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Simulation of protection against unbalanced high-voltage asynchronous drive of recycle compressor in fuel hydrotreating unit

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Abstract
In the oil and gas industry, continuous processes such as oil and gas refining play a great role and are sensitive to many external factors. Such processes require special procedures for stopping and restarting. In order to maintain a sustainable process, the entire system needs to be cleaned by removing of unreacted components. Rejected raw materials are often dumped into a flare leading to tangible environmental problems and significant economic disadvantages. Electrotechnical systems (ETS) play an important role in ensuring continuous technological processes in oil and gas industry. Electric motors are one of the key elements of ETS. The majority of the electrical machines used in industry today are Asynchronous motors (AM) – no less than 80 %. Ensuring their trouble-free operation is one of the key factors in the design, simulation, and analysis of asynchronous motor relay protection systems, including unbalanced conditions of their operation. These conditions can occur due to unbalanced AM connection circuits, supply voltage unbalance, or as any faults in a machine itself. Operating a motor under these conditions will result in shorter motor life, reduced power, wear and aging of the insulation. The study subject was an Asynchronous motor drive of a recycle compressor of a gasoline hydrotreating unit at the fuel hydrotreating integrated unit at the Astrakhan Gas Refining Plant (AGRP). The authors used Matlab simulations to study the facility and its protection systems/devices operation. The method of symmetrical components was selected as the main theoretical method. The authors developed a model of an asynchronous motor drive of a recycle compressor. This involved establishing a set of relay protections (RP) and developing the models of the following protections: sequence filter (symmetrical component filter) (SF), negative sequence (nps) O/C protection, and overload protection. It was demonstrated that the specified relay protection complex fully protects the motor from unbalanced operation conditions. The authors conducted a study of the protection complex operation under different supply voltage unbalances, with different motor loads. They formed a conclusion about the performance of the developed protection complex, and gave recommendations for its technical implementation in a business environment. The study findings can be used as a basis for the development and testing of relay protection components of the entire electrical system of the fuel hydrotreating unit at the Astrakhan Gas Refining Plant.

Keywords
asynchronous motor, unbalanced conditions of operation, unbalanced supply voltage, relay protection, structural simulation, sequence filter, negative sequence O/C protection, overload protection, Sepam1000+, Matlab, Simulink

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ЭНЕРГЕТИКА, АВТОМАТИЗАЦИЯ И ЭНЕРГОЭФФЕКТИВНОСТЬ

Научная статья

Моделирование защиты от несимметричных режимов работы высоковольтного асинхронного привода циркуляционного компрессора в установке гидроочистки топлив

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Аннотация
В нефтегазовой промышленности большую роль играют непрерывные технологические процессы, например, нефте- и газопереработка, которые чувствительны к многим внешним факторам. Такие процессы требуют реализации специальных процедур для остановки и повторного пуска. Для на-

ладки технологического процесса необходимы очистка всей системы от непрореагировавших компонентов и их удаление. Забракованное сырьё зачастую сбрасывается на факел, что влечет за собой ощутимые экологические проблемы и значительный экономический ущерб. Важную роль в обеспечении непрерывных технологических процессов в нефтегазовой промышленности играют электротехнические системы (ЭТС), одним из ключевых элементов которых являются электродвигатели. Большую часть, не менее 80 %, используемых сегодня в промышленности электрических машин, составляют асинхронные двигатели (АД). Безаварийная их работа является одной из ключевых задач, что обеспечивает актуальность проектирования, моделирования и анализа действия систем релейных защит асинхронного двигателя, включая несимметричные режимы их работы. Эти режимы могут возникнуть при несимметричных схемах включения АД, несимметрии питающего напряжения, а также в результате каких-либо неисправностей в самой машине. Работа двигателя в таких условиях приведет к сокращению срока его службы, снижению мощности, износу и старению изоляции. В качестве исследуемого объекта выбран асинхронный электропривод циркуляционного компрессора блока гидроочистки бензина в комбинированной установке гидроочистки топлив, расположенного на Астраханском газоперерабатывающем заводе (АГПЗ). Для исследования работы и его защит авторы использовали моделирование в программе Matlab. В качестве основного теоретического метода выбран метод симметричных составляющих. Авторы разработали модель асинхронного электропривода циркуляционного компрессора; сформировали комплекс релейных защит (РЗ) и разработали модели следующих защит: «фильтр симметричных составляющих» (ФСС), максимальная токовая защита обратной последовательности «МТЗ $I_{\text{max обр}}$», защита от перегрузки. Продемонстрировано, что указанный комплекс релейной защиты полностью защищает двигатель от несимметричных режимов работы. Авторами было проведено исследование работы комплекса защит при различных несимметриях питающего напряжения, при различной загрузке двигателя, сделан вывод о работоспособности разработанной защиты, а также даны рекомендации по его технической реализации на производстве. Выполненная работа может быть положена в основу разработки и тестирования релейной защиты элементов всей электротехнической системы установки гидроочистки топлив на Астраханском ГПЗ.

Ключевые слова
асинхронный двигатель, несимметричные режимы работы, несимметрия питающего напряжения, релейная защита, структурное моделирование, фильтр симметричных составляющих, максимальная токовая защита, защита от перегрузки, Sepam1000+, Matlab, Simulink

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Introduction. Statement of problem

In the oil and gas industry, continuous processes such as oil and gas refining play a great role and are sensitive to many external factors. Such processes require special procedures for stopping and restarting. In order to maintain a sustainable process, the entire system needs to be cleaned by removing unreacted components. The rejected raw materials are often dumped into a flare leading to tangible environmental problems and significant economic disadvantages. Electrotechnical systems (ETS) play an important role in ensuring continuous technological processes in oil and gas industry. Electric motors are one of the key elements of ETSs. The majority of the electrical machines used in industry today are Asynchronous motors (AM) – no less than 80 %. Ensuring their trouble-free operation is one of the key factors in the design, simulation, and analysis of asynchronous motor relay protection systems, including unbalanced conditions of their operation.

This paper discusses the design and simulation of a number of relay protections against unbalanced conditions of operation of an asynchronous motor [1]. The causes of such conditions can be both external, such as unbalance in the voltage supplied to the motor [2], and defects in the machine itself. If unbalance occurs due to imperfections in the rotor circuit of the motor, the torque is the sum of the torques of the positive-phase-sequence M_1 and negative-phase-sequence M_2:

$$M(s) = M_1 + M_2, \quad (1)$$

and this dependence curve will have a dip at torque creep $s \approx 0.5$. Since a negative-phase-sequence field is stationary with respect to the stator, it does not create currents in the stator. Therefore, the torque due to this field will be zero. If $0 \le s \le 0.5$. The magnetic field will rotate relative to the stator in the negative direction, and the torque M_2 will act on the rotor in the direction of rotation. If $0.5 \le s \le 1$, the field rotates relative to the stator in the positive direction, and the torque M_2 created by this field will act on the rotor against the direction of rotation. If there is significant resistance unbalance in the secondary circuit, the motor will not reach normal R.p.m. This effect is maximal when one rotor phase fails.

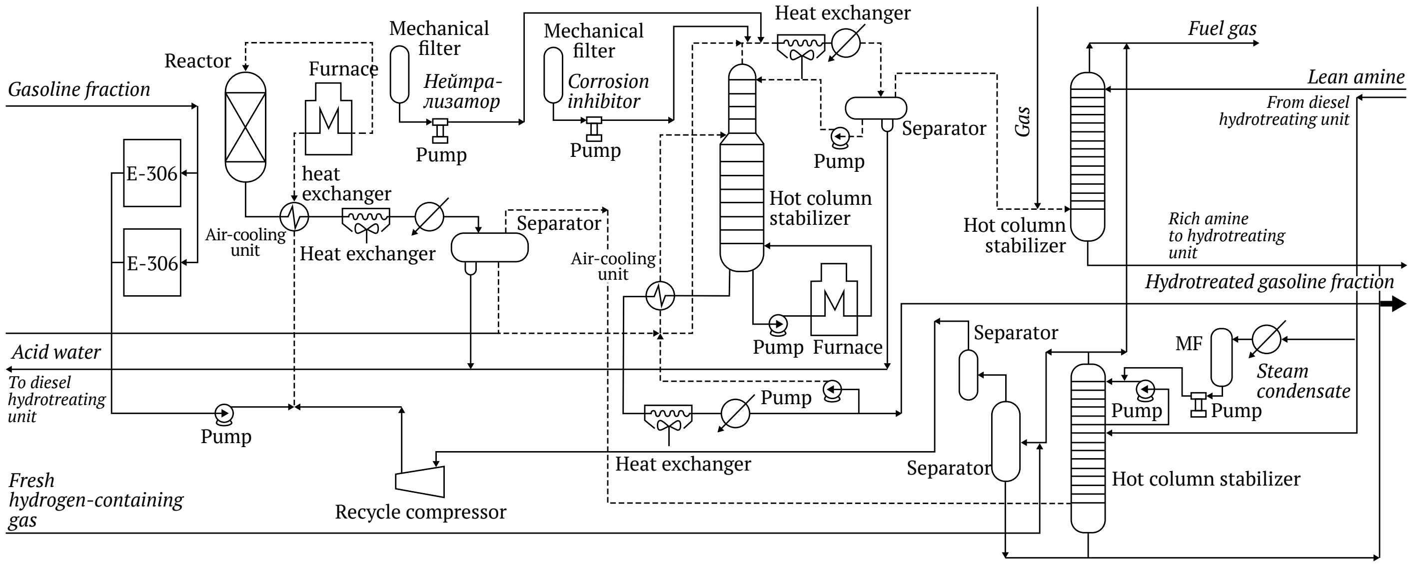

Fig. 1. Basic process flow diagram of gasoline fraction hydrotreating unit

If the cause of unbalanced AM operation conditions is the unbalance of voltages supplied to the stator winding ($U_{AB} \neq U_{BC} \neq U_{CA}$), the phase voltages will not be equal to each other ($U_A \neq U_B \neq U_C$). The influence of unbalance [3] on the operation of an asynchronous motor is investigated by the method of symmetrical components. In the case of an unbalanced power supply, the maximum $M_{\max}$ and starting M_{start} torques of the motor are reduced and the torque creep increases, while the loading torque remains unchanged due to the influence of the negative-phase-sequence. In addition, when the motor is supplied with unbalanced voltage, its efficiency decreases, the losses increase, and consequently motor heating also increases. This can affect the life of the winding insulation. For example, with a voltage unbalance of 2 %, the service life of a motor is reduced by 10 % due to additional losses of active power. For this reason, if there is a strong voltage unbalance, the motor power has to be reduced. Thus, the work of an asynchronous motor at unbalanced supply voltage is undesirable, and the study of asynchronous motor protection systems is an urgent task.

Currently, in Russia, the quality indicators of electrical energy according to the national technical standard GOST 32144-2013 are standardized in terms of the negative-phase-sequence voltage unbalance factor K_{2U} and zero-phase-sequence voltage unbalance factor K_{0U}. The maximum permissible values for these quality indicators are 2% and 4% respectively, which are averaged in the time interval of 10 minutes for 95% and 100% of the time for a week[1].

[1] GOST 32144–2013. Quality standards of electrical energy in power supply systems of general purpose. Moscow: Standards Publishers; 2014. 15 p.

Description of the research subject

The study subject was an asynchronous motor drive of a recycle compressor of a gasoline hydrotreating unit of the fuel hydrotreating integrated unit at the Astrakhan Gas Refining Plant (AGRP). It is a more rational choice to study unbalanced motor operation conditions on powerful motors, as the effect of unbalance in this case will be better expressed.

The hydrotreating unit is designed for hydrotreating of 2 million tons/year of straight-run broad gasoline fraction NK-180°C (with possible weighting of the boiling point to 230°C) produced from Astrakhan gas condensate, broad fraction of light hydrocarbons, and distillate gasoline from a diesel hydrotreating unit. The working hours of the hydrotreating unit are 8000 hours per year. The operating regime of the unit is continuous. The process flow sheet of the gasoline hydrotreating is shown in Fig. 1. The process flow sheet of the gasoline hydrotreating unit includes:

– hydrotreating of raw feedstock with alumina-cobalt-molybdenum catalyst;

– cold separation of the gas-feedstock mixture;

– hydrotreated feed stabilization;

– gas-air regeneration of the catalyst;

– purification of hydrogen-containing gas and hydrocarbon gas with diethanolamine;

– corrosion inhibitor protection.

Fig. 1 shows the main unit components: a reactor, column-stabilizers, mechanical filters, pumps, heat exchangers, separators, and storage tanks (E-306). The direction of movement of NK-180 gasoline fraction is indicated by arrows. The facility under study is a **recycle compressor**, which pressurizes hydrogen-containing gas to produce a gas-feedstock mixture, which

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then goes through various process cycles: heating, hydrogenation, stabilization, cooling, and the resulting hydrogenate is taken out of the unit.

Control of the technological processes of the gasoline hydrotreating unit and the facilities of the gasoline hydrotreating unit with a pumping station is managed from an automated control system (APCS) from a single workplace of a process control operator. The APCS is a hierarchical multifunctional commercial design-composable software and hardware complex based on microprocessor hardware with modular architecture [4]. The system provides on-line monitoring and control of all process operations of the unit, collection, accumulation, processing and displaying of information on the technological process, stabilization of key parameters, alarming of equipment operation and valve positions, blocking and protection of the unit from emergency situations, emergency alarms, and equipment fault detection.

The power supply system of the gasoline hydrotreating unit includes a distribution point. The scheme is shown in Fig. 2:

– TsK-1, TsK-2 are VSG 2GC2-47/35-44M UHL4 recycle compressors (complete with 1000/TF/LB/D00908 dry gas seals control panel). Asynchronous electric motors 4 AZMP-2000/6000 UHL4 (U_{rated} = 6000 V; P_{rated} = 2000 kW; n = 3000 rpm; explosion protection IExdIIBT4) are installed as drives;

– N-1/1, N-1/2, N-1/3 — 1NPS-E200/700 centrifugal vertical split casing oil pumps (with flat body connector). IBAO-560S-4Y2,5-T asynchronous motors are installed as drives. The product to be refined is a gasoline fraction. These pumps are used to feed gasoline fraction to the hydrotreating unit;

– UK-1 is capacitor unit (U_{rated} = 6000 V; Q = 450 kVAr (reactive kilovolt-ampere)) included in the scheme for compensation of reactive power, released on the electric motors TsK-1 (TsK-2);

– 1T, 2T are double-winding three-phase power transformers TSZL-1600/6/0.4 for powering transformer substation low-voltage load.

Research techniques

In order to study the operation of an asynchronous motor under unbalanced conditions, we used mathematical simulation. *Matlab* software package was used [5, 6] as a simulation program. We traditionally used the method of symmetrical components [7] in compiling the mathematical model of an AM.

The most suitable way of protecting electric motors is the development of protection equipment [8]. The complexity of its design, cost-effectiveness, accuracy of operation, and reliability are considered when evaluating the equipment. In order to avoid technological losses associated with asynchronous motor unbalanced operation conditions, a range of protection methods are applied [9, 10]. Since abnormal operation conditions will affect not just the motor, but also the protection itself, the protection equipment must have a high level of reliability [10, 11]. The methods of protection of electric motors from damage at unbalanced conditions of operation can be divided into preventive and technical. This requires the development and implementation of up-to-date protective means made on a microprocessor base [12, 13].

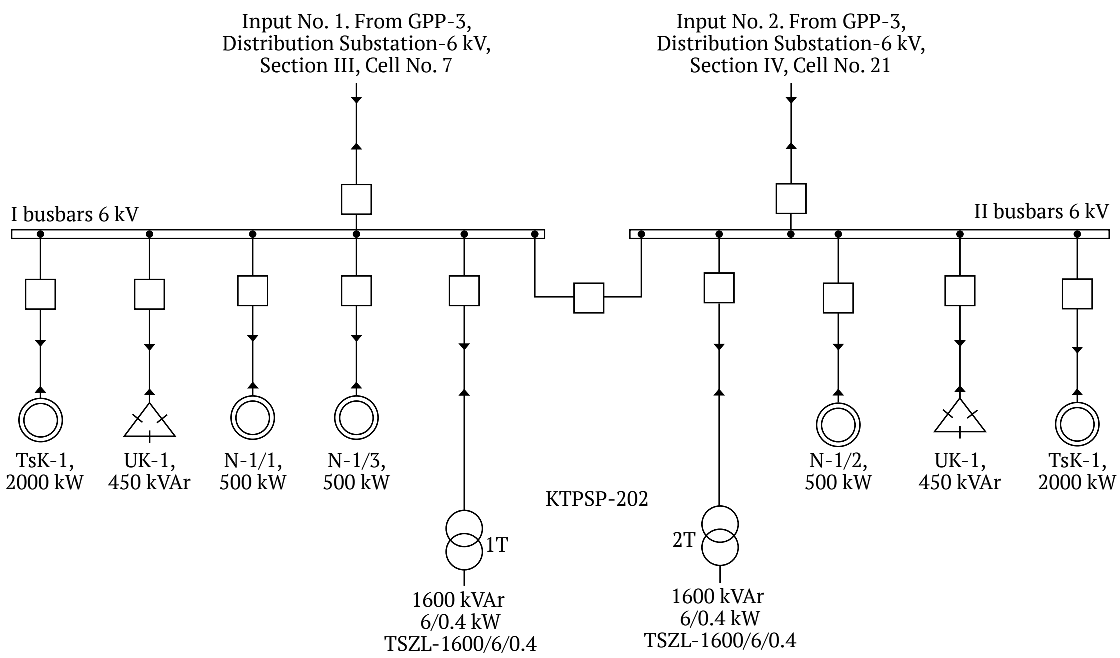

Fig. 2. Power supply diagram for gasoline hydrotreating unit

Devices of indirect type, tripping when stator windings temperature exceeds a preset level (devices of built-in temperature protection, phase-sensitive protection) and those of direct action, reacting to occurrence of negative- or zero-phase-sequence of voltage or current can be used to protect electric motors from unbalanced and single-phase conditions [14, 15].

Because these protections correspond not to the unbalance itself, but to its consequences, their operation is characterized by a large error of tripping, low reliability and response speed. Other disadvantages of these protections are complicated circuits, large mass and dimensions, and a high cost. In this regard, direct action devices are more promising, namely, special protection devices based on sequence filters.

Devices for AM protection against supply voltage unbalance can be based on zero and negative sequence filters and react to current or voltage unbalances.

Let us consider the advantages and disadvantages of relay protection based on current relays. Current protections with negative and zero sequence filters respond to all unbalanced conditions. These devices monitor the current as it flows through the stator phase circuits. Tripping of protections based on them does not depend on the point of connection. However, the use of current transformers decreases the protection reliability, increases power consumption and mass and dimensions of the devices. In addition, due to transformer core saturation, the protection has insufficient tripping accuracy [16]. Biased protections are used to increase the sensitivity of current filter protections.

If a protection is implemented on a voltage relay, it should be borne in mind that voltage relays do not have versatility, because they detect only one failure. The most suitable type of AM protection is the use of so-called voltage monitors which monitor several types of accidents (failures). Such monitors are bases on microprocessor devices. They are versatile, highly reliable, simple, inexpensive, and ensure timely shutdown of an electric motor in the event of unbalanced and single-phase conditions [12, 17].

At present, series 80 Sepam 1000+ microprocessor protection is being implemented at the facility in question, in order to ensure the protection of electrical equipment.

Let us consider the capabilities of Sepam 1000+ in the area of unbalanced power supply protection. In order to protect an asynchronous motor from overloads caused by unbalanced line voltage, a positive-phase-sequence minimum voltage protection $U^{(1)}$ is used. This protection trips when the component $U^{(1)}$ of a three-phase voltage system falls below the design tripping set-point of the protection U_{trip}. Protection against phase imbalance is implemented by measuring $U^{(2)}$. The time delay of both protections is independent.

Sepam 1000+ for implementing these protections operates on line or phase voltage and allows tuning out based on negative-phase-sequence voltage unbalance factor [14]

$$K_{2U} = \frac{U^{(2)}}{U^{(1)}} 100\,\%.$$

Negative-phase-sequence voltage unbalance factor and time delay set-points are set, in order to provide the protection against unbalance: K_{2U} = 20 % and t = 10 s. Current protections which identify unbalanced operation conditions include negative sequence overcurrent (O/C) protection, overload protection, and thermal protection. Negative sequence overcurrent protection produces a value of unbalance factor based on the negative-phase-sequence current. The protection has a dependent and independent time delay. Overload protection and thermal protection are designed to protect a motor against the overloads caused by unbalanced loads in operating conditions or abnormal grid regimes. They also detect the consequences of unbalance rather than unbalance itself, and are therefore less accurate.

The range of set-points of these protections is shown in Table 1[2].

Table 1

Range of set-points of Series 80 Sepam 1000+ protections

Protection function	Setting range	Time delay range, s
Protection against unbalanced supply voltage	$K_{2U} = 0 \div 50$ %	0.05–300
Negative sequence O/C protection with independent Δt	22.3–1130 A	0.1–300
Negative sequence O/C protection with dependent Δt	22.3–1130 A	0.1–1
Overload protection with independent Δt	1–6250 A	0.05–300
Overload protection with dependent Δt	1–6250 A	0.1–12.5 for 2260 A
Thermal protection	60–200°C	1–600 min

[2] Sepam 1000+ (Series 80) Installation and Application Manual.

Development of an asynchronous motor model and models of devices for relay protection against unbalanced operation conditions in Matlab Simulink

We will use the Asynchronous Machine block in the Matlab Simulink software package [18] to simulate an AM. 4AZM-2000/6000 UHL4 motor nameplate data are given in Table 2.

Table 2

4AZM-2000/6000 UHL4 motor nameplate data

Power, kW	2000
Rotation velocity, rpm	2973
Weight, kg	5600
Stator current, A	226
Slip, %	0,9
KPI	96.7
Power factor, p.u.	0.88
Peak torque brevity	1.9
Starting torque brevity	0.77
Starting current brevity	4.7

Based on the motor nameplate data, let us calculate the values of the motor model parameters in Matlab Simulink by the method described in [19]. The obtained parameters required for simulation are presented in Table 3.

Table 3

Parameters of 4AZM-2000/6000 UHL4 motor in Simulink

Reduced rotor active resistance, Ohm	0.419724
Active stator resistance, Ohm	0.888812
Reduced stator and rotor leakage inductance, henry	0.003531
Excitation circuit inductance, henry	0.127834
Moment of inertia, kg·m^2	187.07

The model of asynchronous motor protection against unbalanced supply voltage modes is based on the existing Sepam 1000+ protection. The protection set-points to be reflected in the model are given in Table 4. In order to simulate the unbalanced operation conditions of a motor and the means of its protection against unbalance, a scheme was constructed using the Matlab Simulink software package. It is shown in Fig. 3.

Table 4

Protection model set-points in Matlab Simulink

	Tripping	Release (reset)	t_{tr}, s
Sequence filter-based protection	$K_{2U} = 8$ %	$K_{2Uo} = 6$ %	10
Overload protection	$I_{trip} = 350$ A	$I_{rel} = 300$ A	18
Negative sequence O/C protection	$I_{negative\ sequence\ O/C\ protection\ tripping} = 60$ A	$I_{rel} = 20$ A	10

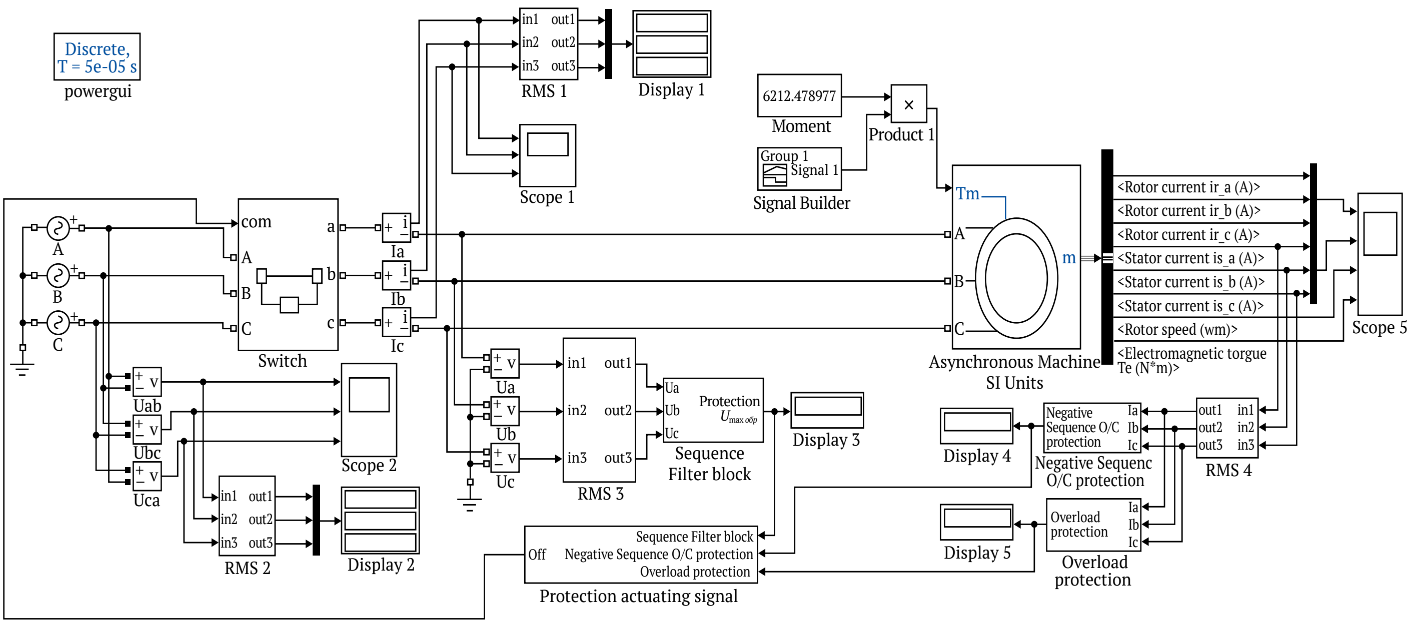

Fig. 3. Schematic of an asynchronous motor simulation in Simulink: in1 – input 1; in2 – input 2; in3 – Input 3; out1 – output 1; out2 – Output 2; out3 – Output 3

Explanations for the scheme of simulation of an asynchronous motor in Simulink:

1. The input three-phase voltage is formed by three single-phase sources in the form of AC *Voltage Source* elements of *SimPowerToolbox* package: amplitude $A = 4898.98$ V, frequency $f = 50$ Hz; initial phase: 0° for phase *A*, −120° for phase *B*, and 120° for phase *C*.

2. Asynchronous motor: set by *Asynchronous Machine* block. The block parameters are selected in accordance with Table 3. The torque is set by *Signal Builder*, *Constant*, *Product*1 blocks for the soft start of a motor.

3. Three-phase breaker: set by *Three-Phase Breaker* block. This block is controlled by a signal, the open and closed key position resistances are stored by default at 10^6 и 10^{-2} ohms, respectively.

4. Current and voltage meters are set by *Current Measurement* and *Voltage Measurement*.

5. RMS1-RMS4 blocks are designed to measure rms current or voltage values.

6. Sequence filter protection: input quantities for the block are effective (rms) phase voltages, while the output quantities are the protection tripping signal and the value of negative-phase-sequence voltage unbalance factor. The measured voltages are converted into balanced (symmetrical) components of the positive- and negative-phase-sequence with the use of *Magnitude-Angle to Complex* block. *Divide* block is used to calculate K_{2U}; when the set-point set by *Relay* block $K_{2U} = 0.08$ is exceeded, a tripping signal is given with a time delay of 10 s.

7. Negative Sequence O/C protection: the input values are the motor stator rms currents, while the output is a tripping (protection actuating) signal. Similarly to the sequence filter, based on the measured line currents, negative-phase-sequence current is obtained and compared with a set-point. If the set-point is exceeded ($I_{trip} = 60$ A), the protection system gives a signal for tripping with a time delay of 10 s.

8. Overload protection: the input values are the motor stator rms currents, while the output is a tripping (protection actuating) signal. Maximum effective current is calculated using MinMax block and then compared with a corresponding set-point. If the set-point $I_{trip} = 350$ A is exceeded, a signal for tripping is given with a time delay of 18 s.

9. "Tripping signal": the input values are signals of tripped sequence filter, Negative Sequence O/C protection, and overload protection, while the output value is a tripping signal. *Logical Operator* 1–3 and Monostable blocks are used to open a breaker, and since this is accompanied by tripping the protections, no signal is given to activate the motor, so there is no looping of the simulation.

The internal structure of the above blocks complies with the protection algorithms. For a more compact and concise presentation, all of the above protections are enclosed in *Subsystem* blocks. As an example, Fig. 4 presents the "Sequence Filter" protection circuit.

The developed motor model and its protection circuit can be verified by simulating its rated operating conditions. Simulation of a motor operation at rated operating conditions presents transients which coincide with the reference processes of an asynchronous motor in terms of phase currents, line voltages, rotor and stator currents, rotor rpm, and electromagnetic torque of a motor.

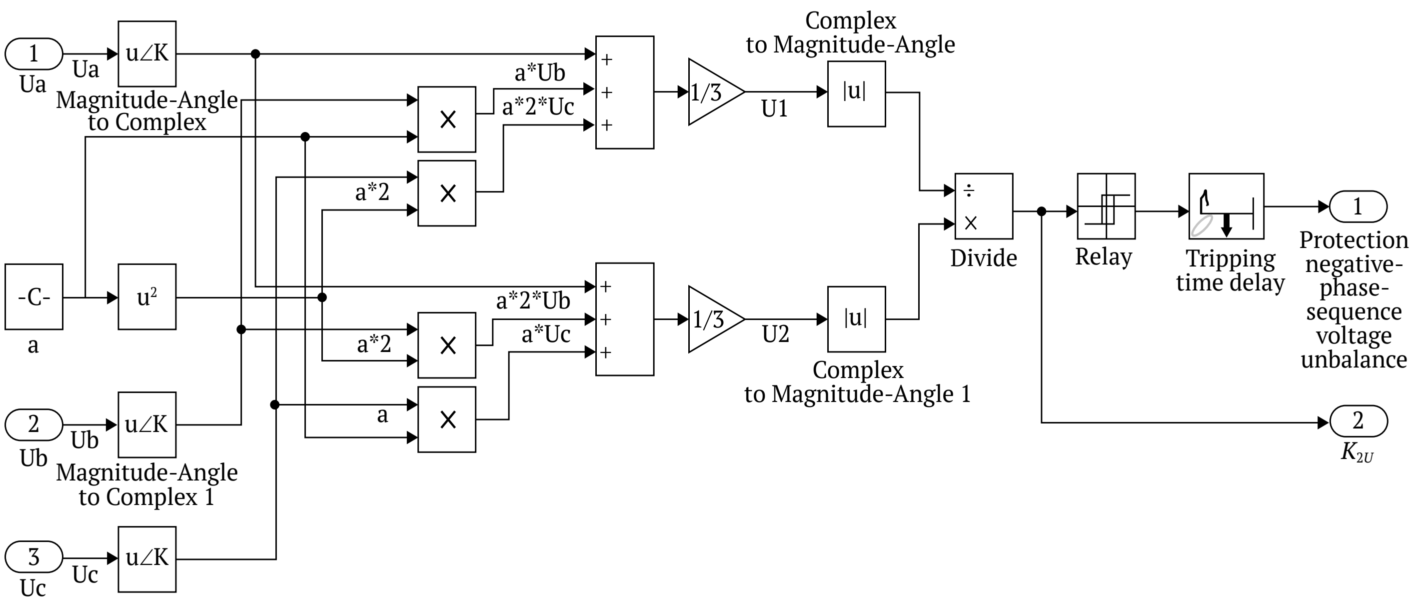

Fig. 4. Internal structure of the Sequence Filter block

1. Line currents during start-up (t = 0–8 c) are about 6 times the rated current; this corresponds to the motor nameplate data. When the motor reaches the rated r.p.m., the currents decrease and reach the rated values I_{rated} = 226 A.

2. Line voltages corresponding to the rated value throughout the simulation time $U_{l\text{-}rated}$ = 6000 V.

3. Signals formed by the protections models demonstrate that at the rated operating conditions, the protections do not trip, forming signal 0 on their outputs. These conditions correspond to 1 on the "Tripping Signal" block output, since when such a signal is applied to the circuit breaker, the breaker is closed.

Let us check the functionality of the installed protections by considering their operation under abnormal conditions of motor operation. The tests conducted by the authors have shown that when the load torque increases by 50 %, the overload protection trips. The other protections do not trip, since there are no negative-phase-sequence currents and voltages. The time diagrams show the protection tripping at time t = 18 s.

Let us now consider the operation of the protections when voltage changes in one of phases. When the voltage in phase A increases by 20 %, in line with voltage unbalance, current unbalance arises. However, at a given deviation, the level of negative-phase-sequence voltage unbalance factor K_{2U} = 6.07 % < $K_{2U\max}$ = 8 % is not enough for tripping a corresponding protection. The current deviation is sufficient to cause a negative-phase-sequence current exceeding the set-point of the negative sequence O/C protection I_2 = 80 A > $I_{2\max}$ = 60 A. The time diagrams show the protection tripping at time t = 10 s. The overload protection does not trip, since the stator currents decrease before reaching the time set-point t = 18 s.

If the voltage in one of the phases is reduced, the currents will decrease. However, a deviation of more than 20 % is necessary for the negative-phase-sequence voltage unbalance protection to trip. In this case, K_{2U} = 8.95 % > $K_{2U\max}$ = 8 %, and therefore the voltage unbalance protection trips, but I_2 = 50 A < $I_{2\max}$ = 60 A, so the negative sequence overcurrent protection does not trip.

We can see that the protections operate selectively and protect the motor from unbalanced operation conditions within the preset set-point limits. Consequently, the digital model developed allows not only motor operation at unbalanced supply voltage to be studied, but also conditions with the use of overload protection detected, negative sequence overcurrent protection. It also allows for protection based on a sequence filter.

Performance Results. Simulation of the processes in an asynchronous motor with unbalanced supply voltage

Let us consider model operation when the supply voltage is unbalanced [20]. By varying the voltages in each phase by $\Delta U = \pm 15$ % U_{rated}, we can consider the deviations (changes) of negative-phase-sequence currents and voltage unbalance factor K_{2U}. Fig. 5 shows these voltage deviations. This diagram shows the values of deviation ΔU, %, in phases in the course of 43 tests. The legend of the diagram explains the display color of each phase. The same diagram shows the deviations in K_{2U} factor.

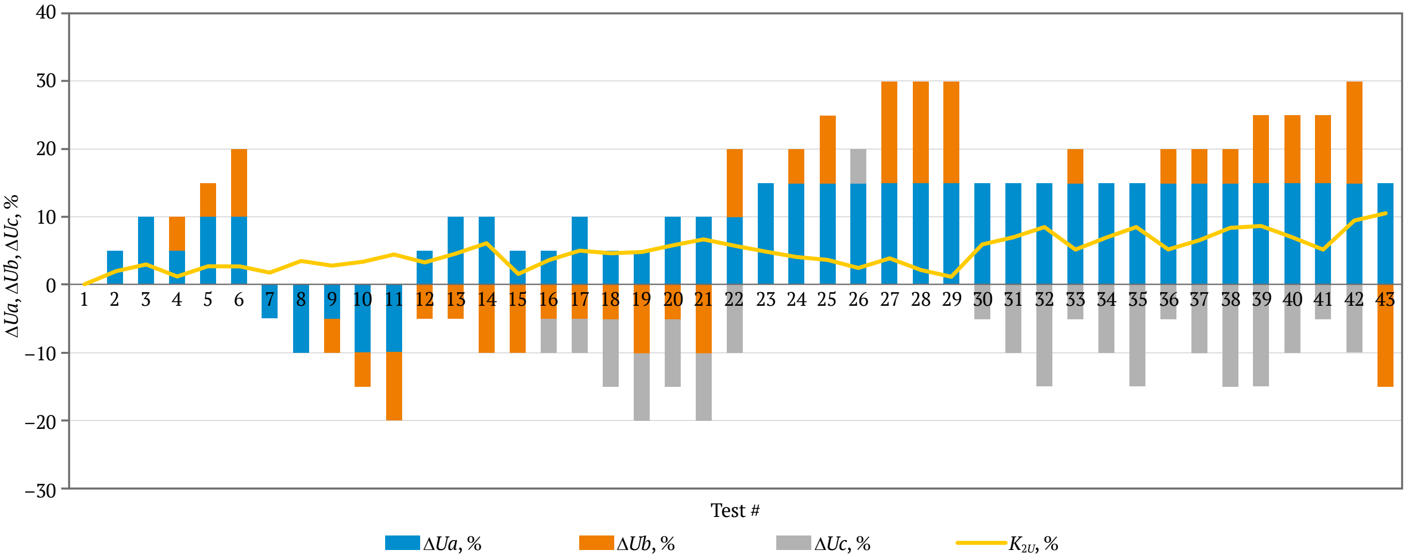

Fig. 5. Values of deviations in supply voltage phases

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Next, Fig. 6 shows the dependence of negative-phase-sequence voltage unbalance factor K_{2U} on the deviations of the voltages in the phases.

The third diagram (Fig. 7) presents the currents in the motor phases *Ia*, *Ib*, *Ic* as functions of the voltages unbalance in the phases.

The tripping of simulated protections is also of interest. Table 5 presents the operations of protections operation and shows the results of the most representative part of the tests (those in which the protections trip).

Analysis of research findings

Fig. 8 shows an example of the simulation results in Simulink. The simulation results show that the negative-phase-sequence overcurrent (O/C) protection trips more often when the supply voltage is unbalanced. This can be explained by the fact that when the voltage level changes even in one of the phases of the source, this causes a change in currents in all motor phases. This, in turn, causes the unbalance of currents and arising negative-phase-sequence currents [21]. If the negative-phase-sequence current exceeds the set-point level of the time-delayed protection, the protection trips and the power supply is switched off. The simulation results allow the conclusion that the protection does not always respond equally to the same levels of voltage unbalance. For example, at K_{2U} = 4,9 % in one case (ΔUa = 5 %; ΔUb = 0 %; ΔUc = −10 %) the negative sequence overcurrent protection trips, while in another case it does not (ΔUa = 15 %; ΔUb = 0 %; ΔUc = 0 %). In cases where the level of unbalance is K_{2U} > 5 %, negative sequence overcurrent protection trips, and when it is K_{2U} > 8 %, the sequence filter protection also trips.

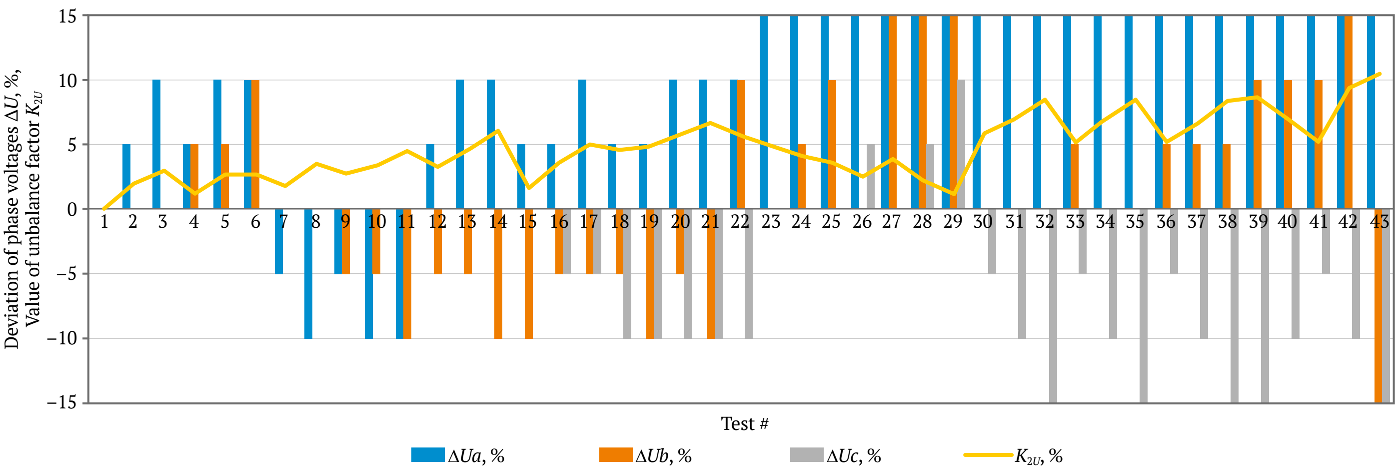

Fig. 6. Dependence of negative-phase-sequence voltage unbalance factor K_{2U} on phase voltage deviations ΔU, %

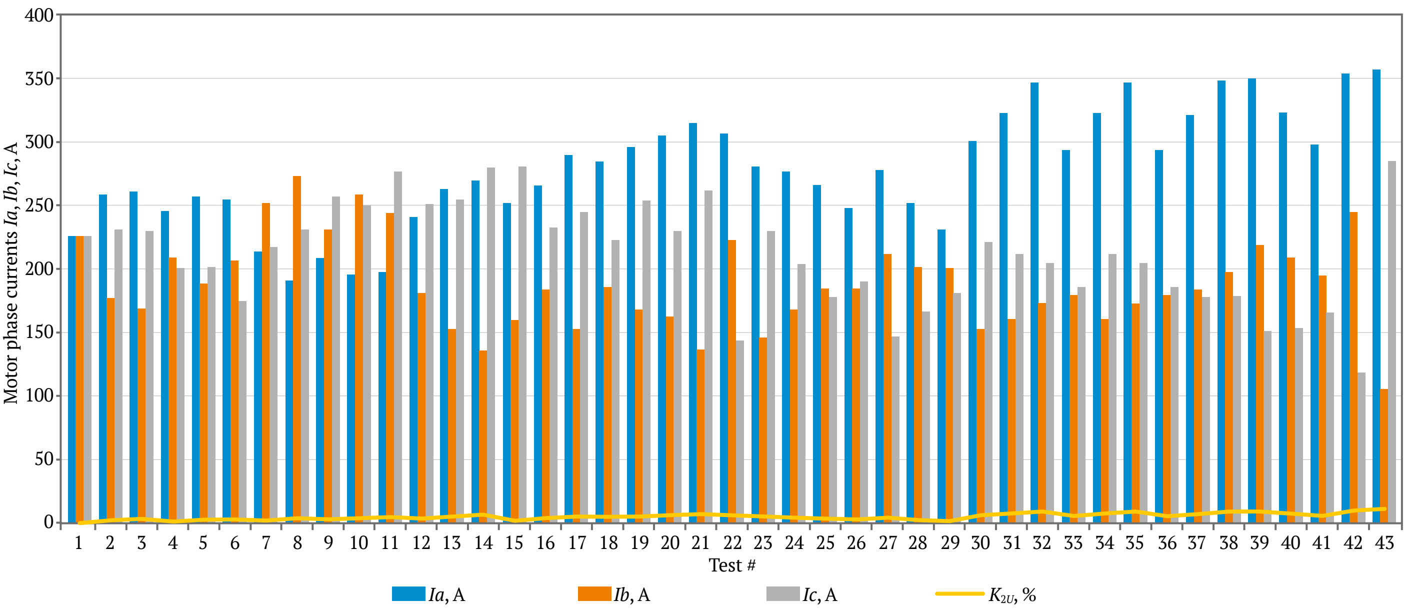

Fig. 7. The currents in a motor phases *Ia*, *Ib*, *Ic* as functions of the negative-phase-sequence voltage unbalance factor K_{2U}

Analysis of the dependence of currents in phases on the unbalance factor shows that significant current unbalance occurs even at small values of the unbalance factor K_{2U}. This means that for full-fledged motor protection, in addition to sequence filter protection, negative sequence overcurrent protection should be in place, since it is under the action of negative-phase-sequence currents a motor heating occurs, losses increase, and thereby the service life is reduced.

Now let us consider the effect of voltage unbalance on motor phase currents at different shaft loads. For this purpose the load will vary from 0 to 120 %. The examples of the study results for no-load, rated conditions, and overload are presented in Tables 6–8.

It is important to note that when the load on the motor shaft is 120% of the rated load, and when the voltages in phases A, B, C deviate by −10, −10 and 0 % respectively, the overload protection trips. This is because even a small voltage unbalance during overload causes currents in excess of the protection set-point.

The data presented in the tables shows that at the same deviations in phase voltages, the currents have greater unbalance at higher load factors. This is because the more loaded motor produces greater currents, and with an unbalanced supply voltage, the magnitude of these increased currents has a greater effect on the unbalance, thus causing greater negative-phase-sequence (nps) current. Therefore, unbalanced supply voltage conditions are unacceptable at high motor loads.

Table 5

Simulation results for AM operation under conditions of unbalanced supply voltage

Phase voltage deviations, %			Currents in motor phases, A			K_{2U}, %	Tripping
Δ*Ua*	Δ*Ub*	Δ*Uc*	*Ia*	*Ib*	*Ic*		
10	−10	0	270	136	280	6,1	Negative Sequence O/C protection
5	−10	−10	296	168	254	4,9	Negative Sequence O/C protection
10	−5	−10	305	163	230	5,8	Negative Sequence O/C protection
10	−10	−10	315	137	262	6,7	Negative Sequence O/C protection
10	10	−10	307	223	144	5,7	Negative Sequence O/C protection
15	0	−5	301	153	221	5,9	Negative Sequence O/C protection
15	0	−10	323	161	212	7	Negative Sequence O/C protection
15	0	−15	347	173	205	8,5	Negative Sequence O/C protection, sequence filter
15	5	−5	294	180	186	5,2	Negative Sequence O/C protection
15	0	−10	323	161	212	7	Negative Sequence O/C protection
15	0	−15	347	173	205	8,5	Negative Sequence O/C protection, sequence filter
15	5	−5	294	180	186	5,2	Negative Sequence O/C protection
15	5	−10	321	184	178	6,6	Negative Sequence O/C protection
15	5	−15	348	198	179	8,4	Negative Sequence O/C protection, sequence filter
15	10	−15	350	219	151	8,7	Negative Sequence O/C protection, sequence filter
15	10	−10	323	209	154	7	Negative Sequence O/C protection
15	10	−5	298	195	166	5,2	Negative Sequence O/C protection
15	15	−10	354	245	119	9,4	Negative Sequence O/C protection, sequence filter
15	−15	−15	357	106	285	10,5	Negative Sequence O/C protection, sequence filter

Let us now consider the rotor rpm and torque produced by the motor under different unbalanced supply voltage conditions as a function of time. We will investigate the operation of the motor with rated load when the voltage in the phases deviates from the rated value as follows:

1) phase voltage deviations: Δ*Ua* = 15 %; Δ*Ub* = 10 %; Δ*Uc* = 0 %;

2) phase voltage deviations: Δ*Ua* = 10 %; Δ*Ub* = 5 %; Δ*Uc* = 0 %;

3) phase voltage deviations: Δ*Ua* = −15 %; Δ*Ub* = −5 %; Δ*Uc* = 0 %;

4) phase voltage deviations: Δ*Ua* = −10 %; Δ*Ub* = 0 %; Δ*Uc* = 0 %.

In the conditions under consideration, the motor has time to reach steady-state operation conditions before the overload protection trips Thus, the negative sequence overcurrent protection and sequence filter-based protection do not trip. To obtain a more illustrative study, the stator and rotor currents, as

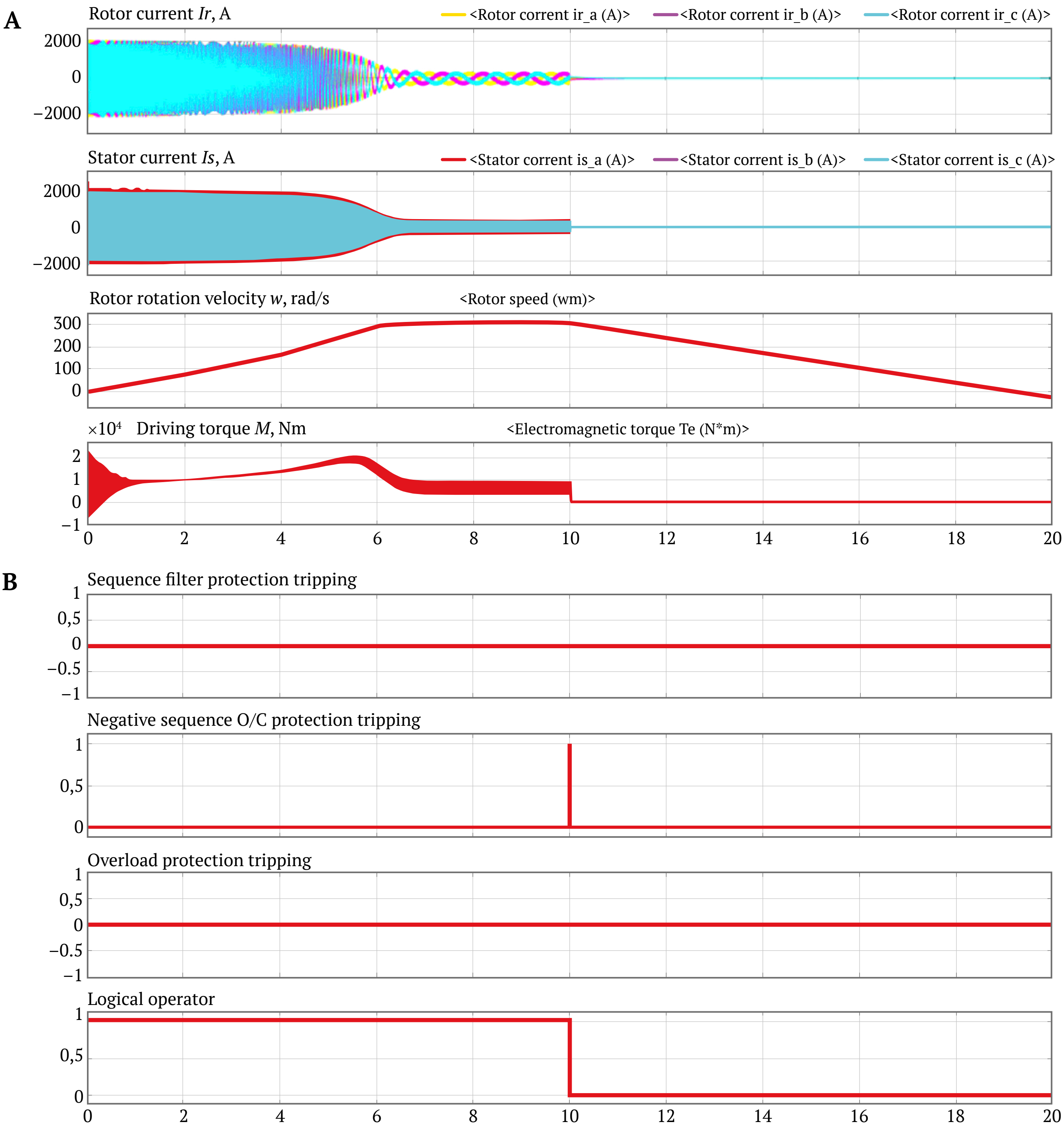

Fig. 8. Timing diagrams: *A* – line rotor currents, stator currents, rotor rpm, and electromagnetic torque of a motor with an increase in phase A voltage by 20 %; *B* – protection signals with an increase in phase A voltage by 20 %

well as the rotor rpm and the motor torque for 13 s of simulation are considered. The simulation results are presented in Table 9. Fig. 9 shows examples of the graphs of changes in the rotor currents, stator currents, rotation velocity and drive torque of an asynchronous motor at the considered negative-phase-sequence voltage unbalance factor values K_{2U}.

The figures presented show that the supply voltage unbalance causes currents unbalance and, consequently, negative-phase-sequence current. This violates the normal regime of motor operation by changing the shape of stator and rotor current curves, as well as the rotor rpm and the motor torque, that is, by creating oscillations of these parameters. The

Table 6

Simulation of unbalanced motor operation conditions at 100% load

Voltage deviations in phases, %			K_{2U}, %	Motor phase currents, A			Tripping
Δ*Ua*	Δ*Ub*	Δ*Uc*		*Ia*	*Ib*	*Ic*	
−10	−10	0	4	197.7	244.1	277.2	Protections fall to function
10	−5	−10	6	304.8	162.8	229.9	Negative Sequence O/C protection
15	0	−5	6	300.5	153.4	221.4	Negative Sequence O/C protection
15	0	−10	7	322.6	161.2	211.9	Negative Sequence O/C protection
15	10	−15	9	350.2	219.1	151.0	Negative Sequence O/C protection, sequence filter
15	−15	−15	11	356.9	106.0	285.2	Negative Sequence O/C protection, sequence filter

Table 7

Simulation of unbalanced operation conditions at 0% load

Voltage deviations in phases, %			K_{2U}, %	Motor phase currents, A			Tripping
Δ*Ua*	Δ*Ub*	Δ*Uc*		*Ia*	*Ib*	*Ic*	
−10	−10	0	4	81.6	23.5	117.7	Protections fall to function
10	−5	−10	6	162.6	92.3	70.6	Negative Sequence O/C protection
15	0	−5	6	178.4	120.3	58.8	Negative Sequence O/C protection
15	0	−10	7	192.8	145.6	56.4	Negative Sequence O/C protection
15	10	−15	9	205.2	204.0	60.3	Negative Sequence O/C protection, sequence filter
15	−15	−15	11	237.6	148.2	126.2	Negative Sequence O/C protection, sequence filter

Table 8

Simulation of unbalanced operation conditions at 120% load

Voltage deviations in phases, %			K_{2U}, %	Motor phase currents, A			Tripping
Δ*Ua*	Δ*Ub*	Δ*Uc*		*Ia*	*Ib*	*Ic*	
−10	−10	0	4	243.2	300.0	327.6	Overload protection
10	−5	−10	6	348.8	205.4	275.0	Negative Sequence O/C protection
15	0	−5	6	341.6	192.2	261.7	Negative Sequence O/C protection
15	0	−10	7	365.1	198.9	250.3	Negative Sequence O/C protection
15	10	−15	9	383.5	245.4	188.6	Negative Sequence O/C protection, sequence filter
15	−15	−15	11	396.2	148.6	333.6	Negative Sequence O/C protection, sequence filter

Table 9

Motor dynamic characteristics simulation results

Voltage deviations in phases, %			Phase voltages, V			Motor phase currents, A			Unbalance factor K_{2U}, %
Δ*Ua*	Δ*Ub*	Δ*Uc*	Δ*Ua*	Δ*Ub*	Δ*Uc*	*Ia*	*Ib*	*Ic*	
15	10	0	5634	5389	4899	274.1	196.2	181.7	4.1
10	5	0	5389	5144	4899	257.9	196.6	203.4	2.8
−15	−5	0	4164	4654	4899	184.9	292.7	262	4.7
−10	0	0	4409	4899	4899	198	277.5	232.2	3.4

resulting oscillations have a larger amplitude with a higher negative-phase-sequence voltage unbalance factor. Unbalanced voltage conditions have an adverse impact on motor operation, since it causes fluctuations in the motor torque and rotor rpm, resulting in vibrations that reduce the motor service life. For better visualization let us display graphically the signals of rotor rpm and motor torque from identical circuits working in parallel with different ratios of supply voltages, according to Table 9. Fig. 10 shows such graphs of changes in the effective values of rotation velocity and torque of the asynchronous motor at different negative-phase-sequence voltage unbalance factors.

The graphs show that the changes in the rotor rpm and motor torque depend mostly on the nature of the voltage change rather than on the unbalance factor. At lowered voltage, it is more difficult to start the motor and the rated rotation velocity is reached more slowly. Let us compare the graphs of the torque changes at K_{2U} = 0, 4.7, 3.4 %. Since K_{2U} = 0 % at the ra-ted supply voltage conditions, no negative-phase-sequence torque occurs $-M_2 = 0$, and the motor torque is fully determined by positive-phase-sequence torque $-M_{rated} = M_1$. In order to assess the effect of unbalanced voltage on the motor torque, we assume that at K_{2U} = 4.7, 3.4 % the positive-phase-sequence torque is approximately equal to the torque at the rated motor operating conditions. This statement is justified by the fact that the voltage level in the cases under consideration does not differ significantly from the rated voltage. Consequently, the character of the curves depends on this to a lesser extent. Since negative-phase-sequence currents arise when the supply voltage is unbalanced, negative-phase-sequence torque also arises. It has a negative value of $M_2 < 0$: the resulting torque equal to the sum of positive- and negative-phase-sequence torques $-M = M_1 + M_2 = M_{rated} + M_2$ will decrease by increasing the unbalance factor as clearly expressed in the peaks of the curves in question. A similar statement is true for the change in torques at K_{2U} = 4.1, 2.48%. However, this is due to the fact that the voltage unbalance was introduced by increasing the voltages in the phases, both positive- and negative-phase-sequence currents increased along with the voltage which caused an increase in the corresponding torques. In this case, with a higher unbalance factor, the torque becomes greater when compared to the rated one. It may thus be concluded that a deviation from voltage balance is accompanied by a decrease in the resulting torque and, consequently, by an increase in losses and a decrease in motor efficiency, as well as by heating of the windings as a result of negative-phase-sequence currents.

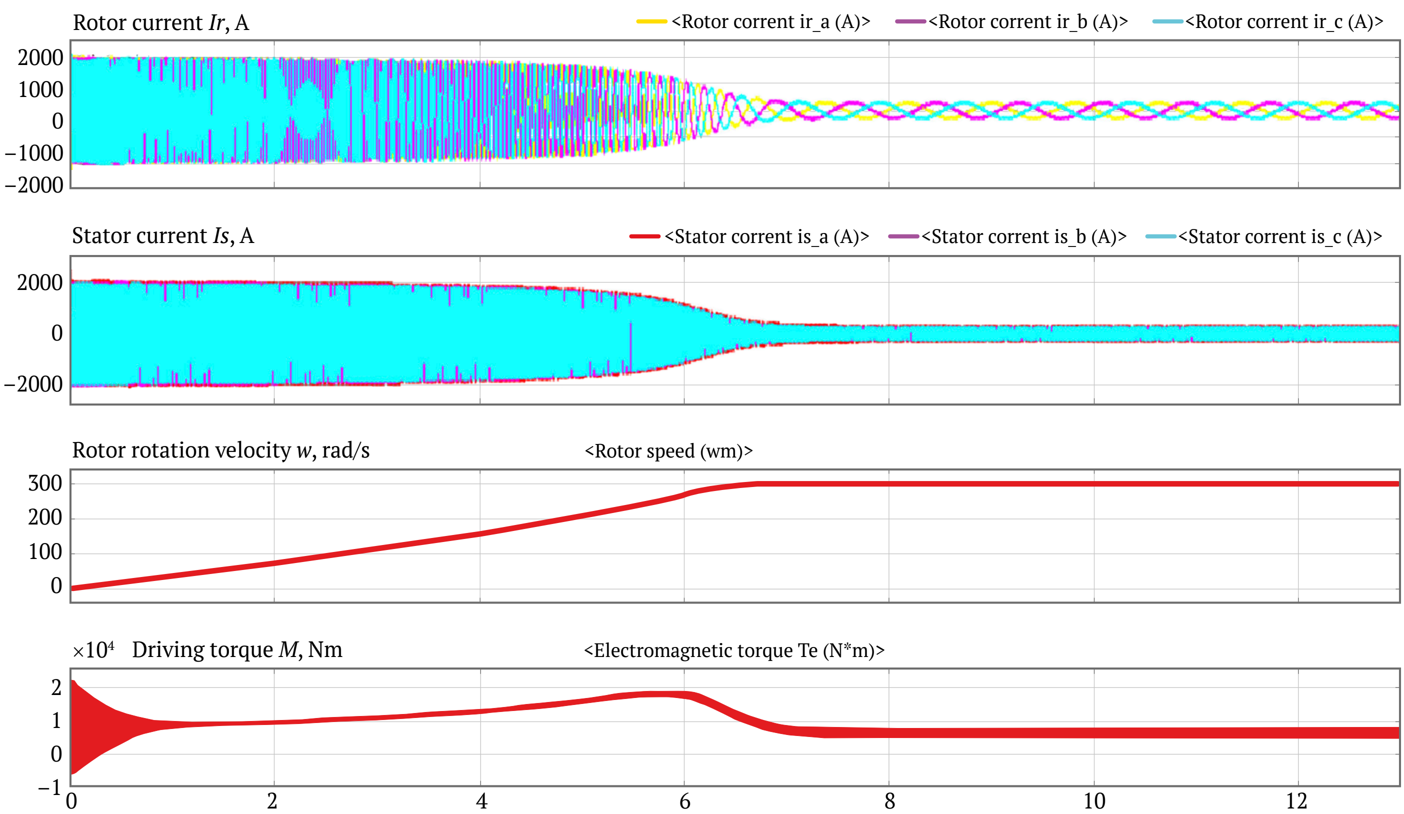

Fig. 9. Graphs of changes in rotor currents, stator currents, rotation velocity and drive torque of an asynchronous motor at the considered negative-phase-sequence voltage (unbalance) factor K_{2U} = 4.1 %

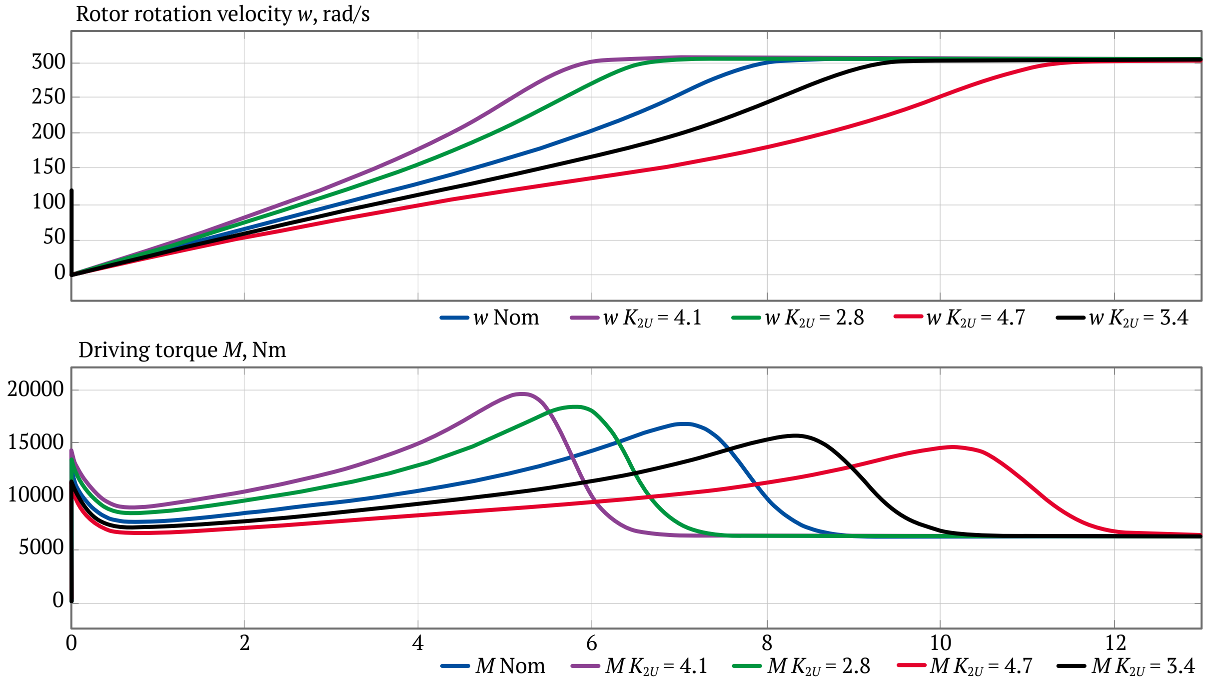

Fig. 10. Graphs of changes in the effective values of rotation velocity and torque of the asynchronous motor at rated operating conditions (K_{2U} = 0 %) and at different negative-phase-sequence voltage unbalance factor values K_{2U} = 4.1, 2.8, 3.4, 4.7 %

Conclusions

The authors conducted a study of high-voltage asynchronous motor drive protections of a recycle compressor in the fuel hydrotreating unit at the Astrakhan Gas Refining Plant. The studies showed that sequence filter relay protections, negative-phase-sequence protection, and overload protection should be selected in the aims of protecting the motor against supply voltage unbalance. A simulation of the joint operation of the AM and its protections was performed. The study findings allow for quantitative assessment of the effect of supply voltage unbalance on the operation of a high-voltage asynchronous motor. The analysis of the protections operation showed that, in the event of voltage unbalance, the negative sequence overcurrent protection trips more often, because an unbalance of currents arises. The authors conclude that this protection must be implemented, because the consequence of unbalanced voltage supply conditions, namely, the unbalance of currents, creates a negative-phase-sequence torque. This leads to a reduction of motor efficiency and service life. Evaluation of the protections operation at different motor load factors showed that the effect of voltage unbalance has a greater influence on the motor operation at higher load factors. The analysis of the motor characteristics at different unbalances of the supply voltage allowed changes in the effective values of the motor rpm and torque at different unbalance factors to be assessed. The feasibility of implementation of the developed relay protection system on the basis of series 80 Sepam 1000+ microprocessor protection has been confirmed.

In terms of commercial application, the study findings can be used as a basis for relay protection of all components of the fuel hydrotreating unit at the Astrakhan gas refining plant. The authors are currently further developing this system.

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