Its efficiency little depends on the level of compensation detuning. It can operate either at the stage of waiting for autonomous extinction of short-circuit or at the stage of forcing the active component of earth current.

The presented protection works as a rule in the conditions of non-stationary and nonlinear transients. It does not detect direct and stationary resistance limited short circuits. Therefore it can be used as supplementary to classical earth fault protection systems.

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