Mathematical Modeling of New Algorithms for Single-Phase Earth Faults Protection in a Compensated Electrical Network

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Abstract. New algorithms have been developed for selective protection against phase-to-earth faults in power supply systems of 6–35 kV. In such, due to the impact of an arc-suppressing compensating reactor (Petersen coil), the selective action of traditional protection devices is not ensured. The purpose of the work is to develop new algorithms for selective protection against phase-to-earth faults in power supply systems with Petersen coil. Mathematical modeling showed that at frequencies of 200–400 Hz, the Petersen coil practically does not reduce the capacitive current in the damaged junction when the phase is shorted to ground, unlike in the case of fundamental frequency. Therefore, to protection device current and voltage with a frequency of 300 Hz are used. This current and voltage are extracted from the current and voltage of zero-sequence using band-pass frequency filters and are used to determine the direction of reactive power. Scientific novelty comprises determining the direction of reactive power using both the current and voltage after the filters, and also their derivatives, which significantly improves the sensitivity and stability of the relay; the performance of filters being controlled depending on the instantaneous values of the zero sequence voltage amplitude, which ensures the stability of the filters; the implementation of a two-channel protection relay for receiving a constant (instead of a pulsating) signal at the output device. The effectiveness of the developed protection is confirmed by the results of the mathematical modeling, tests on a laboratory bench and the supply of full-scale signals registered by the recorders in real networks.
Keywords**:** power supply system, compensated power grid, mathematical model, digital filter, phase to earth fault, Petersen coil.
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Modelarea matematică a algoritmilor noi de protecție împotriva defectelor de pământ monofazate într-o rețea electrică compensată

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Rezumat**.** Rețelele de distribuție de medie tensiune din Ucraina, ca și în multe alte țări, pentru a reduce curenții de avarie și pentru a spori fiabilitatea, funcționează în primul rând într-un mod neutru la sol rezonant. Scopul lucrării este de a elabora noi algoritmi pentru protecția selectivă împotriva defectelor fază-pământ în sistemele de alimentare cu tensiune de 6-35 kV, în care, datorită influenței unui reactor de compensare a suprimării arcului (bobina Petersen), acțiunea selectivă a dispozitivelor tradiționale de protecție nu este asigurată. Studiile folosind modelul matematic elaborat al rețelei au arătat că, la frecvențe de 200-400 Hz, bobina lui Petersen practic nu reduce curentul capacitiv în conexiunea deteriorată atunci când faza este scurtcircuitată la masă, spre deosebire de 50 Hz. Astfel, obiectivul este realizat prin utilizarea de curenți și tensiuni cu o frecvență de 300 Hz pentru a determina direcția puterii reactive. Componentele frecvenței menționate sunt separate de curenții și tensiunile secvenței zero utilizând filtre de frecvență de trecere. Noutatea științifică constă în: determinarea direcției puterii reactive nu numai cu ajutorul semnalelor de curent și tensiune după filtre, dar și a derivaților acestora, ceea ce îmbunătățește sensibilitatea și stabilitatea releului; în performanța filtrelor controlate în funcție de valorile instantanee ale amplitudinii tensiunii secvenței zero, asigurând astfel stabilitatea filtrelor; în realizarea unui releu de protecție cu două canale pentru primirea unui semnal constant, în loc de un semnal pulsatoriu, la intrarea organului de ieșire.
Cuvinte-cheie: sistem de alimentare cu energie electrică, rețea electrică compensată, model matematic, filtru digital, fază la pământ, bobină Petersen.

Математическое моделирование новых алгоритмов защиты от однофазных замыканий на землю в компенсированной электрической сети

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Аннотация**.** Распределительные сети среднего напряжения в Украине, как и во многих других странах, для уменьшения токов замыкания на землю и повышения надежности работают преимущественно в режиме резонансно заземленной нейтрали. Цель работы состоит в разработке новых алгоритмов

селективной защиты от замыканий фазы на землю в системах электроснабжения напряжением 6-35 кВ, в которых из-за влияния дугогасящего компенсирующего реактора (катушки Петерсена) не обеспечивается селективное действие традиционных устройств защиты. Исследования с помощью разработанной математической модели сети показало, что на частотах 200-400 Гц катушка Петерсена практически не уменьшает емкостный ток в поврежденном присоединении при замыкании фазы на землю, в отличие от того, как это имеет место на частоте 50 Гц. Таким образом, поставленная цель достигается путем использования токов и напряжений частотой 300 Гц для определения направления реактивной мощности. Составляющие упомянутой частоты выделяют из токов и напряжений нулевой последовательности с помощью полосовых частотных фильтров. Научная новизна заключается: в определении направления реактивной мощности не только с помощью сигналов токов и напряжений после фильтров, но и их производных, что значительно улучшает чувствительность и стабильность работы реле; в исполнении фильтров управляемыми в зависимости от мгновенных значений амплитуды напряжения нулевой последовательности, за счет чего обеспечивается устойчивость фильтров; в исполнении реле защиты с двумя каналами для получения постоянного, вместо пульсирующего, сигнала на входе выходного органа. Эффективность разработанной защиты подтверждена результатами математического моделирования, испытаниями на лабораторном стенде и проверкой работы при подаче натурных сигналов, записанных регистраторами в реальных сетях.

Ключевые слова: система электроснабжения, компенсированная электросеть, математическая модель, цифровой фильтр, замыкания фазы на землю, катушка Петерсена.

Problem and State of the Issue. In the power supply system of the Ukraine, as in many other countries, the 6--10 kV networks are mainly used. With respect to the capacitive ground currents, the network neutral is performed either isolated, resonant earthed (compensated) [1] via the inductive reactor (Petersen coil), or grounded via the paralleled reactor and resistor [2]. This mode of the neutral has many advantages. However, in many cases, the sensitivity and selectivity of protection against the single-phase earth faults cannot be ensured because of the relatively low currents and complicated character of transient processes at earth faults via an arc [3].

As the disadvantages of the 6--10 kV networks, the appearance of the single phase-to-earth fault (PEF) overvoltages can also be considered, particularly, if in the location of the earth faults an unstable electric arc occurs [4]. These kinds of the PEFs often turn into interphase earth faults and require an emergency switching off of one or several connections. Such disadvantages occur to a lesser extent in a compensated 6--10 kV networks at a resonant tuning of the Petersen coil, therefore they are used more often in the energy systems [5]. The resonant grounded neutral requires the use of the tuning automatic regulator for the Petersen coil [6]. In [7], it is shown that the use of the neutral ground via resistor both increases the ground current and frequency of overvoltages compared to the resonant neutral grounding. Thus, the creation of reliable devices for protection against the single phase-to-earth faults is urgent.

Review of the Publications and Disadvantages of the Common Solutions. In [8, 9] the authors make the attempts to classify the common methods for the protection against the single phase-to-earth faults. In [10] the generalized approach is proposed to the analysis of information in the channels of the relay protection and the network automatics. In [3, 11, etc.], it is shown that at 6--10 kV networks using the common current and current-directed protections it is difficult, and sometimes even impossible, to ensure the protection against the PEF with a necessary sensitivity and selectivity. In [12, 13], it is proposed to use the current injection from a special source into the zero-sequence circuit of the network to simplify the search the fault location. In [14] the peculiarities of the unstable arc short circuit are studied, and, in [15], shunting of the damaged phase is suggested to be applied additionally. However, these methods need substantial modernization of the substations' equipment. In [16], the collective PEF protection is proposed. In [17], a multi-frequency distance PEF protection is proposed, since the distance protection at the frequency of the power supply network cannot operate in the networks with the resonant earthed neutral. In the PEF compensated networks with respect to the extent of the reactor compensation, the direction of the current in the damaged connection can be similar to that of the undamaged. In [18], the arc model in the fault location is studied, in [19], the attempt was made to localize the coordinate of the short-circuit using the parameters of the transient process. The application of various methods is known to analyze the ground current, with Prony's method [20] among them, on the use of a detector of single phase-to-earth faults, based on

Gilbert's transformation [21], on the use of information on the energy spectrum of the processes during the short circuit on the ground [22]. In our opinion, promising in the development of the selective protection is a further progress of the idea of selection by means of the frequency digital filters, the currents and voltages of the zero sequence, the components, with a frequency higher than industrial [23, 24]. For this, the relevant studies of the PEF transient processes are needed alongside with the development of new efficient algorithms. In addition, in this case a system approach is necessary with a simultaneous analysis of the PEF transient processes, both in the primary circuits of the network and in the protection circuits. The development of the appropriate mathematic models is the most advisable in this situation. The mathematic models of the 6--10 kV networks are described in [25], and the models of the algorithms of protection are presented in [26]. Also, in [27], a similar algorithm of protection was described using for selection the necessary frequency components of the Fourier transformation. The program complexes described in [16], to our mind, do not ensure the required flexibility and transparency of the models. Therefore, the solution of the above problems is urgent.

The Aim of the Studies. The development of new algorithms of the selective protection against the single phase-to-earth faults in compensated networks and investigations, using the mathematic models of the power supply network and protection devices.

The Results of the Investigations. To study the transient processes in the compensated networks the mathematic model of [28] is taken as a basis, and, the equations of the algorithms of protection will be added to it. For the preset scheme of the arbitrary structure, it is necessary to form vectors-columns using the parameters of the branches such as the active resistances R, inductances L, capacities C and insulation resistances Rc to the ground, phase emf $e(t)$ of the source of power, currents of branches $i(t)$, voltages of the nodes Uuz and on capacities $uc(t)$, equivalent counter-emf $Eekv$, and also the matrices-connections of the branches with nodes P and branches' resistances Zp. The PEF protection is modeled according to the algorithms developed below and, it is a part of the model.

The matrix vector equations of the mathematic model during the calculations of the PEF processes using the method of the node voltages look like as follows:

$$Zp = diag\left[R + \frac{a_0}{h} L + \frac{h \cdot Rc}{a_0 \cdot C \cdot Rc + h} \right]; \quad (1)$$

$$Uuz = \left[P \cdot Zp^{-1} \cdot P^{tr} \right]^{-1} \cdot P \cdot Zp^{-1} \cdot (e(t) - Eekv); \quad (2)$$

$$i(t) = Zp^{-1}(e(t) - Eekv - P^{tr} \cdot Uuz); \quad (3)$$

$$\Delta uc(t) = \frac{Rc \cdot C}{a_0 \cdot Rc \cdot C + h} \sum_{s=1}^{p} a_s \cdot uc^{(n+1-s)};$$

$$uc(t) = \frac{h \cdot Rc \cdot i(t)}{a_0 \cdot Rc \cdot C + h} - \Delta uc(t); \quad (4)$$

$$Eekv = \frac{L}{h} \sum_{s=1}^{p} a_s \cdot i^{(n+1-s)} - \Delta uc(t). \quad (5)$$

To increase the numeric stability of the mathematic model the solutions of the differential equations for the currents and voltages of the branches are carried out using the implicit method of the second order (p = 2) with the values of polinomials' coefficients, which approximate the derivatives, being equal to $a_0 = 1,5; a_1 = -2; a_2 = 0,5$, according to [8].

Further, as an example let us consider modeling of the transient processes and the PEF protection for one of the typical schemes of the power supply shown in Fig. 1.

The scheme comprises the feeding transformer (branches 13, 14, 15), three feeders (F1, F2, F3) with the phase capacities to ground equal, correspondingly, to 2, 5 and 10 μF and integral interphase capacity of 10 μF of all feeders (branches 10, 11, 12), as well as the Petersen coil (branch 16) with a resonant inductance of 0,198 H.

Each phase of the cable line and transformer is presented by the branch with a longitudinally connected active resistance and inductance, and also the capacity and active resistance of the insulation paralleled and connected to the protective grounding. The insulation resistance of the feeders' branches in the pre-emergency mode was 1 Mohm, and it was (1.4 or 7)-0.1-20 Ohm at a dead PEF for the damaged branch. Arcing faults were modeled by changing the breakdown voltage of the insulation gap and resistance of earth connection to ground.

Since for the intended protection we outlined the use of the currents and voltages with a frequency higher than industrial, then according to equations (1--5), the calculations were performed of the efficient values of the reactive components of the zero-sequence currents in the network branches (Fig. 1) at the PEF with various degree of compensation of the capacitive current, using the Petersen coil.

In this case, the vector of the power supply voltage was located along the transversal axis. Its value equaled nominal 6 kV and frequency varied from 50 to 300 Hz. The results are shown below in Table 1.

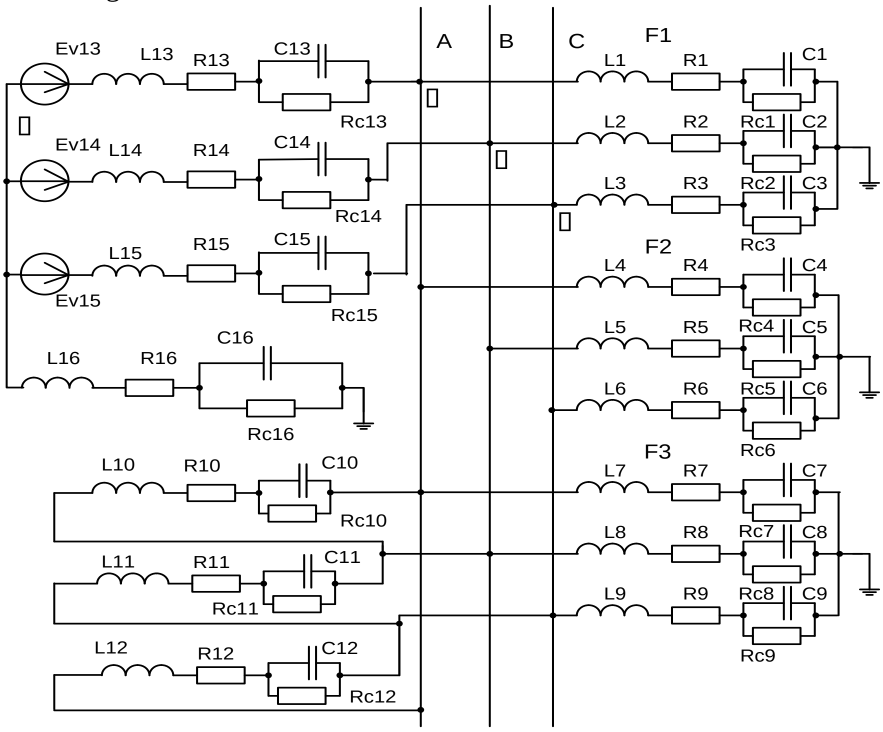

Fig. 1. Scheme of the network model.

Table 1.

Distribution of currents in the network for different frequencies of supply voltage.

Lreaк, Hn	2*Lrez=0,3964 Hn				Lrez=0,1982 Hn				0,5*Lrez=0,0991 Hn			
Frequency, Hz	50	100	200	300	50	100	200	300	50	100	200	300
Ipv, A	22,5	92	243	512	-6,86	76,8	233	502	-65	46	214	481
Inpv1, A	-17,2	-36	-82	-165	-17,0	-35,0	-81	-163	-17	-35	-81	-161
Inpv2, A	-34,5	-72	-170	-356	-34,0	-71,0	-168	-354	-34	-71	-167	-349
Ireak, A	29,1	15	8,65	7,65	58,4	30	17	15,0	116	60	34	30

The data presented show that in all of the modes the currents of the undamaged connections Inpv1 (feeder 2) and Inpv2 (feeder 3) are of a capacitive type and are directed at the PEF towards bus-lines, whereas the current directions of a damaged connection Ipv (feeder 1) depend on the inductance value of the reactor and voltage frequency. Thus, at the resonant tuning of the reactor and at recompensating at a frequency of 50 Hz, the direction of the reactive power is the same as in the undamaged feeders. At the same time, if we take as a basis for the protection the direction of the reactive power for the components the frequencies of 200--300 Hz, then the selectivity of protection is ensured at any values of the reactor inductance. To select the currents and voltages of the indicated frequency from the currents and voltages of the zero sequence let us use the band-pass frequency filters of the second order. Frequency of discreteness in measuring the input signals in accordance with the Kotelnikov-Shannon theorem, must not be below 1 kHz, and then the step of the discrete calculation in modeling can equal 0.001--0.0005 s. Let us accept as a basis a filter with a transmission function that looks like as follows:

$$H(z)=\frac{Y(z)}{X(z)}=\frac{(1-z_0z^{-1})\cdot(1-\overline{z}_0z^{-1})}{(1-z_1z^{-1})\cdot(1-\overline{z}_1z^{-1})}; \quad (6)$$

$$z_0=exp(-w_0T); \quad z_1=exp(-w_1T);$$
$$\overline{z_0}=exp(w_0T); \quad \overline{z_1}=exp(w_1T), \quad (7)$$

In (6), (7), z_0 and $\overline{z_0}$ are the associated complexes, which are the zero points on Z-plane for the components of the circular frequency $w_0 = 2\pi f_0$, and z_1, $\overline{z_1}$ are the points of the poles for the components of a higher frequency $w_1 = 2\pi f_1$, T is the sampling period, which equals the calculation step $T = h$.

Thus, if f_0=50 Hz, f_1=300Hz, h=0,0005s, then from (7) we have $z_0 = 0,988 + j0,156$; $\overline{z}_0 = 0,988 - j0,156$; $z_1 = 0,588 + j0,809$; $\overline{z}_1 = 0,588 - j0,809$.

The amplitude of the output signals of filter H(z) for frequency f_0 is equal to zero, and for f_1 it is fairly large and is of the order of $3,188 \times 10^{15}$.

The block scheme of the selective relay of protection developed using the filter under study is shown in Fig. 2. It contains analog-to-digital converter units ADC, at the input of which in the analog form the voltage and current of the zero sequence are fed of the connections being protected. The discrete signals after the ADC are fed to F filters. After the filters, for the purpose of obtaining the 300 Hz signals of orthogonal components of voltage and current, the corresponding differentiators of $p = d / dt$ are introduced into the block scheme. In more detail, the obtaining of orthogonal components is described in [29]. These blocks change by 90 degrees the phase of the input sinusoidal signal of frequency f_1, which allows one to determine the reactive power of connection such as $Q = u \cdot pi - pu \cdot i$.

To calculate the power the block scheme contains as well the multiplier units MU, summation unit +, comparator K and the output device OD. The latter responds if power Q is positive and exceeds a preset threshold value Q_{thresh} in the comparator.

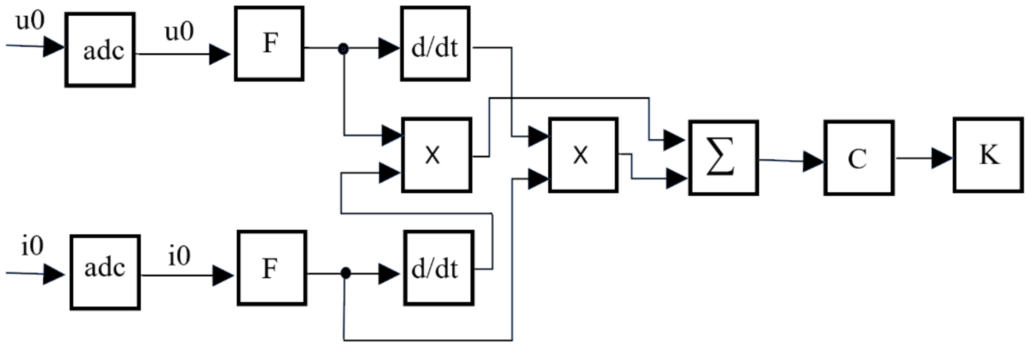

Fig. 2. Block scheme of selective relay of protection against PEF according to algorithm N1.

Let us now examine the operation of filter F in the time region. For this purpose, we shall obtain a finite-difference equation from (6) to determine a signal at filter output y with input signal x being known. This equation under the condition that z^{-1} implies the delay of signals x or y for one step, and z^{-2} for two steps, looks like as follows:

$$y_n = (z_1 + \overline{z}_1) y_{n-1} - y_{n-2} + x_n - \\ - (z_0 + \overline{z}_0) x_{n-1} + x_{n-2} \qquad (8)$$

The results of the PEF modeling according to equations (1-5), (8) during the resonant tuning of the reactor are shown in Fig. 3. In the figure, the currents and voltages i0, u0 of the zero sequence, the currents and voltages after filters if, uf at a frequency of 300 Hz, components of reactive power q1, q2 and their sum Q, which enters into comparator K, are shown.

The duration of the short circuit was of the order of 0.12 s, and, as is seen from Fig. 3, a precise respond of the output device of the protection relay takes place. During the PEF modeling with overcompensation and undercompensation of the capacity currents, the selective action of protection took place as well. However, certain disadvantages were also revealed. Among them were insufficient sensitivity of protection at the PEF via the resistance above 10 Ohm, alongside with a possibility of a nonselective operation of the protection owing to a self-excitation of the filters accepted as a basis with a continuous pulse characteristic.

Let us consider the reasons for the disadvantages and the ways of their removal.

One reason for the nonselective protective operation was that in the filters after disappearing of the input signal, the self-generation of the output signal occurs, which results in erroneous nonselective operation of the protection in the presence of the repeated instantaneous short-circuit to ground in the network.

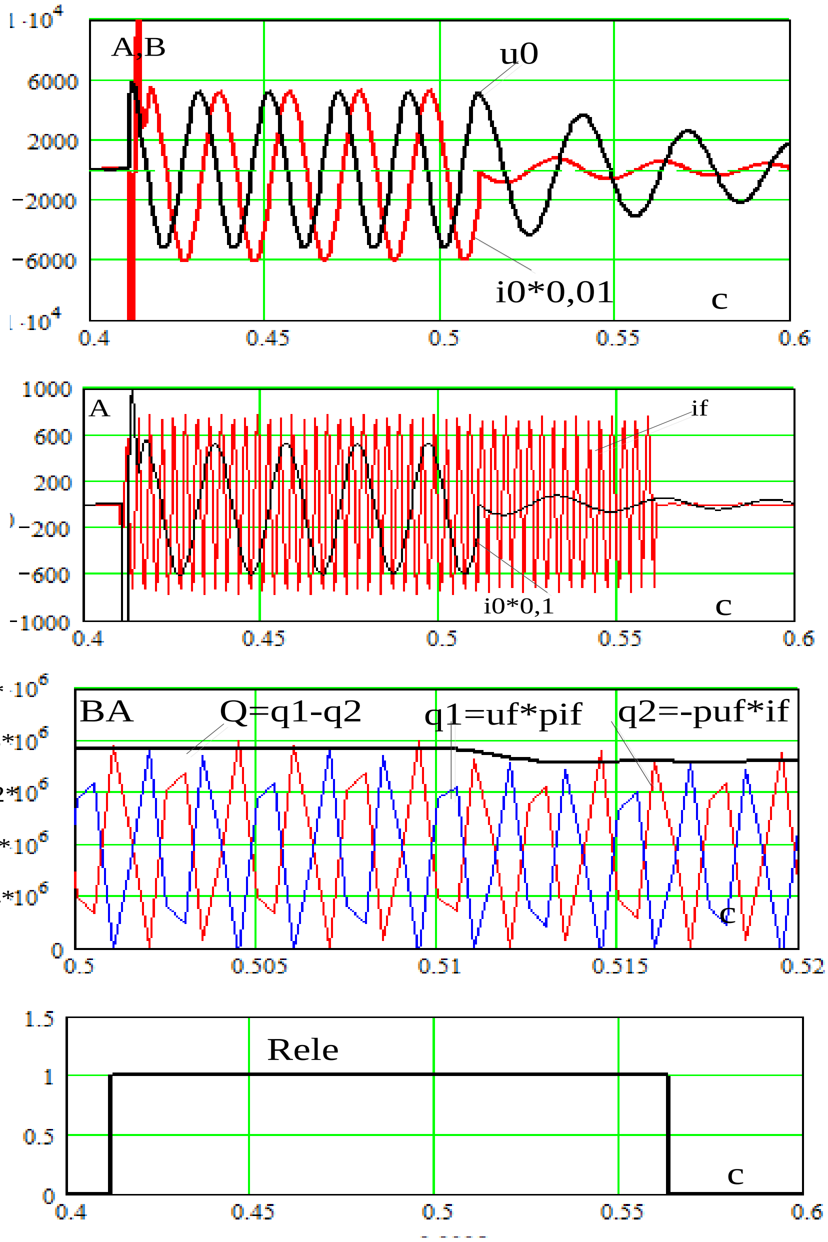

Fig. 3. Waveforms during the earth fault modeling on resonant compensated system (algorithm №1).

The failure in the stable operation of the filters is caused by the fact that the module of the pole and the point of the pole are at a unit circle of Z-plane. The common methods for the removal of this disadvantage by changing the filter coefficients cause the abrupt decrease in the coefficient of amplification and necessity of taking into account the decay time of the output signal.

We proposed to use the controlled filters. As a control signal, the discrete value of the amplitude (of the module) of the zero-sequence voltage must be used, which is calculated by its orthogonal components determined by means of three selections of the instantaneous values:

$$Um = \sqrt{u_n^2 + \left[\frac{3u_n - 4u_{n-1} + u_{n-2}}{2h \cdot w_0}\right]^2} \qquad (9)$$

If the voltage amplitude exceeds the threshold value (set value), this should be considered as the PEF presence. If the voltage amplitude is below the threshold value, the filter operation is being blocked (the output signal becomes zero), if it is higher, the filter operation is permissible. The set value is selected from the tuning out condition from the imbalance voltage in the normal mode and is about 12-15% of the nominal voltage.

To solve the problem of improving the protection sensibility and the relay characteristics the protection algorithm N2 was developed and studied. The peculiarity of this algorithm consists in that the blocks of the derivatives are absent in it, and instead, two filters of a secondary order, F1 and F2, are used with different phase-frequency characteristics. The latter ensure the phase shift of their output signals by 90 degrees when similar signals are fed into the input.

The reactive power here is calculated as follows:

$$Q_n = Q1_n - Q2_n = i1^{(n)}_{out}\cdot u2^{(n)}_{out} - i2^{(n)}_{out}\cdot u1^{(n)}_{out} \qquad (10)$$

The transfer functions of F1, F2 filters consist of transfer function of $H(z)$, (6), and to ensure the angle phase shift by 90 degrees the first of them $H1(z)$ is multiplied additionally by $1+z^{-1}$, and the second $H2(z)$ by $1-z^{-1}$. The obtained transfer functions and their finite-difference equations look like as follows:

$$H1(z) = (1+z^{-1})\frac{(1-z_0 z^{-1})\cdot(1-\overline{z}_0 z^{-1})}{(1-z_1 z^{-1})\cdot(1-\overline{z}_1 z^{-1})}; \qquad (11)$$

$$H2(z) = (1-z^{-1})\frac{(1-z_0 z^{-1})\cdot(1-\overline{z}_0 z^{-1})}{(1-z_1 z^{-1})\cdot(1-\overline{z}_1 z^{-1})}; \qquad (12)$$

$$y1_n = -y1_{n-2} + (z_1+\overline{z_1})\cdot y1_{n-1} - x_{n-3} + (z_0+\overline{z_0}+1)\cdot x_{n-2} - (z_0+\overline{z_0}+1)x_{n-1} + x_n, \qquad (13)$$

$$y2_n = -y2_{n-2} + (z_1+\overline{z_1})\cdot y2_{n-1} + x_{n-3} - (z_0+\overline{z_0}-1)\cdot x_{n-2} + (z_0+\overline{z_0}-1)\cdot x_{n-1}. \qquad (14)$$

The results of modeling the operation of the first and second variants of protection confirmed their correct functioning for the networks with different parameters of their elements and the values of capacitive currents. While being compared, the protection variants showed that the first variant has a certain advantage, since the filters used in it are one-type, and the distinction in their characteristics impacts less the protection operation.

Based on the analysis of the operation of both variants, to improve the protection characteristics the ultimate hybride variant of protection (HVP) was developed, which joined the blocks of structural schemes of the first and second variants into one (Fig. 4).

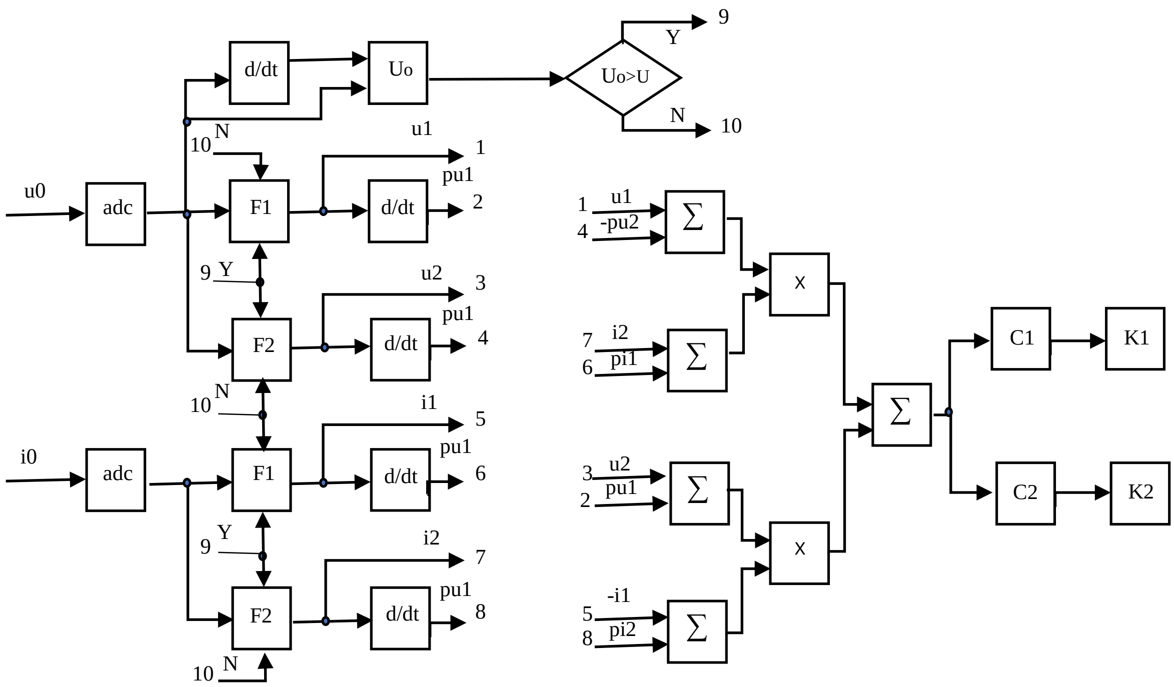

Fig. 4. Structural scheme of final form of hybrid variant of protection relay (HVP).

In this scheme, in each channel of current and voltage measurement after the ADC two filters, F1 and F2, were connected in parallel. Signals from the output of each filter via the block of differentiation are fed to one of the inputs of the summator, to the other input of which the signal from the output of the relevant filter is fed. The output signals from the summators are fed to the multiplier units. In this variant, the relay responds both to the output signals of the filters and to their derivatives, which increases substantially their PEF protection sensitivity. For the transparency, in the scheme of Fig. 4, ten output and ten input contact clips are shown, which should be connected between each other with similar numbers. As is seen from the scheme, to the input of each summator an output signal is fed after the first or the second filter and the derivative of the signal after the second or the first filter. These signals are in phase, that is why after multiplying them in the MU we obtain a reactive power in the form of a unipolar pulsating signal. Since there are two channels of the kind in the relay, their total power will not have already a pulsating character. It will be increased and improve as a whole the operation of the relay.

The reactive power at the input of the comparators is calculated according to the following expression:

$$Q = (u1 - pu2)\cdot(i2 + pi1) + (u2 + pu1)\cdot(-i1 + pi2)$$

In the scheme of the HVP relay, the same as in the previous variants, to ensure the stability of filters they are performed to be controlled with respect to the amplitude of the input voltage: two output devices register the PEF both in the zone of protection, and beyond the zone and, in addition, they ensure the relay diagnostics. The results of the mathematic modeling of the PEF in the branched compensated networks supported the correctness of the relay operation.

Sensitivity of the final algorithm is by 15-20 times higher than that of the previous ones.

Figure 5 shows a few digital schemes for the signals at the inputs and outputs of the main units of the HVP relay that were obtained using the mathematic model in modeling the network PEF (Fig. 1) during the reactor resonant tuning

Figure 6 shows voltage 3U and currents 3I of the zero sequence of frequency of 50 Hz, and also the results of their transformation after the filters and differentiators at a frequency of 300 Hz. The resulting reactive power lacks the discrete signal; however, the output relay has a clearly defined response.

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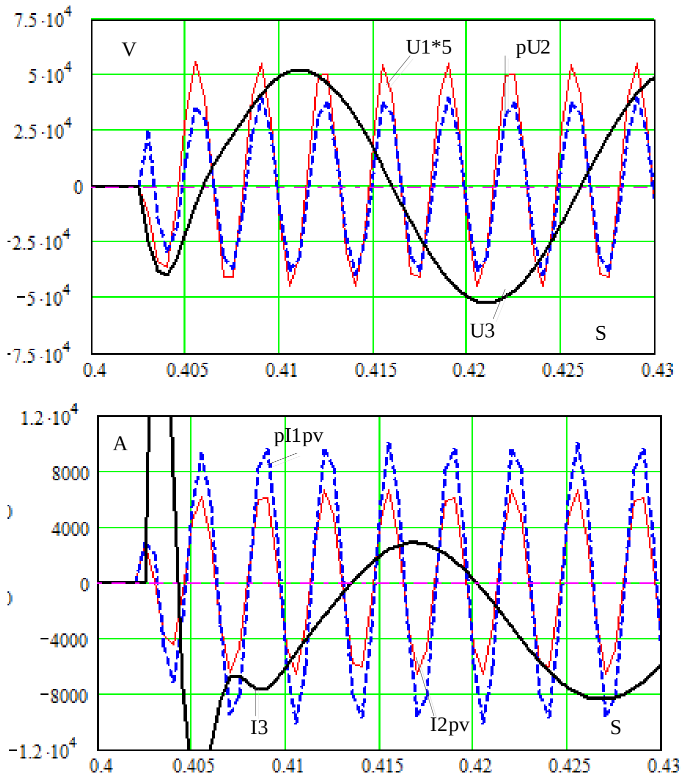

Fig. 5. Modeling of HVP relay operation.

Authenticity of the developed relay is supported as well by the results of the study of the test sample at a physical model. The physical model was constructed according to the equivalent circuit (Fig. 1), which was fed by voltage of 0.4 kV, it contained TZLM real transformers of the zero sequence current. The test sample for the protection was realized following a program using an STM32F4 Discovery demoplata.

The testing of the HVP relay was carried out similarly using the emergency files that were obtained in the operational 6 kV networks with the help of digital registers during the real faults on ground (Fig. 6). This testing was performed according to a Mathcad program. The results obtained allow suggesting the developed relay algorithms to be implemented into the real operating devices.

Further investigations are worthwhile to be directed for the supplementation of the mathematic model with measuring transformers and for modeling the transmission circuits of the analog signals of the protection up to the analog-digital converters.

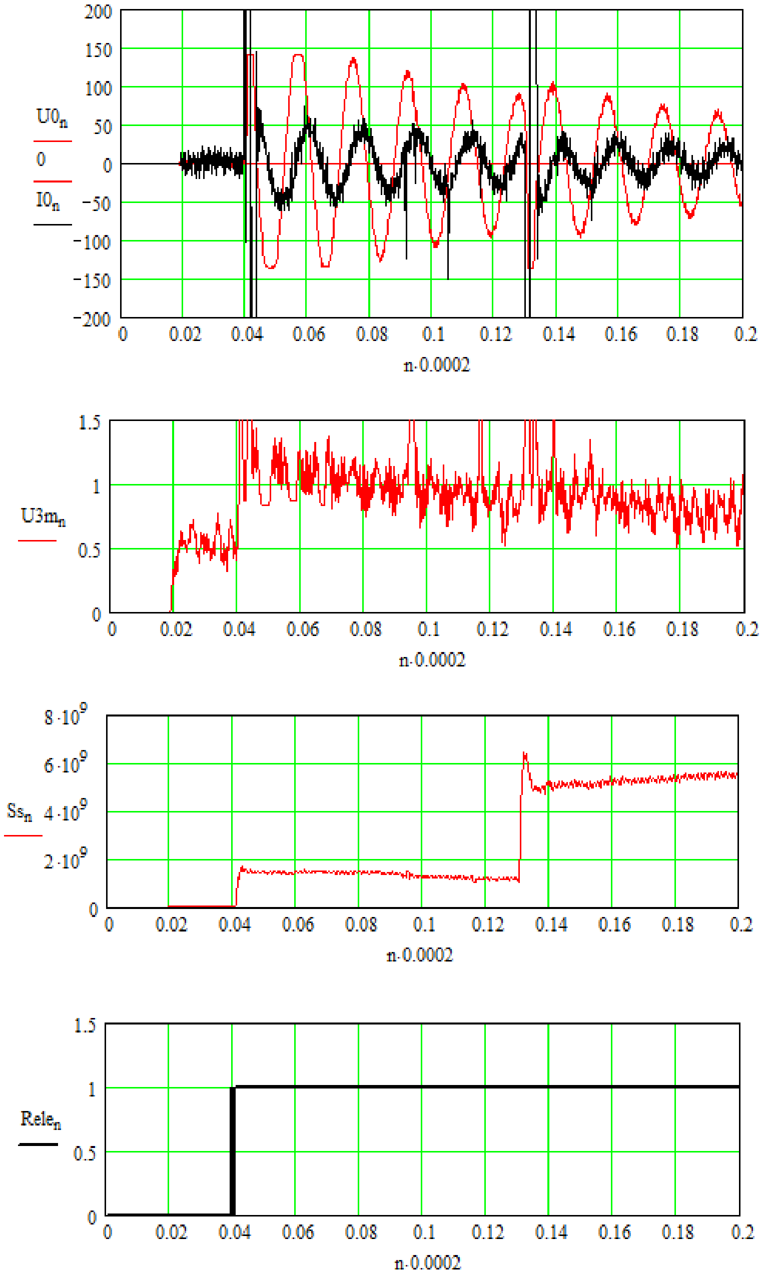

Fig. 6. Results of verifying HVP relay operation using natural emergency files registered during PEF in real network.

Conclusions.

1.The operation principal and new algorithms of a selective microposession protection against the PEF are developed, in which the feature of the reactive power at the PEF is determined according to the currents and voltages of 300 Hz, that are obtained using the band-pass frequency filters from the currents and voltages of the zero sequence of the industrial frequency.

2. To ensure the stability in operation of the filters they are suggested to be performed being controlled according to the amplitude of the zero sequence voltage, and for increasing sensitivity, the protection is performed two-channeled with two filters being used in each channel. Each of the two filters has different phase-frequency characteristics and units for definition of the derivatives after the filters' signals.

3. The efficiency of the protection is confirmed by the results of the mathematic modeling, laboratory tests of the natural sample and correctness of operation during the use of the signals that are registered by the digital recorders at the moment of the phase-to-earth faults in real networks.

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