DOI: https://doi.org/10.15407/techned2021.04.055

APPLICATION OF WAVELET TRANSFORM FOR PHASE-TO-GROUND FAULT PROTECTION IN MEDIUM VOLTAGE ELECTRICAL NETWORKS

V.F. Syvokobylenko*, V.A. Lysenko**
Donetsk National Technical University,
Shibankova sq., 2, Pokrovsk, Donetsk region, 85300, Ukraine.
E-mail: svf1934@gmail.com ; viktor.lysenko@donntu.edu.ua

For electrical networks with voltage of 6-35 kV with a compensated, isolated or resistor-grounded neutral, a phase-to-ground protection has been developed, in which, based on the results of the time-frequency wavelet transform of zero-sequence currents, voltages and their derivatives, using the obtained analytical expression, the total reactive power wavelet for different frequencies is determined. It is shown that at the initial moment of a phase-to-ground fault on the damaged feeder the power is always positive, and on the undamaged feeder it is negative, regardless of the operating mode of the neutral. Wavelet transform coefficients are found by convolution of discrete values of measured signals with sine-cosine signals of the Morlet mother function. The time-reversed sequence of these signals is obtained using a matrix for which the rules for its formation are stated. An excess of the zero phase sequence voltage amplitude of the set value is used as a starting protection element. With the help of a mathematical model of the network, studies of the behavior of protection in case of blind and arc phase-to-ground faults at various degrees of compensation of capacitive currents, at various voltage values at the moment of the short circuit have been carried out. In all modes, a reliable protection operation is obtained, the sensitivity of which is an order of magnitude higher than the protection based on Fourier transforms. Positive results of testing a protection sample implemented on a microprocessor-based element base at a laboratory stand are obtained. References 20, figures 7, tables 2.
Key words: electrical network, current, voltage, zero phase sequence, wavelet transform, reactive power, protection against phase-to-ground faults.

The relevance of the problem and its connection with applied problems. Electric networks with voltage of 6 – 35 kV, operating with a compensated or isolated neutral of the network, are taken as the basis for power supply systems of industrial enterprises, cities, and the auxiliary needs of power plants. Taking into account the large length and widespread prevalence of such networks, the problem of protecting networks against the most common insulation damage – a single-phase-to-ground fault is urgent. A significant part of ground faults are transient and short-term processes accompanied by an electric arc. In such cases, steady-state current and mains voltage ground-fault protection devices are not able to operate correctly. We also note that the use of a Petersen coil to compensate the capacitive ground fault current complicates the operation of protection devices, since it significantly reduces the single-phase ground fault current in the steady state. In addition, the phase of the current in relation to the voltage depends on the degree of compensation of the capacitive current by the reactor, which makes it difficult implementation of selective protection.

Review of publications and disadvantages of known solutions. The problem of analyzing transients in networks with ungrounded neutral in order to create an effective algorithm for protection against unstable ground faults is being actively studied in Europe and around the world [1-3]. In particular, in [3], the aperiodic component of the transient of a single-phase-to-ground fault is investigated and its influence on the operation of known methods of protection against such faults is analyzed; the EMTP code is used to simulate the network. Much attention is paid to the features of mathematical modeling of an electric arc at the site of damage and methods of detecting and classifying damage, here the MATLAB-SIMULINK code is used to model the network [4]. The PSCAD code is also widely used. The work [5] explores the possibility of using voltages and currents not only of zero, but also of negative sequence to identify single-phase-to-ground faults. In [6], an attempt was made to obtain additional information on the ground fault due to a significant (up to 1 Msample per second) increase in the signal sampling frequency. Mathematical models of electrical networks including models of relay protection devices are investigated [7]. The search for optimal parameters of mathematical methods for processing signals from primary current and voltage sensors is

ORCID ID: * https://orcid.org/0000-0002-7720-0540 ; **https://orcid.org/0000-0002-6411-3114

underway [7, 8, 9]. Methods for identifying single-phase-to-ground faults are being developed and the sensitivity of such methods is analyzed in conditions of high resistances at the fault point [9]. It is also known about the use of a logical algorithm for making decisions based on the results of comparing the coefficients obtained as a result of wavelet transforms (WT) [10]. The WT is used to analyze transient processes in distribution networks with a resonantly grounded neutral [11], as well as in electric power systems [12-14]. As a rule, the scale of electric power systems does not allow to draw a clear boundary between the transient and steady-state mode [15, 16], which results in the application of the WT in cases where there is no complete certainty that there is no transient process at the moment. However, the WT mechanism by itself does not guarantee the desired result. For this reason, active research on transient processes and the development of protection methods using WT algorithms are still ongoing, and the search for the optimal base (kernel, mother) WT function is underway [17, 18]. The selection of frequency components can be carried out using both WT and classical digital filters [19, 20]. Numerous attempts have been made to use various methods based on artificial neural networks (ANNs) to protect against single-phase-to-ground faults, however, in our opinion, the possibilities of simpler approaches have not been exhausted, among which the most attractive is the analysis and use of components of different frequencies in currents 3i0 and voltages 3u0 of zero phase sequence.

Problem definition and the goal of the work. To develop protection against single-phase-to-ground faults (SGF) of directional action for electrical networks with isolated or compensated neutral. The protection should be based on the WT of zero phase sequence voltages and currents arising from phase-to-ground faults during the discharge and recharge of the network capacities. To do this, it is necessary to obtain: analytical expressions for identifying higher harmonic components in currents, voltages and their derivatives with the help of WT; expressions for using this information in protection of directional action; to develop and investigate a microprocessor-based version of the implementation of the obtained analytical expressions.

Main material and the results obtained. The study of transients at single-phase-to-ground faults and their analysis for the development of principles for constructing protection is carried out using a mathematical model of the electrical network, a description of which is given in [7]. Consider a typical transformer substation for a 6 kV power supply system (Fig. 1), which consists of 110/6 kV step-down power transformer T1, busbars of the first sections BB-1, from which three cable lines F1-F3 are powered, each of which has zero phase sequence current transformers TA0. Measuring voltage transformers VT0, are connected to the busbars. Phase-to-ground faults protection relay (R1-R3) are connected to the secondary circuits of TA0 and VT0. The neutral of the network is grounded through a reactor (Petersen coil) (PC) with a resonant inductance (L_{res}) of 0.16 H, and the capacitances of the phases to the ground of the feeders connected to this section are 1, 9 and 12 μF, respectively. The total capacitive current of the section at the SGF is 72 A. The mathematical model of the network is based on the differential equations of the network elements, the solution of which, in order to increase the numerical stability, is carried out by implicit

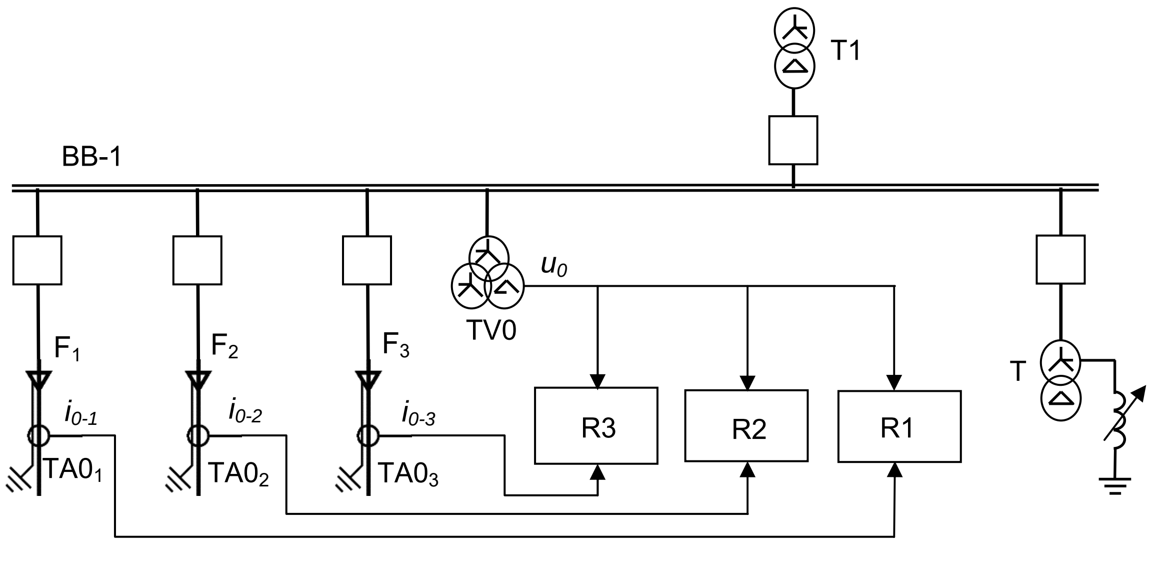


Fig. 1

methods with a calculation step of 0.5 ms. The calculation results are presented in relative units with the basic ones: for voltage $Ub = \sqrt{2} \cdot 6000 / \sqrt{3} = 4900\ \text{V}$, for current $Ib = \sqrt{2} \cdot I_{SGF} = \sqrt{2} \cdot 72 = 101{,}8\ \text{A}$, for power $Qb = Ub \cdot Ib = 0{,}5\ \text{MVA}$.

The proposed in this work protection method is based on the use of time-frequency dependencies of harmonic components in currents $i=3i_0$ and voltages $u=3u_0$ of zero phase sequence and in their orthogonal components, which are derivatives *pi, pu, (p=d/dt)*. Determination of the latter is carried out by numerical differentiation of the initial currents and voltages arising in the transient process during SGF. For this, for example, when using three instantaneous values of current (voltage), formula (1) is used, in which h is the calculation step, and ω=314 s^{-1} (hereinafter, the calculation step is the same as the integration step of the differential equations of the mathematical model, we will denote it as h, the sampling period of the ADC of the protection device is also assumed to be equal h):

$$px = \frac{d}{dt}(x) = \frac{1}{2\omega h}(3x_n - 4x_{n-1} + x_{n-2})\,. \tag{1}$$

The nature of the transient in the case of the SGF, as can be seen from Fig. 1, is non-stationary and largely depends on the instantaneous value of the voltage at the damaged phase at the moment of the occurrence of the SGF. In this case, the free components have the highest intensity of change at u=u_{max}, and the lowest one at u=u_{min}=0. It follows from Fig. 2 that in the case of the SGF, the derivatives also have an intense character of change.

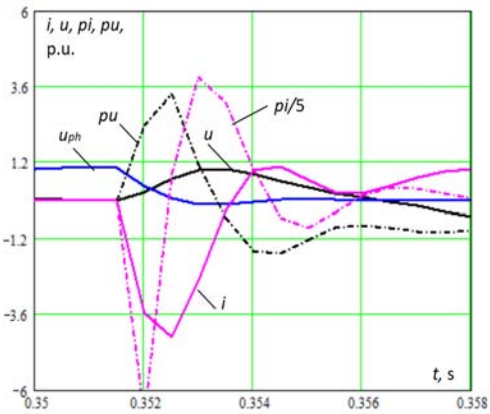


Fig. 2

As is known [8], for the frequency transform of transient time signals, instead of the Fourier transform, it is more correct to use an integral WT specially developed for such processes, which has the form:

$$Wx(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t) \cdot G(\frac{t-b}{a}) \cdot dt\,. \tag{2}$$

Expression (2) is a convolution of the time signal *x(t)* and the mother wavelet (basis function) *G((t-b)/a)*, depending on time t and on the scale factors – a as well as on the shift in time – b. On the other hand, *Wx(a,b)* can be considered as the output of a bandpass digital filter in which a is inversely proportional to the allocated center frequency and determines the time duration of the wavelet, and b – the time shift that determines the locations of the frequency localization.

As the parent (basic) wavelet, we take the Morlet wavelet, which is a complex function oscillating with given frequency and modulated by a damped Gaussian function. This choice is due to the complex nature of the function, which further facilitates the determination of the phase of the frequency components:

$$G(t) = \exp(-\frac{\pi \cdot t^2}{2}) \cdot \exp(j2\pi \cdot t)\,. \tag{3}$$

If instead of t substituting *(t-b)/a* in (3) and considering it in relation to a discrete input signal having N samples (n = 1,2,...N) during the period of the network fundamental frequency f_n at the sampling frequency f_s, then the mother wavelet (3) takes the form:

$$G(\frac{n-b}{a}) = J(n,a,b) \cdot \exp\left[j2\pi \frac{(n-b)}{a} \right] = gC(n,a,b) + j \cdot gS(n,a,b), \tag{4}$$

where the amplitude *J(n,a,b),* cosine *gC(n,a,b)* and *gS(n,a,b)* sine components respectively equal to

$$J(n,a,b) = \frac{1}{\sqrt{a}} \exp\left[-\pi \frac{(n-b)^2}{a^2} \right]; \tag{5}$$

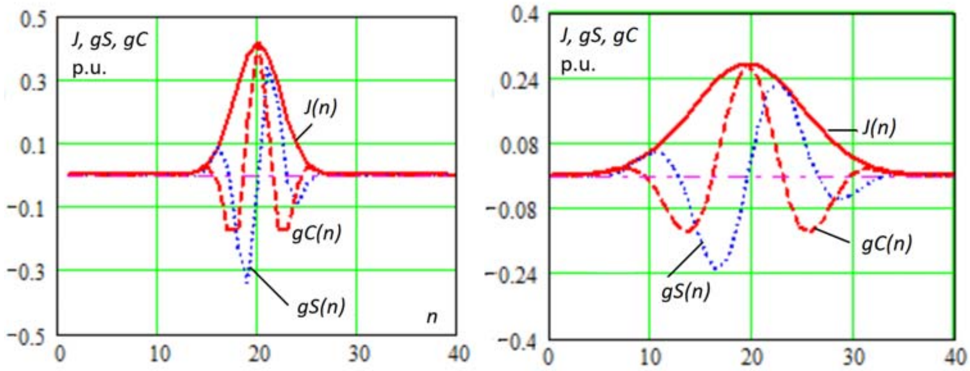
$$gC(n,a,b) = J(n,a,b) \cdot cos(\frac{2\pi(n-b)}{a}); \quad gS(n,a,b) = J(n,a,b) \cdot \sin(\frac{2\pi(n-b)}{a})\,. \tag{6}$$

The nature of the change in the amplitudes and oscillations of functions (5), (6) for two different frequencies is shown as an example in Fig. 3.

Fig. 3. Mother sine-cosine Morlet wavelet functions for N=40, h=0.5 ms, frequencies 350 Hz (a) and 150 Hz (b).

Now, having written (2) in discrete form, we can determine some k-th (k = 1,2,... N..) wavelet coefficients of transforms *WC(k,a,b)* for cosine and *WS(k,a,b)* for sine components of the mother function G:

$$WC(k,a,b)=\sum_{n=1}^{N}x(k-n)\cdot gC(n,a,b), \qquad WS(k,a,b)=\sum_{n=1}^{N}x(k-n)\cdot gS(n,a,b). \qquad (7),(8)$$



a *b*

Fig. 3

Expressions (7), (8) represent the convolution of the input discrete signal and the mother wavelet. It can be defined as the cross-correlation of one of the sequences with the second one which is inverse in time. This operation can be performed using the square size NxN matrix of the convolution kernel $\boldsymbol{M}$(g), which is a function of vectors gC or gS. The matrix $\boldsymbol{M}$(g) is formed as follows: all elements of its main diagonal are equal to g_1, elements on the diagonal below the main one are equal to g_2, even lower – to g_3, etc. On the diagonal, located above the main one, all elements are equal to g_N, then on the next one – to g_{N-1}, etc. The general form of the matrix $\boldsymbol{M}$(g), as well as the example for N=5, are given below:

$$\boldsymbol{M}(\mathrm{g})=\begin{bmatrix} g_1 & g_N & g_{N-1} & \cdots & g_2 \\ g_2 & g_1 & g_N & \cdots & g_3 \\ g_3 & g_2 & g_1 & \cdots & g_4 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ g_N & g_{N-1} & g_{N-2} & \cdots & g_1 \end{bmatrix}; \qquad \boldsymbol{M}(\mathrm{g})=\begin{bmatrix} g_1 & g_5 & g_4 & g_3 & g_2 \\ g_2 & g_1 & g_5 & g_4 & g_3 \\ g_3 & g_2 & g_1 & g_5 & g_4 \\ g_4 & g_3 & g_2 & g_1 & g_5 \\ g_5 & g_4 & g_3 & g_2 & g_1 \end{bmatrix}. \qquad (9)$$

We find the WT coefficients by multiplying the matrix $\boldsymbol{M}$(g) by the vector of the input signal. So, for input signals of protection against SGF of currents i, voltages u and their derivatives pi, pu, the WT coefficients cosine *WCI, WCU, WCpI, WCpU* and sine *WSI, WSU, WSpI, WSpU* are respectively found from the expressions:

$$\boldsymbol{WCpI}(n)=\boldsymbol{M}(gC)\cdot\boldsymbol{pi}(n); \qquad \boldsymbol{WSI}(n)=\boldsymbol{M}(gS)\cdot\boldsymbol{i}(n); \qquad (10)$$

$$\boldsymbol{WSpU}(n)=\boldsymbol{M}(gS)\cdot\boldsymbol{pu}(n); \qquad \boldsymbol{WCU}(n)=\boldsymbol{M}(gC)\cdot\boldsymbol{u}(n); \qquad (11)$$

$$\boldsymbol{WCI}(n)=\boldsymbol{M}(gC)\cdot\boldsymbol{i}(n); \qquad \boldsymbol{WSpI}(n)=\boldsymbol{M}(gS)\cdot\boldsymbol{pi}(n); \qquad (12)$$

$$\boldsymbol{WSU}(n)=\boldsymbol{M}(gS)\cdot\boldsymbol{u}(n); \qquad \boldsymbol{WCpU}(n)=\boldsymbol{M}(gC)\cdot\boldsymbol{pu}(n). \qquad (13)$$

With the help of the WT coefficients obtained as a result of the decomposition of the initial signals into the basic ones, it seems possible to analyze the dynamics of the appearance and disappearance of individual harmonics during the SGF. For this, as a criterion for the protection operation, we take the positive direction of the wavelet-transformed reactive power WQ, defined as the sum of the products of the corresponding wavelet coefficients of currents and voltages with the same serial numbers. It is characteristic that these coefficients correspond to the same frequencies and coincide or opposite in phase. For example, the wavelets coefficients *WSpU, WCU* and also *WCpI, WSI* are in phase, *WCI, WSpI* as well *WSU, WCpU* are opposite in phase. This is due to the fact that differentiation, and then a sine or cosine WTof the signal changes the phase of the signal by 180° or 360°.

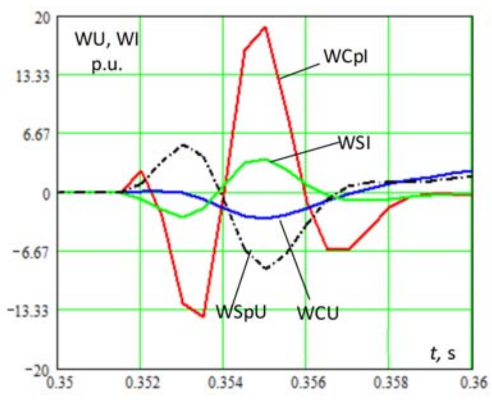


Fig. 4

The nature of the change of obtained using (10) - (13) wavelet coefficients is shown in Fig. 4 (example is given for wavelet coefficients with serial number 16).

Taking into account the above phase relationships between wavelets, two analytical expressions for determining the power *WQ* are obtained in this work. We find it at each calculation step as the average value of the dot product of the corresponding combined *WC* vectors for currents *WI* and for voltages *WU*:

$$WQ_1 == N^{-1}(WCpI - WSI)\cdot(WSpU + WCU)\,; \tag{14}$$

$$WQ_2 = N^{-1}(WCI + WSpI)\cdot(WSU - WCpU). \tag{15}$$

The simulation results established that WQ_1=WQ_2 and this connection, we use below only one of them, which requires calculating only a part of expressions (10)-(13). Note that expressions (14), (15) are obtained for the scale *a* and shift *b* factors corresponding to the selection of only one central frequency by the filter. To increase the protection sensitivity, we will use several filters with different frequencies, which correspond to the sets a_r, b_r (r =1,.., R). Then for each of them it is necessary to determine vectors of mother functions gC_r, gS_r, matrices of convolution kernels $\boldsymbol{M(g)}_r$, WT coefficients (10), (11), powers $WQ1_r$ and their sum $WQ1_\Sigma = \sum_{r=1}^{R} WQ1_r$. However, with this approach, the total computational costs and the duration of the protection action increase, since it is required at each computation step to perform *R* calculations of matrices $M(g)_r$ and find their total sum and use it in (10), (11) to determine the WT, i.e. it is necessary to determine:

$$\boldsymbol{MC}_\Sigma = \boldsymbol{M}(gC(n,a_1,b_1)) + ... + \boldsymbol{M}(gC(n,a_R,b_R)) = \sum_{r=1}^{R} \boldsymbol{M}(gC(n,a_r,b_r)), \tag{16}$$

$$\boldsymbol{MS}_\Sigma = \boldsymbol{M}(gS(n,a_1,b_1)) + ... + \boldsymbol{M}(gS(n,a_R,b_R)) = \sum_{r=1}^{R} \boldsymbol{M}(gS(n,a_r,b_r)). \tag{17}$$

However, the simulation results found that there is a linear relationship between the matrix M and the mother function G, which consists in the fact that the sum of matrices from several vectors of the mother function of the same dimension is equal to the matrix of the sum of these vectors, i.e.:

$$\boldsymbol{MC}_\Sigma = \boldsymbol{M}(\sum_{r=1}^{R} gC(n,a_r,b_r); \quad \boldsymbol{MS}_\Sigma = \boldsymbol{M}(\sum_{r=1}^{R} gS(n,a_r,b_r). \tag{18}$$

Application of (18) allows to eliminate the above-mentioned disadvantage, since it practically does not increase the computational costs when using several filters with different frequencies compared to one. At the same time, the sensitivity of the protection increases significantly.

On the basis of the presented mathematical description (1)-(18), a microprocessor protection against SGF is developed, the block diagram of the calculation part of which is shown in Fig. 5. It contains analog-to-digital converters ADC for converting analog signals 3u0, 3i0 into discrete ones, d/dt blocks for calculating derivatives of input signals, blocks for forming and calculating the elements of the matrix ***M(g)*** of the mother function kernel, as well as blocks for summation ∑, product X as well as *WQ* comparators. If in the first of them the power exceeds the threshold value *Qp*, then the first output element of protection – "SGF in the zone" is triggered, if the power is less – *Qp*, then the second output element – "SGF outside the zone" is triggered.

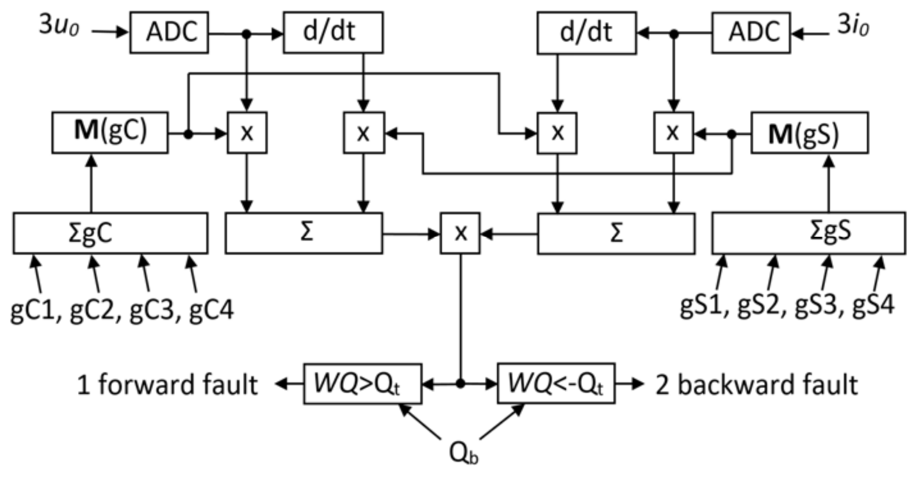


Fig. 5

The protection also provides for a trigging element that allows the protection to operate if the amplitude value U_m of the zero phase sequence voltage is at least 15% of the nominal one:

$$U_m = \sqrt{(3u_0)^2 + (p(3u_0))^2} \geq 0{,}15U_{ном}.$$

Below the results are presented of a study of protection, in which at each period of the network fundamental frequency f_n = 50 Hz, N = 40 discrete values with a sampling frequency f_s = 2000 Hz were allocated. The WT is carried out using four filters with frequencies of 350, 250, 150, 100 Hz, for which, taking into account the fact that $a=f_s/f_n$, the values of the coefficients a, b were:

$$a_1 = 5,7, b_1 = 20; a_2 = 8, b_2 = 20; a_3 = 13,3, b_3 = 20; a_4 = 20, b_4 = 20 .$$

Results of calculations of the wavelet power *WQ* in relative units for the SGF on feeders with the smallest (F1) and largest (F3) capacitances are given in Table 1.

Table 1

Feeder power, WQ, p.u.	Reactor inductance	SGF on feeder F1 at fault phase voltage			SGF on feeder F3 at fault phase voltage		
		u=Umax	*u*=0.5Umax	*u*=0.1Umax	*u*=Umax	*u*=0.5Umax	*u*=0.1Umax
F1 (C=1 μF)	Lres	48.0	32.0	6.5	-3.09	-2.23	-0.89
	3*Lres	54.4	38.0	11.4	-3.1	-2.24	-0.76
	0.33*Lres	38.0	25.0	4.5	-3.0	-2.20	-0.78
F2 (C=9 μF)	Lres	-23.0	-16.4	-5.4	-25	-17.8	-6.0
	3*Lres	-23.8	-16.9	-5.5	-25	-17.8	-6.0
	0.33*Lres	-22.2	-16.1	-5.2	-25	-17.8	-6.0
F3 (C=12 μF)	Lres	-32.6	-23.2	-7.8	20	13.33	2.69
	3*Lres	-33.9	-23.9	-7.9	24.4	17.8	4.58
	0.33*Lres	-32.2	-22.8	-7.5	20	13.7	2.7

As can be seen from the data presented, regardless of the degree of tuning of the reactor, the power of the damaged feeder is always positive, and that of the undamaged one is negative. Its values are maximum at the amplitude voltage on the phase at the moment of damage, and minimum at close to zero. However, when the threshold power value is equal to the basic one Qp = Qb, the correct operation of the protection takes place in all the considered cases of the SGF.

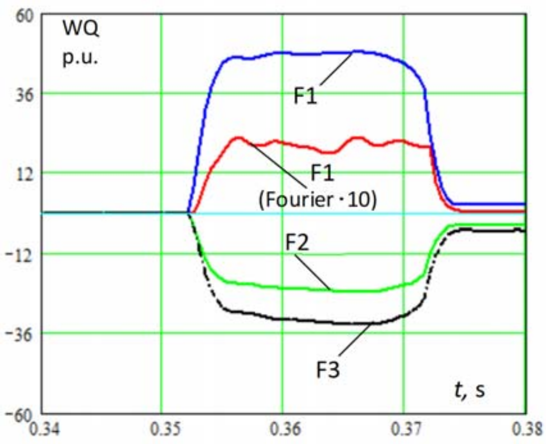


Fig. 6

The nature of the power change in the case of the SGF on the damaged F1 feeder and on the undamaged F2, F3 ones is shown in Fig. 6. It also shows the power value when the same harmonics are separated using the Fourier transform, which is more than an order of magnitude lower than with the proposed WT.

The results of the analysis of the protection operation when an active resistance R = 500 Ω is connected in parallel to the reactor showed that, as follows from the data given in Table 2, the power values practically do not depend on the resistance value, and the protection algorithm also operates reliably.

Table 2

Feeder power, WQ, p.u.	Reactor inductance	SGF on feeder F1 at phase voltage		
		u=Umax	*u*=0.5Umax	*u*=0.1Umax
F1	Lres	47.6	31.8	6.5
	3*Lres	54.5	37.8	11.3
	0,33*Lres	36.7	25.2	4.5
F2	Lres	-22.9	-16.45	-5.4
	3*Lres	-23.6	-16.7	-5.45
	0,33*Lres	-22.3	-15.7	-4.6
F3	Lres	-32.5	-23.8	-7.84
	3*Lres	-33.3	-23.9	-7.9
	0,33*Lres	-31.5	-22.3	-7.5

Figure 7 shows the operation of the output protection element when the zero-sequence voltages and currents are applied to the input, recorded by the mathematical model. Also, positive results of a microprocessor-based protection sample on a laboratory bench have been obtained.

Conclusions.

1. A method of protection against phase-to-ground faults in medium voltage electrical networks has been developed. The method determines the direction of the reactive power wavelet from the wavelet data of the converted zero phase sequence currents and voltages and their derivatives using the Morlet mother function.

2. Matrix-vector analytical expressions are obtained for determining the reactive power wavelet using the coefficients of the wavelet transforms of the measured quantities and the matrix of the kernel of the Morlet mother function, for which the rules of its formation are stated.

3. For the matrix of the kernel of the mother Morlet function, a linear relationship was established between the sum of matrices of several vectors with different frequencies and the matrix of the sum of these vectors, which made it possible to increase the protection sensitivity practically without increasing computational costs by increasing the number of allocated harmonics, and, consequently, the total wavelet coefficient of reactive power.

4. With the help of a mathematical model, as well as during tests on a laboratory bench, results were obtained that confirm the high reliability and sensitivity of the developed protection device prototype.

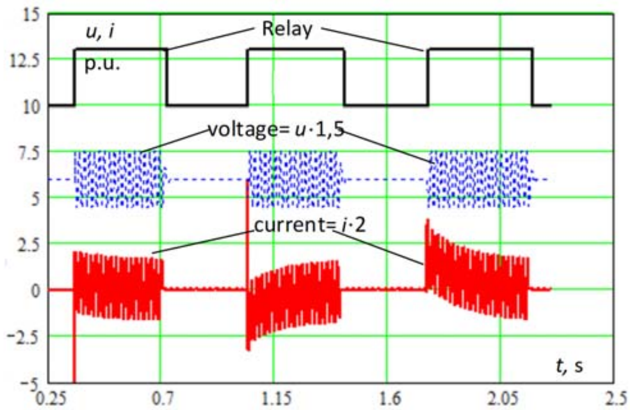


Fig. 7

1. Vaibhav S. Yendole, Kiran A. Dongre. Power System Fault Analysis Using Signal Processing Technique – A Review. *International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering.* 2018. Vol. 6. Issue 5. Pp. 64-67. DOI: https://doi.org/10.17148/IJIREEICE.2018.6514

2. Jabr H.M., Megahed A.I. A Wavelet-FIRANN Technique for High-Impedance Arcing Faults Detection in Distribution Systems. International Conference on *Power Systems Transients* (IPST'05). Montreal, Canada, June 19-23, 2005. Paper No. IPST05 – 035.

3. Yong Guo, Kezunovic M., Deshu Chen. Simplified algorithms for removal of the effect of exponentially decaying DC-offset on the Fourier algorithm. *IEEE Transactions on Power Delivery*. 2003. Vol. 18. No 3. Pp. 711-717. DOI: https://doi.org/10.1109/TPWRD.2003.813894.

4. Debadatta Amaresh Gadanayak, Ranjan Kumar Mallick. Interharmonics based high impedance fault detection in distribution systems using maximum overlap wavelet packet transform and a modified empirical mode decomposition. *International Journal of Electrical Power & Energy Systems*. 2019. Vol. 112. Pp 282-293. DOI: https://doi.org/10.1016/j.ijepes.2019.04.050.

5. Farughian A., Kumpulainen L., Kauhaniemi K. Non-Directional Earth Fault Passage Indication in Isolated Neutral Distribution Networks. *Energies.* 2020. Vol. 13 (18). Pp. 1-10. DOI: https://doi.org/10.3390/en13184732

6. Gomes D.P.S., Ozansoy C., Ulhaq A. Vegetation High-Impedance Faults' High-Frequency Signatures via Sparse Coding. *IEEE Transactions on Instrumentation and Measurement*. 2020. Vol. 69. No 7. Pp. 5233-5242. DOI: https://doi.org/10.1109/TIM.2019.2950822.

7. Syvokobylenko V.F., Lysenko V.A. Earth fault protection for compensated electric networks based on frequency filters. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu.* 2020. No 1. Pp. 69-74. DOI: https://doi.org/10.33271/nvngu/2020-1/069.

8. Das D., Singh N.K., Sinha A.K. A comparison of Fourier transform and wavelet transform methods for detection and classification of faults on transmission lines. *IEEE Power India Conference*. New Delhi, 2006. P. 7. DOI: https://doi.org/10.1109/POWERI.2006.1632580.

9. Syvokobylenko V.F., Lysenko V.A. Earth Fault Protection Improvement on Distribution Networks. *Tekhnichna elektrodynamika.* 2020. No 5. Pp. 54-61. DOI: https://doi.org/10.15407/techned2020.05.054. (Ukr).

10. Ahmed R. Adly, Ragab A. El Sehiemy, Almoataz Y. Abdelaziz, N. M. A. Ayad. An Automated Fault Identification Scheme for Transmission Networks. Proc. *Recent Trends in energy system* Conference*.* Cairo, Egypt, 3 October, 2015. Pp. 289-303.

11. Chaari O., Meunier M., Brouaye F. Wavelets: a new tool for the resonant grounded power distribution systems relaying. *IEEE Transactions on Power Delivery*. 1996. Vol. 11. No 3. Pp. 1301-1308. DOI: https://doi.org/10.1109/61.517484.

12. Wilkinson W.A., Cox M.D. Discrete wavelet analysis of power system transients. *IEEE Transactions on Power Systems*. 1996. Vol. 11. No 4. Pp. 2038-2044. DOI: https://doi.org/10.1109/59.544682.

13. Jurado F., Valverde M. Applications of Signal Processing Tools in a Power Systems Course. *The International Journal of Electrical Engineering & Education*. 2004. Vol. 41(1). Pp. 28-42. DOI: https://doi.org/10.7227/IJEEE.41.1.3

14. Galli A.W., Heydt G.T., Ribeiro P.F. Exploring the power of wavelet analysis. *IEEE Computer Applications in Power*. 1996. Vol. 9. No 4. Pp. 37-41. DOI: https://doi.org/10.1109/67.539845.
15. Lysenko V.A. Model of zero sequence noise in small current grounding system. *Tekhnichna Elektrodynamika.* 2012. No 2. Pp. 44–45. (Ukr)
16. Driesen J., Van Craenenbroeck T., Reekmans R., Van Dommelen D. Analysing time-varying power system harmonics using wavelet transform. Quality Measurement: The Indispensable Bridge between Theory and Reality (No Measurements? No Science!) *IEEE Instrumentation and Measurement Technology* Conference and IMEKO Tec. Brussels, Belgium, 1996. Vol. 1. Pp. 474-479. DOI: https://doi.org/10.1109/IMTC.1996.507428.
17. Ahmed R. Adly, Alaa M. Abdel-hamed, Said A. Kotb, Magdy M. Zaki. Fault Detection for Multi-terminal Transmission Line with Nuclear Power Plant Based on Wavelet Transform. *Arab Journal of Nuclear Sciences and Applications*. 2019. Vol. 52(3). Pp. 144-152. DOI: https://doi.org/10.21608/ajnsa.2019.6832.1162.
18. Borghetti A., Bosetti M., Di Silvestro M., Nucci C.A., Paolone M. Continuous-Wavelet Transform for Fault Location in Distribution Power Networks: Definition of Mother Wavelets Inferred From Fault Originated Transients. *IEEE Transactions on Power Systems*. 2008. Vol. 23. No 2. Pp. 380-388. DOI: https://doi.org/10.1109/TPWRS.2008.919249.
19. Syvokobylenko V.F., Lysenko V.A. Microprocessor selective protection from the phase to the earth fault in electric networks with petersen coil in neutral. *Tekhnichna Elektrodynamika.* 2019. No 2. Pp. 54-62. DOI: https://doi.org/10.15407/techned2019.02.054. (Rus)
20. Gilbert Strang, Truong Nguyen. Wavelets and filter banks. Wellesley-Cambridge Press, 1996. 541 p.

УДК 621.316.925

ЗАСТОСУВАННЯ ВЕЙВЛЕТ-ПЕРЕТВОРЕННЯ ДЛЯ ЗАХИСТУ ВІД ЗАМИКАННЯ ФАЗИ НА ЗЕМЛЮ В ЕЛЕКТРИЧНИХ МЕРЕЖАХ СЕРЕДНЬОЇ НАПРУГИ

В.Ф. Сивокобиленко, докт. техн. наук, **В.А. Лисенко**, канд. техн. наук
Донецький національний технічний університет,
пл. Шибанкова, 2, Покровськ, Донецька обл., 85300, Україна.
E-mail: svf1934@gmail.com; viktor.lysenko@donntu.edu.ua

Для електричних мереж напругою 6-35 кВ з компенсованою, ізольованою або резисторно-заземленою нейтраллю розроблено метод захисту від замикання фази на землю, в якому за результатами частотно-часового вейвлет-перетворення струмів, напруг нульової послідовності та їхніх похідних за допомогою отриманого аналітичного виразу визначають сумарний вейвлет реактивної потужності для різних частот. Показано, що в початковий момент замикання фази на землю на пошкодженому приєднанні потужність завжди позитивна, а на непошкодженому – негативна незалежно від режиму роботи нейтралі. Коефіцієнти вейвлет-перетворень знаходять шляхом згортки дискретних значень вимірюваних сигналів з синусно-косинусними сигналами материнської функції Морле. Звернену в часі послідовність цих сигналів отримують за допомогою матриці, для якої викладено правила її формування. Як пусковий орган захисту використовується перевищення амплітудою напруги нульової послідовності заданого значення. За допомогою математичної моделі мережі виконано дослідження поведінки захисту у разі глухих і дугових замиканнях фази на землю, за різного ступеня компенсації ємнісних струмів, за різних значень миттєвої напруги в момент замикання. У всіх режимах отримано надійну роботу захисту, чутливість якого на порядок перевищує чутливість захисту, заснованого на перетворені Фур'є. Отримано позитивні результати випробувань реалізованого на мікропроцесорній елементній базі зразка захисту на лабораторному стенді. Бібл. 20, рис. 7, табл. 2.

***Ключові слова**:* електрична мережа, струм, напруга, нульова послідовність, вейвлет-перетворення, реактивна потужність, захист від замикань фази на землю.

Надійшла 19.10.2020
Остаточний варіант 11.05.2021