Wavelet criteria for identification of arc intermittent faults in medium voltage networks

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Abstract—**This paper presents two novel criteria for identification of arc earth faults in medium voltage (MV) networks. These criteria are 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 criteria ware tested in a MV network. The test results show that the new criteria are very selective, accurate and effective, especially during arc intermittent short-circuits in compensated networks.**

Keywords-earth fault protection; wavelet criteria; modelling and simulation

I. INTRODUCTION

An important part of single phase earth short-circuits in the medium voltage (MV) networks occur with accompanying arc and nonlinear ground resistance. During such disturbances, earth currents and zero sequence voltages are highly distorted and irregular (non-stationary). Conventional earth fault protection (directional and admittance-based ones) use fundamental harmonics of these quantities for short-circuit identification. In the case of non-stationary arc short-circuits, the parameters of fundamental harmonics (amplitude, phase offset) change along 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 fault protections in Poland, caused mainly by intermittent arc short-circuits is about 5÷15%, most of the malfunctions occur in compensated MV networks. Therefore, attempts are made to develop new criteria of operation of protection systems, better fitted to the signals during arc earth faults. Judging on the basis of the research results presented so far [1÷4], 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 contains a proposal of two novel criteria for identification of non-stationary earth faults based on the application of high frequency details of zero sequence voltage and earth currents and relationships among them. As it follows from the presented results, the proposed criteria are sharply outlined and they could be an alternative for solution described in [4] or solutions based on low frequency signal approximation [1÷3].

II. 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 [5÷7]. 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 $\varphi(t)$

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

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.

In practice, the approximation coefficients $c_{m.n}$ of the lower level are obtained 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 $c_{m-1,n}$ using the high-pass (HP) filter and analogical downsampling (Fig. 1). These processes can be described by the equations:

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

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

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

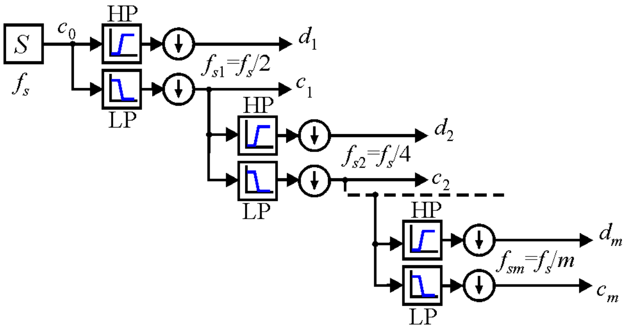

Figure 1. Diagram of multi-resolution wavelet decomposition

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 ensure 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 [10]. They compose a system of four tightly integrated filters; one low- and high-pass (*h and g*) pair is used for analysis, the other one (*h*', *g*') is used for synthesis.

If the QMF filters are related with one wavelet they possess first two features and all come from one low-pass analysis filter *h* which must fulfills conditions of normalization and orthogonalization:

$$\sum_{k=0}^{K-1} h_k = \sqrt{2}\,, \qquad \sum_{k=0}^{K-1} h_{2n+k} h_k = 0\,, \tag{4}$$

where: *K* - number of filter coefficients.

Such filters are asymmetrical (they have nonlinear phase).

To make it possible to use symmetrical wavelets and the symmetrical filters (with linear phase) associated with them the orthogonal condition is replaced by the biorthogonal condition of analysis and synthesis LP filters, i.e.

$$\sum_{k=0}^{K-1} h_{k+2n} h_k' = 0 \tag{5}$$

Then low-pass analysis and synthesis filters are associated with different wavelets which are orthogonal between themselves.

III. Wavelet Criteria for Identification of Arc Earth Faults

The search and examination process of new criteria for identification of earth short circuits was based on simulation studies using the PSCAD software [9]. 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.

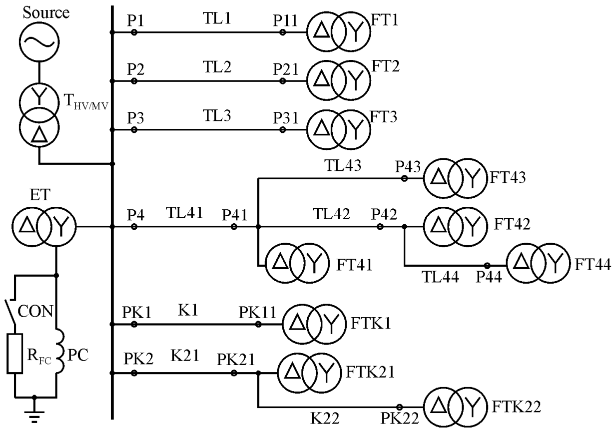

Figure 2. General diagram of the modelled MV network

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 [10]. 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-circuit currents and voltages are also quite well correlated with rbio3.3 and Daubechies db3, db5 wavelets.

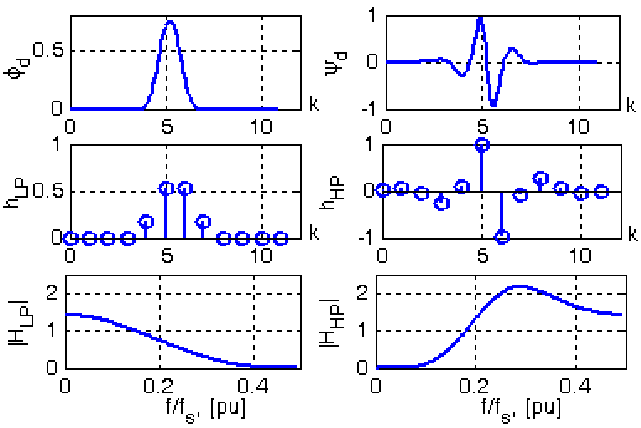

Figure 3. Wavelet of rbio3.5 type ψ_d, its scaling function φ_d, impulse responses and amplitude spectra of filters LP and HP for decompositions associated with this wavelet

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

$$dp_m(n) = dI_m(n) \cdot dU_m(n-1) \quad (6)$$

and averaged signals

$$dp_{ms}(n) = \sum_{k=0}^{K-1} p_m(n-k) h_{LP}(k) \quad (7)$$

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

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 these signals with the Hanning filter containing no more than 10 coefficients allows to obtain practically monopolar impulses. This can be corroborated with results depicted in Figure 4, in which there are revealed 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 regularity described afore occurs in different detail levels, but it is best fulfilled at the second level (it gives the highest signal levels there). Assuming that the initial sampling frequency was equal to 2000 Hz, the details from this level correspond to the frequency level of 250÷500 Hz. Such details may be extracted using single stage decomposition, taking 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 $Op1 = 1$), if the sum of impulses I_{pul} corresponding to the positive instantaneous power of details attains the preset value N_s, i.e.

$$Op1 = \left(\sum I_{pul} \geq N_s\right) \quad (8)$$

The impulses are counted if the logical condition is fulfilled:

$$I_{pul} = (dp_s > P_s) \,\&\, (t_{dp} \geq t_{min}) \,\&\, (\Delta t < T_{ret}) \quad (9)$$

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.

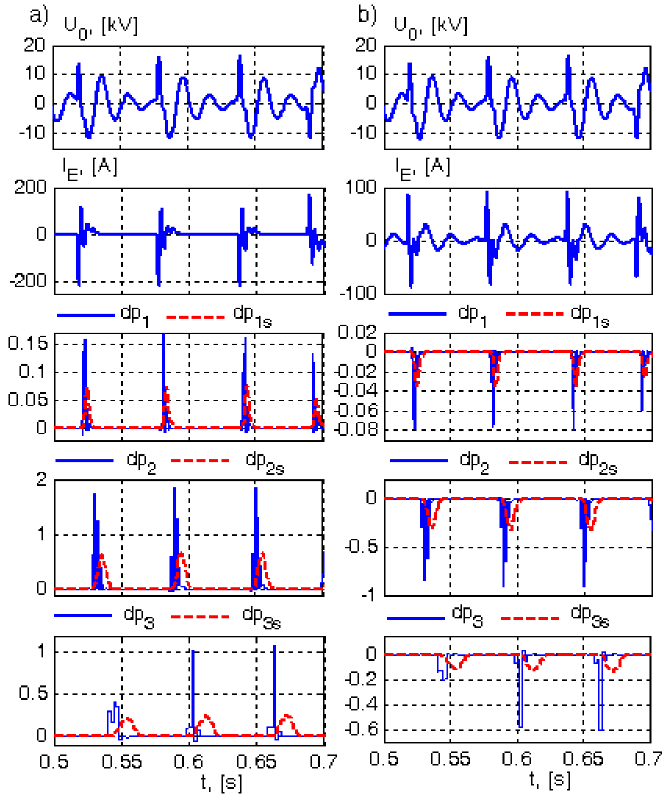

Figure 4. Zero sequence voltage and currents and signals of instantaneous power of details at three levels of decomposition: a) on the line TL4 with earth short circuit; b) on the "healthy" line K2

The protection system, based on counting the impulses of instantaneous power of wavelets obtained from a single step decomposition of signals sampled with the frequency $f_s = 1000$ Hz, is able to detect correctly arc short circuits with arc ignitions occurring once per period of the network frequency or more seldom. In 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 rate, e.g. 2000 Hz, or shorter filters (associated with wavelet rbio3.3 or db3) and obtains current and voltage details with higher resolution in the time domain.

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 Int with the setting value T_{sv}, i.e.

$$Op2 = \left(Int \geq T_{sv}\right) = \left(\int Imp \geq T_{sv}\right) \quad (10)$$

The approximate integration (lag function) can be done for instance with the trapezoidal rule in the form

$$Int(t) = \frac{2\tau - \Delta t_i}{2\tau + \Delta t_i} Int(t - \Delta t) + \frac{G\Delta t_i}{2\tau + \Delta t_i} [Imp(t) + Imp(t - \Delta t_i)] \quad (11)$$

where: Δt_i - integration step, τ - time constant, G - gain factor.

IV. Model of the Earth Fault Protection

The criterion conditions (8), (9) and (10) determine the way of implementation of the protection system. In Figure 5 a simplified model of such protection developed using PSCAD software is presented.

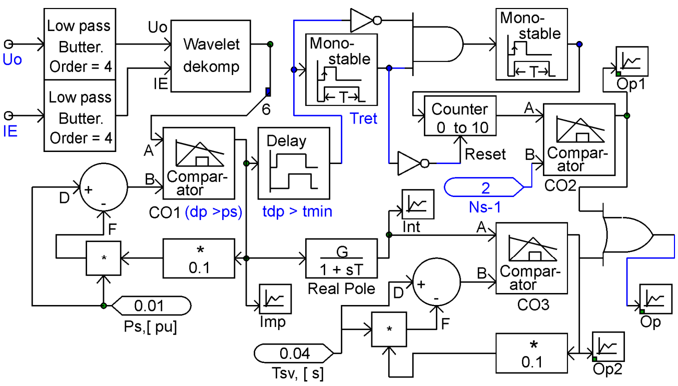

Figure 5. A simplified model of protection using the wavelet criteria

The voltage and current signals in the protection are subjected to initial low-pass filtering, then in the *Wavelet dekomp* block their digitization and wavelet decomposition are made. 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 in $CO1$ is transformed into a logical impulse Imp and, if it fulfills the logical-time conditions (9), it is added to the counter content. After the condition (8) is fulfilled, the operation comparator $CO2$ changes the output state (signal $Op1$) from zero into logical unity, what means the detection of the short circuit. The Imp signal is also approximately integrated by the *Real Pole* component. Its output signal Int is compared with a preset value T_{sv} in the $CO3$ component. If condition (10) is fulfilled the signal $Op2 = 1$, what means short-circuit detection. The protection output signal Op is logical sum of signals $Op1$ and $Op2$. When arc ignitions appear once per cycle or more seldom, a protection operates according to the criterion (8), and when arc ignitions appear more often, it operates according to the criterion (10).

An important problem with the proposed protection is the setting values choice. 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 $P_s = 0{,}002 \div 0{,}01 P_E$, 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 of values $2T_s \leq t_{min} < 5T_s$ ($T_s = 0{,}001$ 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 preset value T_{sv} should be greater or equal to the length of one cycle, i.e. $T_{sv} \geq 0{,}02$ s. To obtain a good linearity of the integration of short impulses and quick automatic zeroing of the *Real Pole*, its time constant τ should be chosen within the range 2÷5 s, and its gain $G = \tau$.

The model depicted in Figure 5 was used to examine the efficiency of short circuits detection with the developed criteria. The tests was performed for the following preset values: $P_s = 0{,}01 P_E$, $N_s = 3$, $t_{min} = 0{,}002$ s, $T_{ret} = 0{,}3$ s, $T_{sv} = 0{,}04$ s, $\tau = 2$ s. The short circuits were simulated in different points of the network depicted in Figure 2 in the case, when the network operates with the 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 intermittent arc short circuits simulation a model of dynamic arc with an exponent dependency [8] was used. The short circuits with high voltage ignitions occurring seldom were simulated mainly.

In Figures 6÷9 the exemplary decompositions of short circuit signals and the actions of the protection system are depicted. In all four cases a proper action of the protection system in the grounded line and lack of action in "healthy" lines are observed. In the cases presented in Figures 6÷8 protection operates according to the criterion (8) however in a case presented in Figure 9 it operates according to the criterion (10).

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.

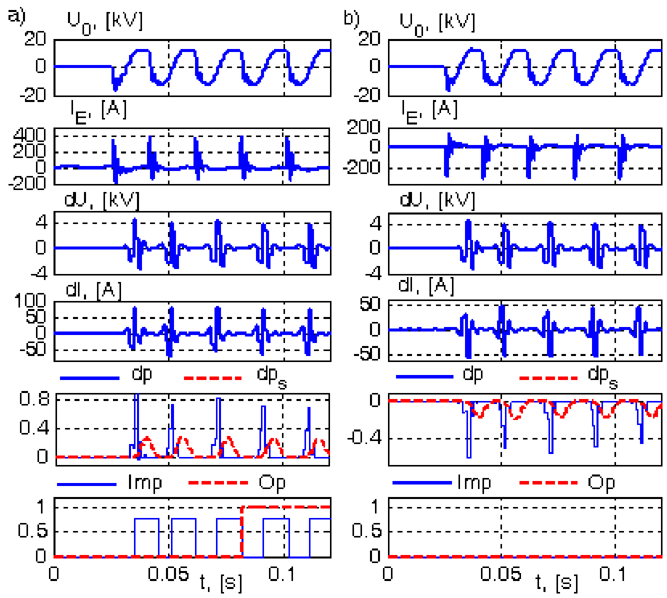

Figure 6. The protection signals in a damaged K2 line (a) and a "healthy" K1 line (b) during a short circuit at the point PK2 in a network with isolated neutral point

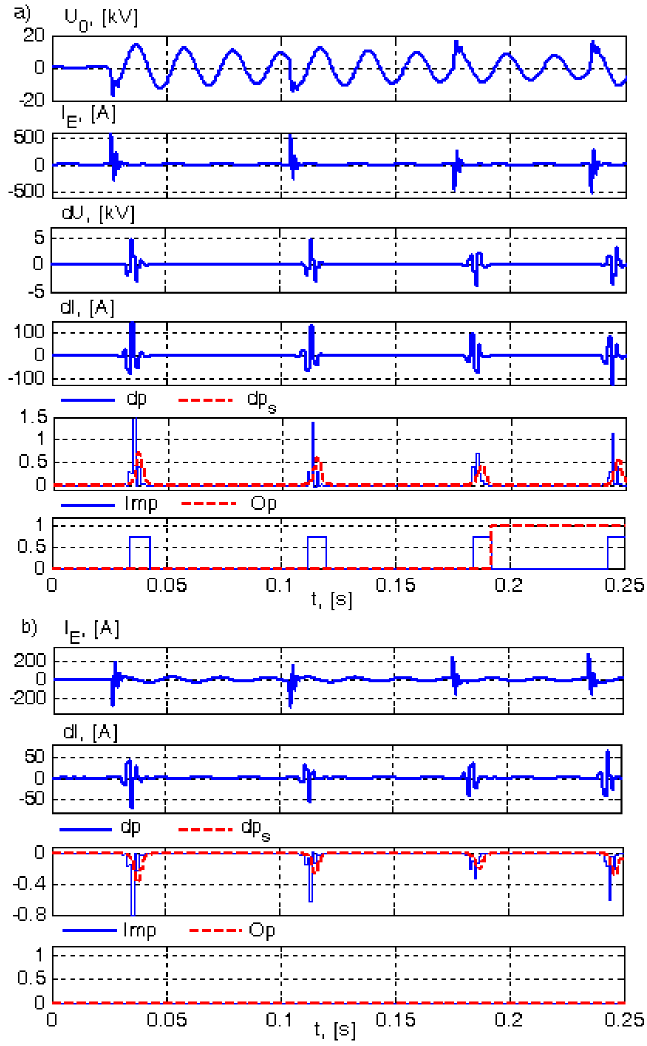

Figure 7. The protection signals in a damaged TL4 line (a) and a "healthy" K2 line (b) during a short circuit at the point P41 in a compensated network (s = - 0,1)

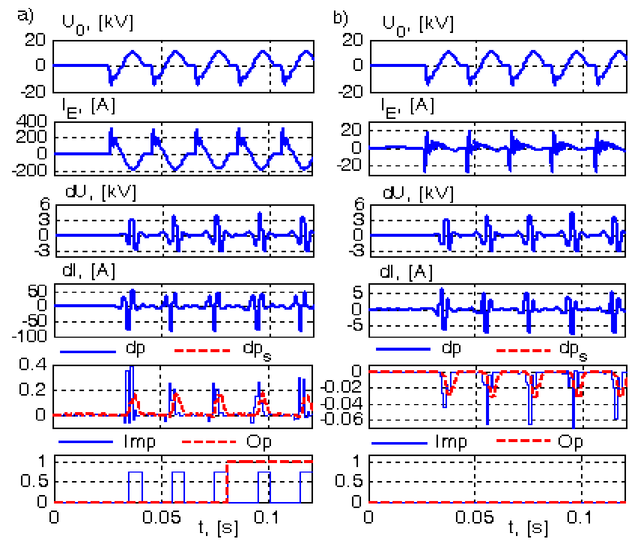

Figure 8. The protection signals in a damaged K2 line (a) and a "healthy" TL3 line (b) during a short circuit at the point PK21 in a network whose neutral point is grounded with a resistor R_N = 58 Ohm (150 A)

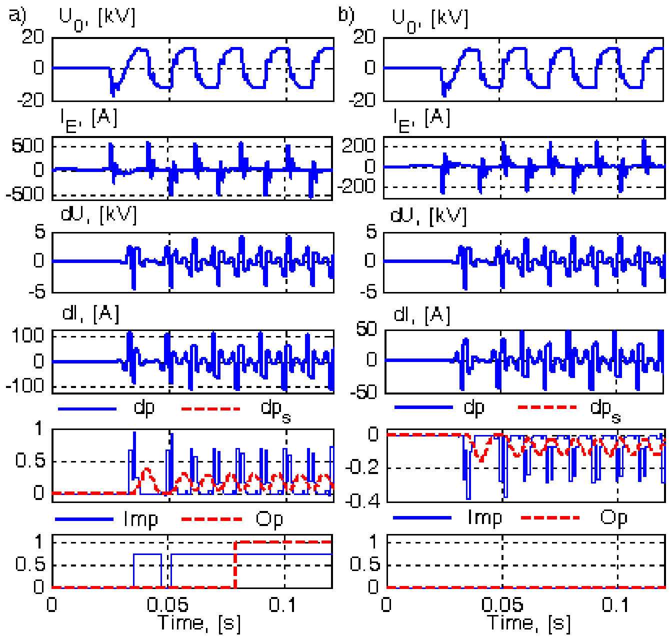

Figure 9. The protection signals in a damaged TL4 line (a) and a "healthy" K1 line (b) during a short circuit with two arc ignition per cycle at the point P4 in a network with isolated neutral point (arc ignition voltage U_{ig} = 8 kV)

The sensitivity of discussed protection k_c depends on distance of short-circuit from the station, because the further it is found the less high frequency details contain voltages and currents at the beginning line. This dependence is illustrated by the table 1 which contains the sensitivity coefficients of the line protections in a compensated network during arc faults at different points of this network. The coefficients k_c were estimated at preset value $P_s = 0{,}002P_E$ for short-circuits about the arc voltage ignition U_{ig} = 10 kV on expectation stage (St. 1) and on forcedness stage (St. 2).

TABLE I. SENSITIVITY OF PROTECTIONS DURING ARC SHORT-CIRCUITS AT DIFFERENT POINTS OF THE COMPENSATED NETWORK

Fault point	**Distance from station, [km]**	**Sensitivity k_c in a case $P_s = 0{,}002P_E$**					
		s = -0,1		s = 0,05		s = 0,1	
		St. 1	*St. 2*	*St. 1*	*St. 2*	*St. 1*	*St. 2*
P4	0	275	300	251	302	274	288
P41	10	486	337	454	438	490	341
P42	25	103	65	97	82	96	87
P43	30	103	76	56	54	62	56
P44	33	52	43	45	43	51	46
P11	30	63	48	56	46	64	48
P21	50	16	10	18	16	16	16
P31	70	9	7	9	7	10	8
PK11	15	208	198	200	178	187	182
P21	10	178	165	155	150	182	149
PK22	17	140	157	158	128	166	165

Simulation research showed also that presented protection system is resistant enough for angular errors, carried in by current and potential transformers. It is proved by the Figure 10, on which the instantaneous power of a current and a voltage details are presented for a damaged K2 line and a "healthy" K1 line during a short circuit in the case when angular error is equal to 0 degrees and in the case when this error carries out 4,5 degrees.

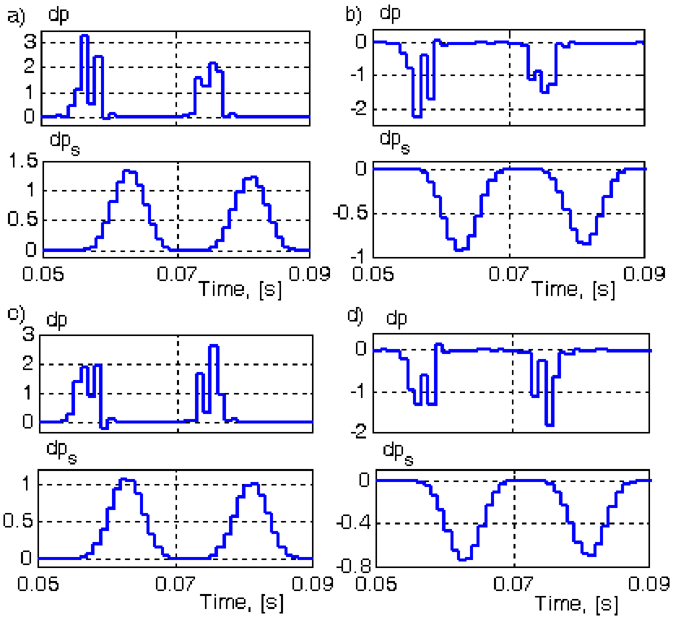

Figure 10. Power impulses of details in a damaged K2 line (a) and a "healthy" K1 line (b) without angular error and with error 4,5 degrees (c, d) during short circuit at the point PK21 in a network with isolated neutral point (arc ignition voltage U_{ig} = 20 kV)

In the case of angular errors between the earth current and the zero sequence voltage within the range of -4,5÷4,5 degrees a positive part of smoothened power impulses dp_s of undamaged lines does not exceed value $dp_{err} < 0{,}001P_E$. This dependence comes true during the any arc fault in the network depicted in Figure 2 with any grounding way of the neutral point. Therefore, the least setting value of power P_{smin}, which can be accepted taking into account the done twice margin, amounts $P_{smin} = 0{,}002P_E$.

In a case of permanent short-circuits or with the participation of the constant fault resistance in the signal *dp* of the earthed line only one positive impulse will appear at the beginning of short-circuit. Such information is insufficient for identification of the permanent short circuit. Thereby the discussed protection should be treated as the supplement to traditional protection systems.

V. Conclusions

A new criteria for identification of earth arc short circuits were proposed, based on counting positive impulses of instantaneous power, or integration of logical impulses corresponding to the positive 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 criteria of short circuit identification was presented. It was shown, that such protection, with decomposition filters associated with reverse biorthogonal wavelet rbio3.5 and signal sampling at f_s = 1000 Hz is able to selectively detect the arc intermittent short-circuits with ignitions occurring both often (several times in the cycle) as seldom (once on several cycles). It shows a very high sensitivity $k_c > 10$ during intermittent short-circuits situated within 50 km from the station. 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 $\pm 0{,}25T_s$).

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 supplement to classical earth fault protection systems.

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