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DEVELOPMENT OF SIX-PHASE SYMMETRICAL COMPONENTS FILTERS FOR SELF-COMPENSATING POWER LINES

Natalya Turturica, ORCID: 0000-0003-3013-9508

Institute of Power Engineering, Chisinau, 5 Academiei str., Republic of Moldova
*Corresponding author: Natalya Turturica, *departpe@gmail.com*

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Abstract. The paper deals with elaboration of hexaphase symmetrical components filters and their modeling to create microprocessor-assisted relay protection of self-compensating power lines. The theory is presented and the basic principial electrical schemes and mathematical models in the Matlab/Simulink of the filters of the hexaphase symmetric components are elaborated. The results of their simulation and testing at the computer are presented. The obtained results demonstrate the possibility of creating in the base on the elaborated filters of hexaphase symmetrical components the modern, efficient and high-sensitivity microprocessor-assisted relay protection of self-compensating power lines. What reacted not to phase electrical values, but symmetrical components of them.

Keywords: *modeling of current filter, power transmission line, relay protection, transfer capacity of the line.*

Rezumat. Lucrarea este dedicată elaborării filtrelor cu componente simetrice hexafazate și modelarea acestora pentru crearea protecției prin relee asistată de microprocesor a liniilor electrice cu autocompensare. Este prezentată teoria și sunt elaborate schemele electrice principiale și modelele matematice în Matlab/Simulink a filtrelor cu componente simetrice hexafazate. Sunt prezentate rezultatele simulării și testării lor la calculator. Rezultatele obținute demonstrează posibilitatea creării în baza filtrelor cu componente simetrice hexafazate a unei protecții eficiente, bazată pe microprocesor de înaltă sensibilitate, care reacționează la diferite deteriorări ale liniilor electrice cu autocompensare nu la mărimi electrice de fază, ci la componentele simetrice.

Cuvinte cheie: *modelare filtru de curent, linie electrică de transport, protecție prin relee, capacitatea de transport a liniei.*

Introduction

From the viewpoint of maximum saving the consumers' electric power supply, fault tolerance of the self-compensating power lines (SCL) [1], increasing the efficiency and sensitivity of a relay protection [2] and selective switching off of a certain faulted phase or several phase circuits, depending on the short-circuit type or a phase break [3], it is necessary to create a relay protection (RP) [4, 5] responsive to the appearance of certain six-phase symmetrical components [6]. Considering the SCL as a six-phase line, the creation of the relay protection responsive to the six-phase symmetrical components simplifies the identification of the short-circuit and phase break types, as well as the protection detuning and enhances its sensitivity, since the occurrence of certain six-phase symmetrical components comply with some sorts of faults.

For the development of the RP and the SCL automatics responsive to the occurrence of various six-phase symmetrical components in fault conditions (of short-circuits and phase breaks), the filters of the symmetrical components [7] of the six-phase expansion [8, 9] are necessary.

For the modern numerical and microprocessor protections the most expedient is mathematic ‘emphasizing’ of the data on symmetrical components at various nonsymmetrical short-circuits, including complex types of failures, for which the combined filter of six-phase symmetrical components of currents and voltages 0, 1, 2, 3, 4, 5 of consequences at computer using complexes Matlab-Simulink environment has been modeled [10].

1. Theoretical bases for the development of the filters of six-phase symmetrical components

The phase currents, which are supplied to the current filter $\dot{I}_A, \dot{I}_{C'}, \dot{I}_B, \dot{I}_{A'}, \dot{I}_C, \dot{I}_{B'}$ of the SCL six-phase system, whose phase A symmetrical components will be designated, using $\dot{I}_0, \dot{I}_1, \dot{I}_2, \dot{I}_3, \dot{I}_4, \dot{I}_5$. The elements, which the filter consists of, are the linear function of Hence, the current at the filter output is

$$\dot{I}_p = \dot{n}_A \cdot \dot{I}_A + \dot{n}_{C'} \cdot \dot{I}_{C'} + \dot{n}_B \cdot \dot{I}_B + \dot{n}_{A'} \cdot \dot{I}_{A'} + \dot{n}_C \cdot \dot{I}_C + \dot{n}_{B'} \cdot \dot{I}_{B'} \tag{1}$$

where the coefficients $\dot{n}_A, \dot{n}_{C'}, \dot{n}_B, \dot{n}_{A'}, \dot{n}_C, \dot{n}_{B'}$ are complex or real values, which characterize the magnitude and phase changes of the currents, supplied to the filter.

The substitution of full currents for their symmetrical components can be described using the following formula:

$$\dot{I}_p = \dot{k}_0\dot{I}_0 + \dot{k}_1\dot{I}_1 + \dot{k}_2\dot{I}_2 + \dot{k}_3\dot{I}_3 + \dot{k}_4\dot{I}_4 + \dot{k}_5\dot{I}_5 \tag{2}$$

where the coefficients of the filter are presented as complex or real values in accordance with the matrix of transition from the phase coordinates to the symmetrical components in the matrix form:

$$\begin{vmatrix} \dot{k}_0 \\ \dot{k}_1 \\ \dot{k}_2 \\ \dot{k}_3 \\ \dot{k}_4 \\ \dot{k}_5 \end{vmatrix} = \begin{vmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & e^{j300} & e^{j240} & e^{j180} & e^{j120} & e^{j60} \\ 1 & e^{j240} & e^{j120} & 1 & e^{j240} & e^{j120} \\ 1 & e^{j180} & 1 & e^{j180} & 1 & e^{j180} \\ 1 & e^{j120} & e^{j240} & 1 & e^{j120} & e^{j240} \\ 1 & e^{j60} & e^{j120} & e^{j180} & e^{j240} & e^{j300} \end{vmatrix} \cdot \begin{vmatrix} \dot{n}_A \\ \dot{n}_{C'} \\ \dot{n}_B \\ \dot{n}_{A'} \\ \dot{n}_C \\ \dot{n}_{B'} \end{vmatrix} \tag{3}$$

Using the inverse transformation of matrix Eq. (3), we can obtain the expression for coefficients *n* via coefficients *k*:

$$\begin{vmatrix} \dot{n}_A \\ \dot{n}_{C'} \\ \dot{n}_B \\ \dot{n}_{A'} \\ \dot{n}_C \\ \dot{n}_{B'} \end{vmatrix} = \frac{1}{6} \begin{vmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & e^{j60} & e^{j120} & e^{j180} & e^{j240} & e^{j300} \\ 1 & e^{j120} & e^{j240} & 1 & e^{j120} & e^{j240} \\ 1 & e^{j180} & 1 & e^{j180} & 1 & e^{j180} \\ 1 & e^{j240} & e^{j120} & 1 & e^{j240} & e^{j120} \\ 1 & e^{j300} & e^{j240} & e^{j180} & e^{j120} & e^{j60} \end{vmatrix} \cdot \begin{vmatrix} \dot{k}_0 \\ \dot{k}_1 \\ \dot{k}_2 \\ \dot{k}_3 \\ \dot{k}_4 \\ \dot{k}_5 \end{vmatrix} \quad (4)$$

Based on Eq (3). and Eq. (4), Table 1 was built up of arguments of complex coefficients of $\dot{n}_A, \dot{n}_{C'}, \dot{n}_B, \dot{n}_{A'}, \dot{n}_C, \dot{n}_{B'}, \dot{n}_{AB}, \dot{n}_{BC}, \dot{n}_{A'B'}, \dot{n}_{B'C'}$ depending on the argument of complex coefficient of filter *k*.

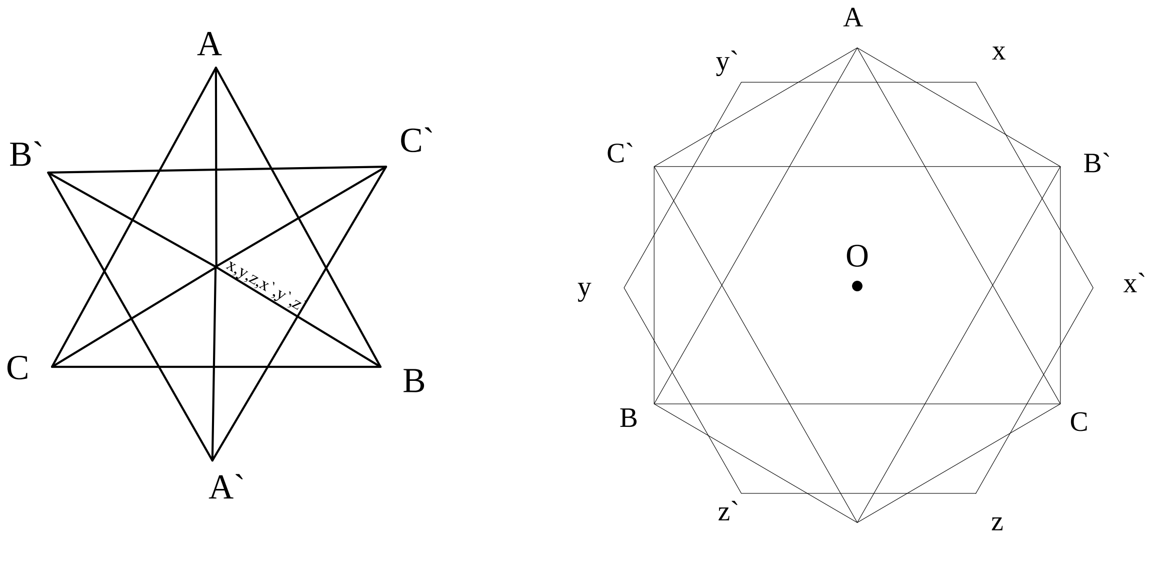
Table 1

Complex coefficients' arguments

k	$\dot{n}_A$	$\dot{n}_{C'}$	$\dot{n}_B$	$\dot{n}_{A'}$	$\dot{n}_C$	$\dot{n}_{B'}$	$\dot{n}_{AB}$	$\dot{n}_{BC}$	$\dot{n}_{A'B'}$	$\dot{n}_{B'C'}$
0°	0°	120°	-120°	0°	120°	-120°	0°	-60°	0°	-60°
30°	30°	150°	-90°	30°	150°	-90°	30°	-30°	30°	-30°
60°	60°	180°	-60°	60°	180°	-60°	60°	0°	60°	0°
90°	90°	-150°	-30°	90°	-150°	-30°	90°	30°	90°	30°
120°	120°	-120°	0°	120°	-120°	0°	120°	60°	120°	60°

For realization the filters of symmetrical components, according to Table 1, it is necessary to sum up the currents or voltages, which are in definite ratios with the electric values supplied to the filter. The phase shift in currents or voltages can be performed using different methods by a relevant choice of the circuits' elements of the filter: active, inductive, capacitive, mixed type and those inductively connected.

The potential diagrams of the six-phase filter are obtained (Figure 1). Upon feeding to the filter the 5-th sequence of voltages (currents), the 1-st sequence voltage (current) equals to 0 at the filter output.



a) b)

Figure 1. Potential diagrams of six-phase filter of voltages: a) for the supplied voltage of direct sequence; b) for the supplied voltage of the 5-th sequence.

Relatively, potentials of points *x, y, z* and *x', y', z'* coincide. On the potential diagram (Figure 1a), points *x, y, z, x', y', z'* are in the center of the potential polyhedron A, C', B, A', C, B'. Whereas upon the supply of the 5-th sequence voltage to the filter, points B` and C`, B and C of the hexagon change their places, and side AA' occupies the position of AC' side, and together with the latter, triangle AA'x potential shifts. If we treat similarly the remaining sides of the hexagon, the potential diagram will look like as in Figure 1.

Six-phase filters, which were created according to the above principle, can serve as a source of symmetrical voltages (currents) at any kind of nonsymmetrical SCL short-circuits, provided that the load resistances are symmetrical and exceed significantly the internal resistance of the filter itself.

2. Modeling the combined filter of six-phase symmetrical components of currents (voltages) in the Mutlab-Simulink environment

For realization the above filters using computer and Matlab-Simulink environment, the equations' solution was performed, which described the obtaining of phase currents (voltages) via the symmetrical components and vice versa, by means of the use of the library SimPowerSystem of the Matlab-Simulink package. Figure 2 shows the simulation model of filter of six symmetrical components, which was realized in the Matlab-Simulink package.

To realize the filter model methods in the library Math Operation the following blocks with their functional capabilities were used:

- block Constant – forms the constant value: a system operator of $a = e^{j120^\circ}$ and $-a = e^{-j60^\circ}$;
- block Math – performs mathematical functions: raises to the square operator a and $-a$;
- block Product – derives the result of multiplication of two input data, according to the matrix expression:

$$\begin{vmatrix} \dot{F}_{A0} \\ \dot{F}_{A1} \\ \dot{F}_{A2} \\ \dot{F}_{A3} \\ \dot{F}_{A4} \\ \dot{F}_{A5} \end{vmatrix} = \frac{1}{6} \begin{vmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & e^{j60^\circ} & e^{j120^\circ} & e^{j180^\circ} & e^{j240^\circ} & e^{j300^\circ} \\ 1 & e^{j120^\circ} & e^{j240^\circ} & 1 & e^{j120^\circ} & e^{j240^\circ} \\ 1 & e^{j180^\circ} & 1 & e^{j180^\circ} & 1 & e^{j180^\circ} \\ 1 & e^{j240^\circ} & e^{j120^\circ} & 1 & e^{j240^\circ} & e^{j120^\circ} \\ 1 & e^{j300^\circ} & e^{j240^\circ} & e^{j180^\circ} & e^{j120^\circ} & e^{j60^\circ} \end{vmatrix} \begin{vmatrix} \dot{F}_{A} \\ \dot{F}_{A'} \\ \dot{F}_{B} \\ \dot{F}_{B'} \\ \dot{F}_{C} \\ \dot{F}_{C'} \end{vmatrix} \quad (5)$$

- block Sum – summarizes the phase components at the inputs;
- block Gain – multiplies the input signal by the constant value.

Subsystems 1, 2, 3, 4 and 5 are responsible for the processing of the measuring information terms of the matrix Eq. (5). Subsystems, which realize emphasizing the relevant sequences, are presented in Figure 3.

The modules, which are presented in Matlab/Simulink (Figure 3), based on the preset values $\dot{F}_A, \dot{F}_{A'}, \dot{F}_B, \dot{F}_{B'}, \dot{F}_C, \dot{F}_{C'}$, allow emphasizing symmetrical components $\dot{F}_0, \dot{F}_1, \dot{F}_2, \dot{F}_3, \dot{F}_4, \dot{F}_5$ of sequences in accordance with Eq. (5). The Matlab-model of the filter can be used to obtain the SCL symmetrical components, which can further be used by certain organs of the microprocessor relay protection as the input data at various short-circuits and nonsymmetrical modes.

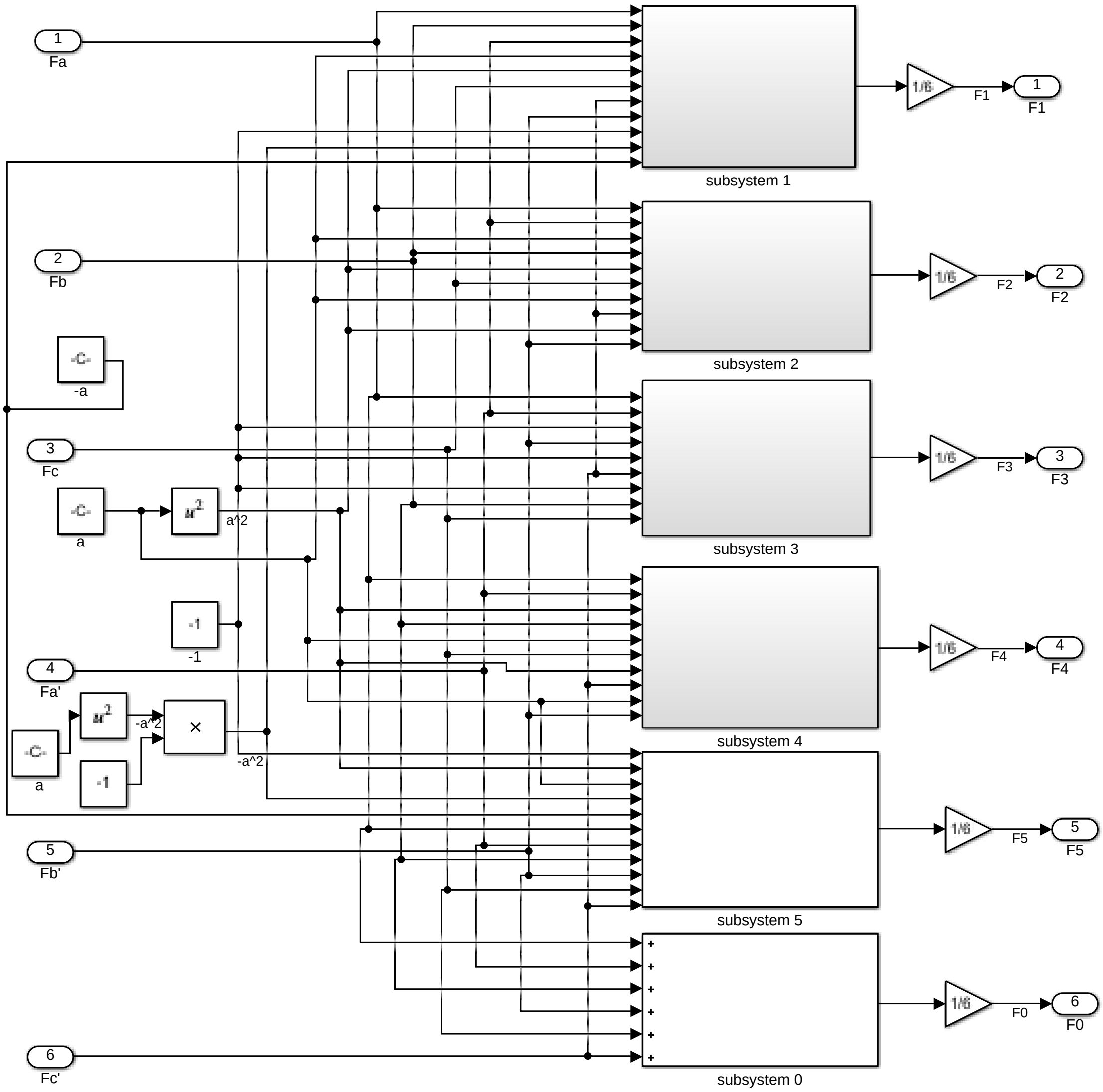
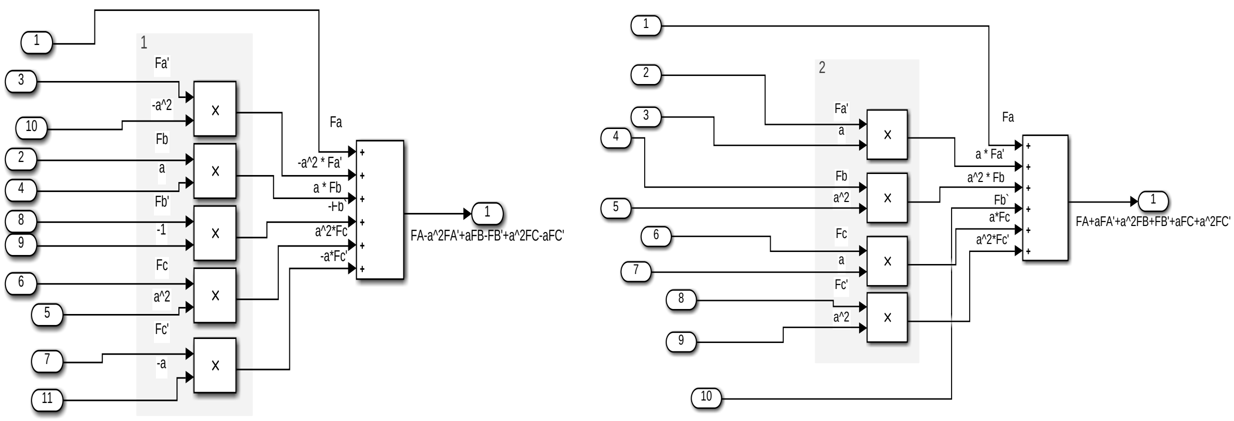


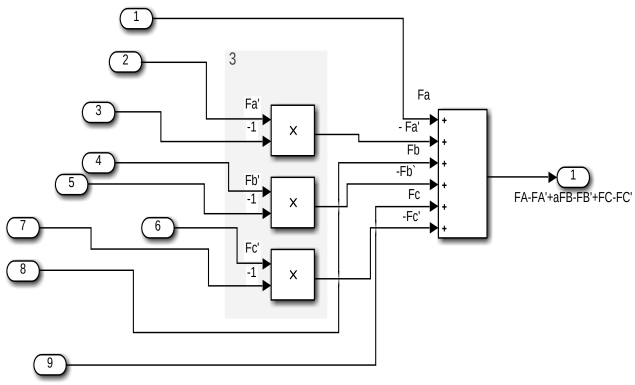
Figure 2. Simulation model of filter of six symmetrical components realized in Matlab-Simulink environment.

3. Results of modelling

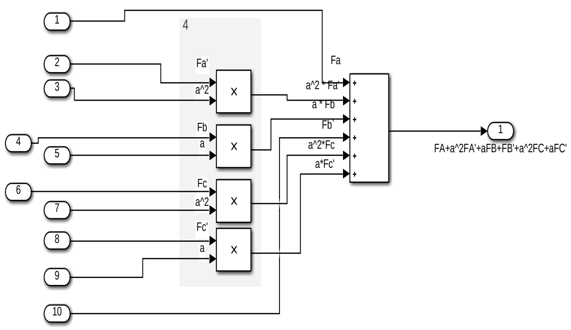
For testing the developed model (Figure 2), the complex model was composed of the six-phase transmission line (SCL) with a two-way feed and a filter with six-symmetrical components of currents (voltages). Figure 4 is a short-circuit of phase A.



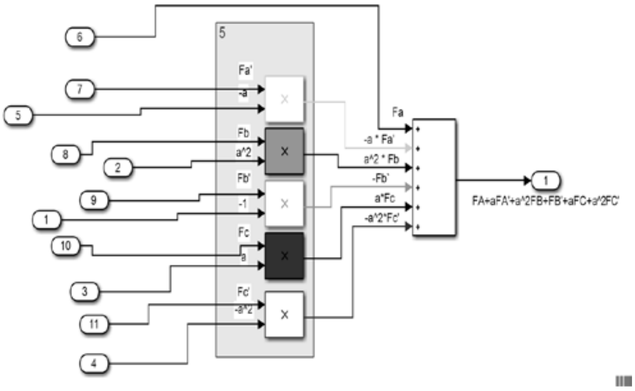
a) b)



c)



d)



e)

Figure 3. Subsystems of components: a) subsystem of the 1-st sequence; b) subsystem of the 2-nd sequence; c) subsystem of the 3-rd sequence; d) subsystem of the 4-th sequence; e) subsystem of the 5-th sequence.

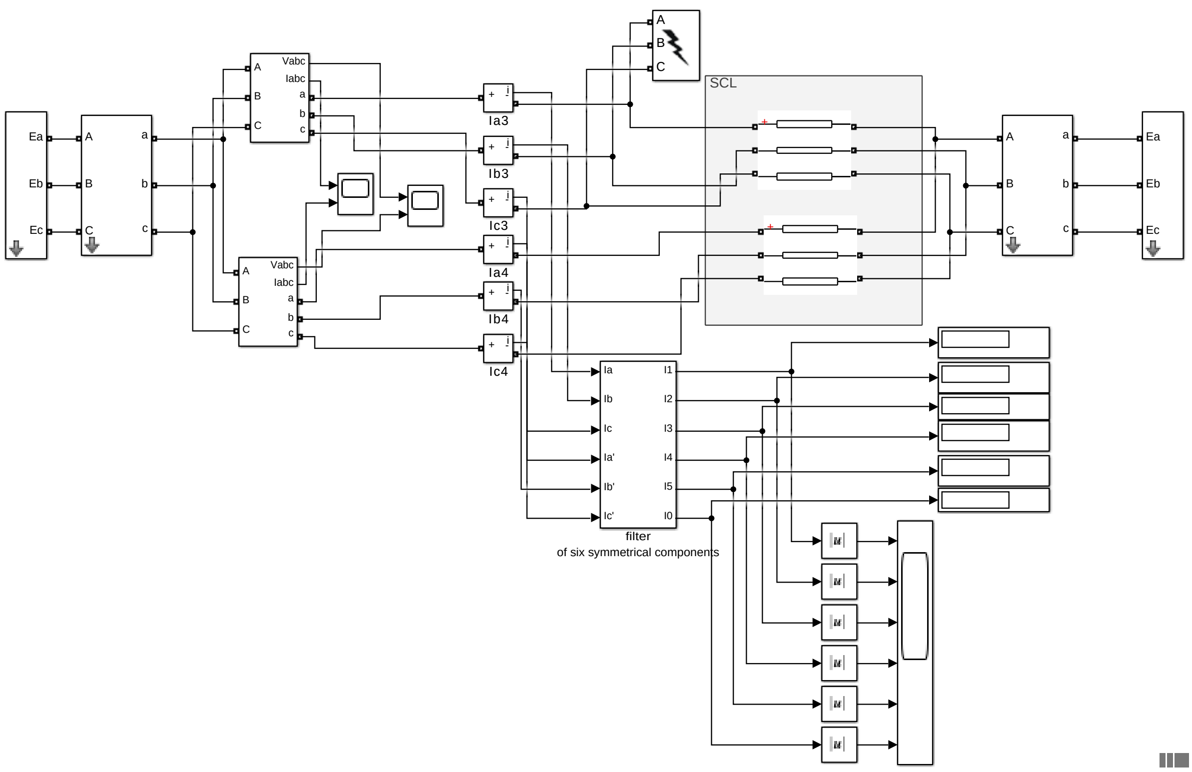


Figure 4. Model for testing the filter of symmetrical components at phase A short-circuit.

Figures 5, 6 show oscillograms of phase and current symmetrical components at phase A short-circuit. The initial time interval of oscillograms (up to 0.3 s) corresponds to a normal mode; finite interval is the occurrence of emergency condition.

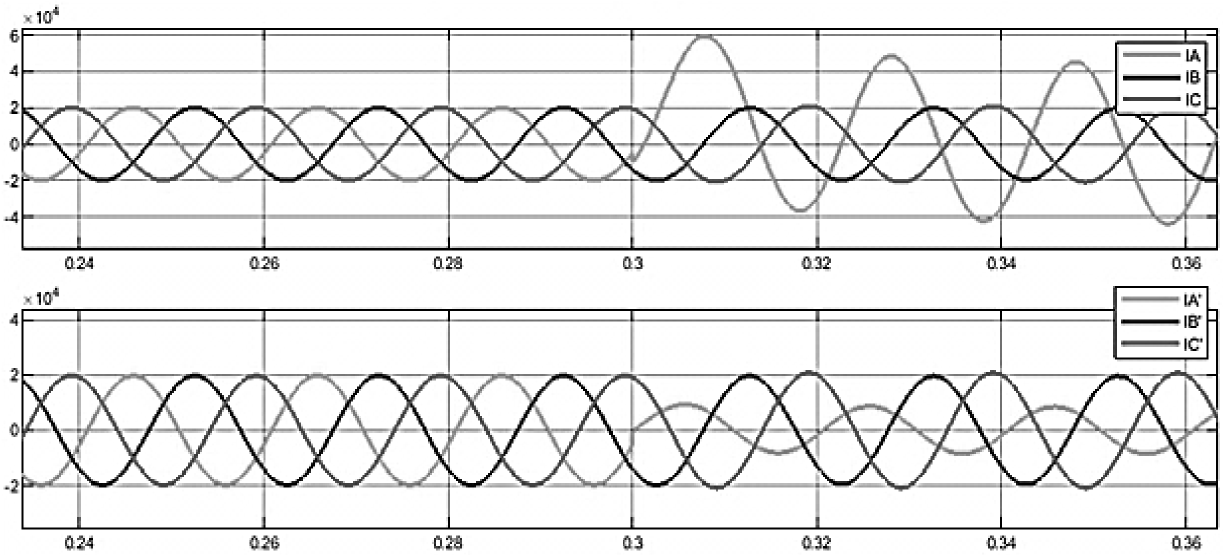


Figure 5. Oscillograms of phase currents at phase A short-circuit.

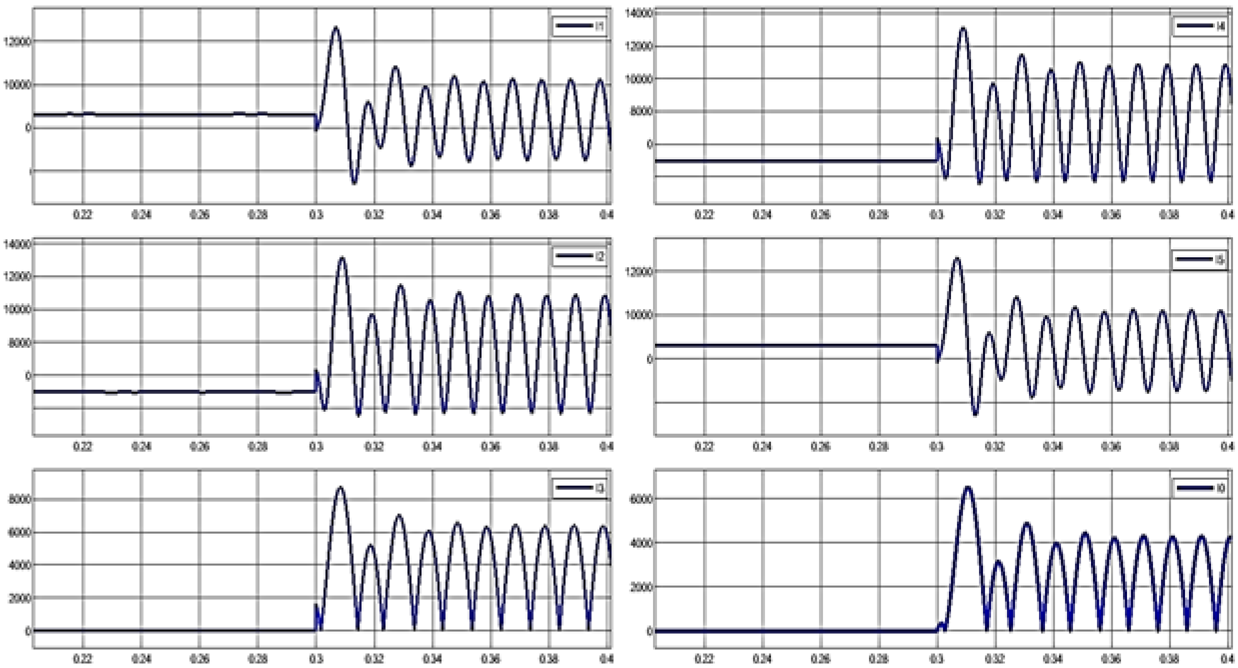


Figure 6. Oscillograms of current symmetrical components at phase A short-circuit.

At a normal mode of current 0, 1, 2, 3, 4 and 5, the sequences at the current filter output equal to zero (Figure 6, time interval from 0 to 0.3 s). Upon phase A short-circuit at a time moment of 0.3 s, current 0, 1, 2, 3, 4, 5 of sequences appears at the filter output.

4. Conclusions

Based on the study results, the following conclusions can be drawn:

1. The theoretical bases and generalized method for creation filters of six symmetrical components for the six-phase transmission line of type SCL are considered.

2. This method makes it possible to calculate the electric values of not only simple, but of complex kinds of faults as well in order to create the efficient relay protection of the required sensitivity, which responses not to the phase values, but to their symmetrical components.
3. The mathematic model is obtained through the program realization of six symmetrical components filters, using the computer and Matlab-Simulink environment, which can be used for creation of the SCL microprocessor relay protection.
4. The results of this work can be used to perform theoretic and experimental studies as well as for the development of the relay protection devices on SCL and ordinary double-circuit transmission lines.

References

1. Postolatij V.M. *Teoreticheskie osnovy i principy sozdaniya upravlyaemyh samokompensiruyushchihsya linij elektroperedachi*. Dissertaciya na soiskanie uchenoj stepeni doktora tekhnicheskih nauk. Chișinău (Kiev), 1987.
2. Waikar D. L., Liew A. C., and Elangovan S. Performance comparison of symmetrical component based fault impedance estimation methods for digital distance relay applications. In: *2nd International Conference on Advances in Power System Control, Operation and Management*, 1993, pp. 83-90.
3. Ciontea C. I., C. L. Bak, F. Blaabjerg, C. I. Ciontea, K. K. Madsen and C. H. Sterregaard. A feeder protection method against the phase-phase fault using symmetrical components. In: *Electric Ship Technologies Symposium (ESTS)*, 2017, pp. 56-63.
4. Kiorsak M.V., Fejgis SH.L. *Fil'try simmetrichnyh sostavlyayushchih shestifaznogo razlozheniya*. Sb. Rezhimy samo-kompensiruyushchihsya linij elektroperedachi. – Chișinău: Shtiinca, 1980.
5. Chiorsac M., Tertea Gh., Sidelnicov V., Turcuman L. Metoda componentelor simetrice în calculul circuitelor polifazate. In: *Conferinţa tehnico-ştiinţifică a colaboratorilor, doctoranzilor şi studenţilor UTM*, 19 noiembrie 2010, pp.427-430.
6. Kiorsak M., Turturica N. Methodology for Assessment the Possibility of Transfer Six-Phase Power Line into the Mode of Operation with Incomplete Number of Phases. In: *Problemele Energeticii Regionale* , 2020, pp.51-58
7. Kiorsak M.; Turturica N., Simulation of Filters of Six Symmetrical Components of Currents (Voltages) of Controlled Self-Compensating Power Lines. In: *2021 International Conference on Electromechanical and Energy Systems (SIELMEN)*, 2021, pp. 371-375.
8. Kiorsak M., Turturica N. Methodology for Assessment the Possibility of Transfer Six-Phase Power Line into the Mode of Operation with Incomplete Number of Phases. In: *Problemele Energeticii Regionale*. 2020, nr. 1(45), pp. 51-58
9. Kiorsak M., Turcuman L., Turturica N. Natalia. Principiul de elaborare a protecţiei prin relee a liniilor electrice aeriene cu autocompensare la scurtcircuite nesimetrice dintre fazele apropiate. In: *Problemele Energeticii Regionale*. 2015, nr. 3(29), pp. 63-66
10. MathWorks is the leading developer of mathematical computing software for engineers and scientists. [online]. © 1994-2022 The MathWorks, Inc. [accesat 10.11.2021]. Disponibil: https://www.mathworks.com/.