EARTH FAULT PROTECTION FOR COMPENSATED ELECTRIC NETWORKS BASED ON FREQUENCY FILTERS

**Purpose.** Development of selective microprocessing earth fault protection in compensated electrical networks of 6–35 kV. Use of the Goertzel algorithm for the separation of components of frequencies higher than fundamental frequency from the zero sequence voltage and currents. For the first time for ground-fault protection in 6–35 kV compensated networks, it is proposed to separate components of frequencies higher than fundamental frequency from the zero sequence voltage and currents using frequency filters created on the basis of the Goertzel algorithm are proposed; the algorithm is an improved modification of the Fourier transform; this method makes it possible to detect earth faults in compensated electric networks of 6–35 kV at phase-to-ground fault the reactive power direction in a in a damaged feeder can be similar to the one in an undamaged feeder; therefore, conventional protections cannot perform selective operation. This action can be provided by protections based on separation of components of fixed frequencies of 200–300 Hz from the zero sequence voltage and currents. Their reactive power in an undamaged connection is always directed off byes, because is hardly compensated by the reactor regardless of degree of its cavity tuning. When applying band-pass frequency filters, the required protection responsibility is not always provided at phase-to-ground fault through resistances exceeding 10–15 Ohm. Moreover, failure of steady operation of filters is possible due to location of their poles on a circular curve of a unit radius, while use of blocks of numerical differentiation of current and voltage can result in running failure at alternate arcing ground. The application of the Goertzel algorithm for high-frequency components detection is proposed. It is implemented through an infinite impulse-response filter of the second order with two real coefficients in back coupling and one complex coefficient in circuit of direct relation. The results of simulation of the behavior of protection in the system of computer algebra Mathcad confirmed the reduction of calculation costs and stable work, regardless of the presence of aperiodic components at different initial phases of the voltage at the time of fault. As part of the protection, a trigger unit is provided that allows the operation if the voltage of the zero sequence exceeds the setpoint, which is 12–15 % of the nominal value. In order to ensure reliable operation of the protection, permanent and arcing faults provide activation of protection impulses in the event of a fault. The positive results of protection algorithm were achieved on the mathematical model of the network as well as when testing a microprocessor prototype of a protective system in a laboratory environment.

**Methodology.** The methods of mathematical modeling and analysis of transients in compensated electric networks of 6–35 kV, Fourier transform and Goertzel algorithm, construction of earth-fault protection algorithms, and experimental research are used.

**Findings.** The results of mathematical modeling show that in compensated electric networks of 6–35 kV at phase-to-ground fault the reactive power direction in a in a damaged feeder can be similar to the one in an undamaged feeder; therefore, conventional protections cannot perform selective operation. This action can be provided by protections based on separation of components of fixed frequencies of 200–300 Hz from the zero sequence voltage and currents. Their reactive power in an undamaged connection is always directed off byes, because is hardly compensated by the reactor regardless of degree of its cavity tuning. When applying band-pass frequency filters, the required protection responsibility is not always provided at phase-to-ground fault through resistances exceeding 10–15 Ohm. Moreover, failure of steady operation of filters is possible due to location of their poles on a circular curve of a unit radius, while use of blocks of numerical differentiation of current and voltage can result in running failure at alternate arcing ground. The application of the Goertzel algorithm for high-frequency components detection is proposed. It is implemented through an infinite impulse-response filter of the second order with two real coefficients in back coupling and one complex coefficient in circuit of direct relation. The results of simulation of the behavior of protection in the system of computer algebra Mathcad confirmed the reduction of calculation costs and stable work, regardless of the presence of aperiodic components at different initial phases of the voltage at the time of fault. As part of the protection, a trigger unit is provided that allows the operation if the voltage of the zero sequence exceeds the setpoint, which is 12–15 % of the nominal value. In order to ensure reliable operation of the protection, permanent and arcing faults provide activation of protection impulses in the event of a fault. The positive results of protection algorithm were achieved on the mathematical model of the network as well as when testing a microprocessor prototype of a protective system in a laboratory environment.

**Originality.** For the first time for ground-fault protection in 6–35 kV compensated networks, it is proposed to separate components of frequencies higher than fundamental frequency from the zero sequence voltage and currents using frequency filters created on the basis of the Goertzel algorithm are proposed; the algorithm is an improved modification of the Fourier transform; this increased the sensitivity, speed and stability of work protection.

**Practical value.** The mathematical model of the compensated electric network allows analyzing the behavior of protection at permanent and arcing ground faults. Selective protection from phase faults on the ground has been developed, which allows increasing the reliability of the power supply systems with a voltage of 6–35 kV.

**Keywords:** compensated network, mathematical model, ground fault, selective protection, frequency filter, Fourier transform, Goertzel algorithm

**Introduction.** Electric networks with a voltage of 6–35 kV are the basis of power supply systems for industrial, mining and agricultural enterprises, cities, and own needs of power plants. Such networks are used to connect renewable energy sources. Networks with a voltage of 6–35 kV work with non-earthed neutral. To reduce the current of a single-phase earth fault in such networks, a Petersen coil is used. The Petersen coil significantly reduces the current of a single-phase earth fault, and also significantly changes the nature of the transient process after breaking a single-phase circuit (for example, after the extinction of an electric arc), which reduces the level of overvoltage. A side issue with the use of the Petersen coil is the deterioration of the working conditions of single-phase earth fault protection. Such protection systems generally react to zero sequence voltage of the network and zero sequence current in a certain feeder of the power supply system. Thus, the problem of constructing reliable selective earth fault protection is relevant and is being actively studied in a professional environment [1, 2].

**Literature review.** The number of publications related to earth faults in compensated networks is large and steadily increasing. The scientific community responds to this by trying to systematize and classify various approaches and methods for solving the problem of earth fault protection [1–3]. A wide range of techniques is used to identify a damaged feeder. There were attempts to solve the problem of earth fault protection by refusing to use the Petersen coil and grounding the neutral of the network through a resistor. Investigations into faulty-phase-earthing are ongoing [4]. Work is underway to create electric arc models and to simulate single-phase earth faults using various software products [5]. It was proposed to use a wide range of digital signal processing methods, as well as a genetic algorithm, methods of fuzzy logic, neural networks, deep learning, gray systems, mixed atom libraries, and various combinations of them [6].

In our opinion, the classical protection algorithms, for example, a power direction relay or an admittance-based relay to earth fault protection have room for further improvement. However, for the proper operation of such protections, certain conditions are required. Illustrative in this regard, for example, is a paper [7] in which a multi-frequency admittance-based relay is considered. The idea of analyzing currents and voltages not only at the industrial frequency (50 Hz) deserves special attention.

Recently, a number of works on creating selective compensations for compensated networks [7, 8], based on selecting their components of a fixed frequency, several times higher than the fundamental frequency from the currents and voltages of zero sequence have appeared. It was shown in [9] that such a frequency can be taken from the range of 150–350 Hz, since the Petersen coil has large impedance and hardly affects the distribution of capacitive currents in the network at such
frequencies. In [8, 9], for directional earth fault protection, components of the frequency of 220 Hz are extracted from currents and voltages of the zero sequence using narrow-band frequency filters, and then the direction of the reactive power is determined from them and the damaged connection is detected. Despite the shortcomings in [9] regarding the choice of the band-pass filter parameters and the construction of protection algorithms, this approach turned out to be very promising. In [10], it was proposed to improve such protection by using filters with improved characteristics and differentia.

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Fig. 1. Schematic diagram of a compensated electrical network 6 kV

| Lr, Hn | f, Hz | If, A | Isp1, A | Isp2, A | Ir, A | Qff, kVA | Qsf1, kVA | Qsf2, kVA | Qr, kVA |
|-------|------|------|---------|---------|-------|--------|----------|----------|--------|
| 0.5Lres | 50 | –88.25 | –27.15 | –40.81 | 156.2 | –317.5 | –97.71 | –146.8 | 562.1 |
| 0.8Lres | 50 | –30 | –27.4 | –41.2 | 98.6 | –109.1 | –99.5 | –149.1 | 357.7 |
| Lres | 50 | –10.35 | –27.48 | –41.31 | 79.14 | –37.7 | –100.1 | –150.5 | 289.1 |
| 1.5Lres | 50 | 16.08 | –27.6 | –41.49 | 53.01 | 58.8 | –100.9 | –151.7 | 193.8 |
| Lres | 100 | 103.2 | –57.46 | –86.96 | 41.22 | 391.7 | –218.2 | –330.2 | 156.7 |
| Lres | 200 | 333.5 | –140.3 | –218.2 | 25.00 | 1530 | –643.4 | –1001 | 114.4 |
| 0.5Lres | 250 | 487.0 | –206.2 | –327.1 | 46.30 | 2610 | –1104 | –1756 | 250.0 |
| Lres | 250 | 519.6 | –209.8 | –333.4 | 23.60 | 2833 | –1144 | –1818 | 129.9 |
| 1.5Lres | 250 | 530 | –211.1 | –335.1 | 16.20 | 2910 | –1157 | –1840 | 87.00 |
| Lres | 300 | 873.7 | –324.4 | –558.9 | 9.60 | 6618 | –2580 | –4230 | 192.0 |

The results of calculations of currents and reactive power in feeders
time, according to the calculated data, selective protection of the damaged connection can be performed using, for example, frequency filters by extracting signals with a fixed frequency selected from the range of 150–300 Hz. The boundary value of 150 Hz is due to the exclusion of the influence of the reactor, and the value of 300 Hz is the simplification of the hardware implementation of the protection. In this case, according to the Shannon theorem, the sampling frequency of the measurement of the input signals should be no less than two times the frequency of the filters, i.e. be more than 600–1000 Hz. When performing the above calculations, the sampling frequency was assumed 1600–2500 Hz, and the step T of a resolution of 0.400–0.625 ms.

The block diagram of the protection algorithm proposed in this work is shown in Fig. 2. It consists of analog-to-digital converters (ADCs) of currents and voltages supplied from current transformers and zero sequence voltage.

The instantaneous discrete values of currents and voltages from the outputs of the ADC are fed to the inputs of Goertzel Discrete Transformation Units (GDTU), which are second-order IIR filters performed by the Goertzel algorithm and used to obtain complex values of the components of currents $i_h + j_q$ and voltages $u_h + j_q$ with a selected frequency of, for example, 250 Hz. Then, using the multiplication unit (X), the components of the reactive power $q_1 = i_h \cdot u_h$ and $q_2 = i_q \cdot u_q$ are calculated which then, after the adder, are fed to the threshold detector, where the resulting power $Q = q_1 - q_2 = i_h \cdot u_h - i_q \cdot u_q$ is compared with the given setpoint $Q_t$. When the power $Q$ exceeds the setting, the decision relay is activated.

In the proposed protection algorithm, as follows from Fig. 2, to calculate the direction of the reactive power during the earth fault, the orthogonal components of the current and voltage of 200–300 Hz are required, which must be extracted from the voltages and currents of the zero sequence. Consider the structural diagram of the implementation of the Goertzel algorithm according to (3, 4) is shown in Fig. 3.

The scheme contains the recursive part of the calculations (its left part), in which the calculations are performed by the iteration method. Calculations with complex values are performed only once at the last iteration, due to which the estimated costs are almost halved compared to the DFT, which was confirmed by the calculations using the DFT and Goertzel algorithms shown in Fig. 4 implemented in the MathCad environment.

To evaluate the efficiency of the DFT and Goertzel algorithms using the indicated routines, Figs. 5, a, b show the results of calculations of the fifth and first harmonic in the input voltage containing harmonics 1, 5, and 33.

After multiplying the numerator and denominator of function (2) by $(1-W_N^k \cdot z^{-1})$ and the corresponding transformations, we obtain the transfer function of the Goertzel algorithm (3) and formulas (4‒6) for calculating the spectral count $S(k)$ using intermediate real values of the auxiliary array iteratively calculated at each step $V(r) = r, 1, 2, ..., N$

$$H(z) = \frac{Y(z)}{X(z)} = \frac{W_N^{-k}}{1 - W_N^{-k} \cdot z^{-1}}. \quad (2)$$

$$G(z) = \frac{Y(z)}{X(z)} = \frac{W_N^{-k} - z^{-1}}{1 - 2 \cos \left(\frac{2\pi k}{N}\right) \cdot z^{-1} + z^{-2}}; \quad (3)$$

$$S(k) = W_N^{-k} \cdot V(N-1) - V(N-2); \quad (4)$$

$$V(r) = s(r) + 2 \cos \left(\frac{2\pi k}{N}\right) \cdot V(r-1) - V(r-2); \quad (5)$$

$$W_N^{-k} = \exp \left(\frac{2\pi k}{N}\right); \quad \alpha = 2 \cdot \cos \left(\frac{2\pi k}{N}\right).$$

The structural diagram of the implementation of the Goertzel algorithm according to (3, 4) is shown in Fig. 3.

As follows from Figs. 5, a, b, the distinguished harmonics are sinusoidal in spite of the considerable noisiness of the initial voltage. At the same time, the results of calculations for both subprograms practically coincide, which makes it possible to use the Goertzel algorithm as a faster one for earth fault protection.

Simulation of the earth fault in a compensated network (Fig. 1), together with the protection according to the algorithm shown in Fig. 2, was carried out at varying degrees of compensation of capacitive currents by the reactor and at various resistances at the point of earth fault. The number of discrete signals in the current and voltage arrays was taken equal, the calculation step was 0.625 ms, the allocated frequency of the signals to determine the reactive power of 250 Hz. In all cases, a reactive power pulse with duration of about 20 ms was clearly visible in the initial section of the earth fault, after which it was picked up, subject to the presence of a voltage of 3U0, and the output relay was triggered.

As example in Figs. 6, a, b and Fig. 7 the results of modeling an arc fault are shown, in which triple ignition and arc extinction occurred, and the ignition occurred at different initial
The shape of currents and voltages at a frequency of 250 Hz and relay pulses are shown in Fig. 7. The laboratory protection sample was implemented based on STM32F4Discovery microcontroller. Its satisfactory performance was achieved on a physical network model with a voltage of 0.4 kV.

In addition, verification of the operation of the protection was carried out by supplying a zero-sequence current and voltage signals recorded in a real network by digital recorders to the protection input. The results of modeling and experiments are the basis for the possibility of introducing the developed protection in electric networks with compensated neutral.

Conclusions.
1. The results of mathematical modeling showed the possibility of performing selective earth faults protection for compensated networks based on monitoring the direction of reactive power, determined by currents and voltages of a frequency of 150–300 Hz, extracted using frequency filters from voltages and currents of zero sequence of industrial frequency. At these frequencies, the reactor inductance practically does not compensate for capacitive currents of this frequency in the damaged connection, which makes it possible to use the direction of reactive power for protection.

2. For the first time, in order to protect against phase-to-ground faults in compensated networks with a voltage of 6–35 kV, it was proposed to isolate frequency components higher than the industrial frequency from zero-sequence voltages and currents using the Goertzel algorithm, which is a modification of the Fourier transform, which made it possible to increase the sensitivity and speed of protection and its work stability.

Fig. 4. Software modules in the MathCad environment for the implementation of the Goertzel algorithm and Fourier transform

Fig. 5. Results of selection of the 5th (a) and 1st (b) harmonics by DFT and Goertzel algorithm filters

Fig. 6. The simulation results of the arc earth faults: a – input voltage 3U0 and currents 3I0 of a frequency of 50 Hz and 250 Hz; b – output pulses of reactive power and contacts relay

Fig. 7. The simulation results of the output protection pulse in an arc earth fault (U, I – voltage and currents of a frequency of 250 Hz; q1 is one of the components of reactive power)

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The effectiveness of the developed protection is confirmed by the results of mathematical modeling, laboratory tests of a full-scale sample and the correctness of the action when using signals recorded using digital recorders with earth faults in real networks. The article is prepared based on the results of taxpayer-funded research and development project “Development of microprocessing selective earth faults protection from in conventional electric power systems and Smart-Grid systems”.

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Практична значимість. Математична модель компенсованої електричної мережі дозволяє аналізувати поведінку захисту при глухих і дугових замиканнях на землю. Розроблений селективний захист від замикань на землю дозволяє підвищити надійність роботи систем електропостачання 6–35 кВ.

Ключові слова: компенсована мережа, математична модель, замикання на землю, селективний захист, частотний фільтр, перетворення Фур'є, алгоритм Гертцеля

Защита от замыканий на землю в компенсированных электрических сетях на основе частотных фильтров

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Цель. Разработка селективной микропроцессорной защиты от замыканий фазы на землю в компенсированных электрических сетях 6–35 кВ. Использование алгоритма Гертцеля для выделения из напряжений и токов нулевой последовательности составляющих более высокой частоты, чем промышленная.

Методика. Используются методы математического моделирования и анализа переходных процессов в компенсированных электрических сетях 6–35 кВ, преобразование Фурье и алгоритм Гертцеля, построение алгоритмов защиты от замыканий на землю, экспериментальные исследования.

Результаты. Результаты математического моделирования показывают, что в компенсированных сетях напряжением 6–35 кВ при замыканиях фазы на землю направление реактивной мощности в поврежденном при соединении может быть таким же, как и в неповрежденном, в связи с чем конвенциональные защиты не могут обеспечивать селективного действия. Такое действие могут обеспечить защиты, основанные на выделении из напряжений и токов нулевой последовательности их составляющих с фиксированной частотой, взятой из диапазона 200–300 Гц. Реактивная мощность для них в поврежденном при соединении всегда направлена от шин, т.к. практически не компенсируется реактором независимо от степени его резонансной настройки. При применении полосовых частотных фильтров требуемая чувствительность защиты не всегда обеспечивается при замыкании фазы на землю через сопротивления, превышающие 10–15 Ом. Кроме того, возможно нарушение устойчивой работы фильтров из-за расположения их полюсов на окружности с единичным радиусом, а применение блоков численного дифференцирования токов и напряжений может привести к сбоям в работе при переключающихся дуговых замыканиях на землю. Предложено применение алгоритма Гертцеля для выделения составляющих повышенной частоты. Он реализован в форме фильтра с бесконечной импульсной характеристикой второго порядка с двумя действительными коэффициентами в обратной связи и одним комплексным коэффициентом в цепи прямой связи. Результаты моделирования поведения защиты в системе компьютерной алгебры Mathcad подтвердили сокращение расчетных затрат и её стабильную работу независимо от наличия апериодических составляющих в токе при разных начальных фазах напряжения в момент замыкания. Защита предусматривает пусковой орган, разрешающий работу защиты, если напряжение нулевой последовательности превышает заданную уставку, равную 12–15 % от номинального. Для обеспечения надежной работы защиты, как при устойчивых, так и при дуговых замыканиях, предусмотрен автоматический подхват импульса срабатывания защиты при появлении замыкания. Получены положительные результаты работы алгоритма защиты на математической модели сети, а также на лабораторной установке образца, реализованного на микропроцессорной основе.

Научная новизна. Впервые для защиты от замыкания фазы на землю в компенсированных сетях напряжением 6–35 кВ предложено выделять из напряжений и токов нулевой последовательности составляющие частоты выше промышленной с помощью частотных фильтров, основанных на алгоритме Гертцеля, являющегося усовершенствованным преобразованием Фурье, что позволило повысить чувствительность, быстродействие защиты и стабильность её работы.

Практическая значимость. Математическая модель компенсированной электрической сети позволяет анализировать поведение защиты при глухих и дуговых замыканиях на землю. Разработанная селективная защита от замыканий на землю позволяет повысить надежность работы систем электроснабжения 6–35 кВ.

Ключевые слова: компенсированная сеть, математическая модель, замыкание на землю, селективная защита, частотный фильтр, преобразование Фурье, алгоритм Гертцеля

Recommended for publication by O. P. Chornyi, Doctor of Technical Sciences. The manuscript was submitted 29.03.19.