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# ELECTROENERGETICS, ELECTROTECHNICS ELECTROMECHANICS + CONTROL

## *Scientific – Industrial Journal*

# TRANSPORTATION OF ENERGY TO COSMIC DISTANCE BY MEANS OF NEUTRINOS

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## Abstract

We investigate the scattering of sufficiently low-energy neutrinos at transversely polarized electrons in a constant homogeneous magnetic field. We calculate the differential probability for the considered processes and the average energy of the scattered neutrino. It is determined that when the ultra-relativistic electrons accelerated up to energies $500-600\ GeV$ pass through the single crystal possessing sufficiently strong internal electrostatic field along its crystal axis or plane, the influence of the external effective magnetic field of the single crystal on the low-energy neutrino-electron scattering becomes essentially and it leads to the amplification of the energy of very low-energy neutrinos, including cosmic relic neutrinos up to energies $\sim 10^2 GeV$. The possibility of the amplification of the energy of very low-energy neutrinos, including cosmic relic neutrinos up to energies $\sim 10^2 GeV$ enables us to realize the transportation of energy to the distances $R \gtrsim 10^9 km$ in the solar system or beyond its boundaries (i.e., in our Galaxy and outer galaxies) by means of neutrinos.

**Keywords:** neutrino-electron scattering, relic neutrino, transverse polarization, energy transportation

## 1. Introduction

Since a neutrino is a neutral particle, the amplification of its energy is not an easy question. Therefore, two natural questions arise. Are there any terrestrial physical conditions that enable us to amplify the energy of a sufficiently low-energy neutrino? Is it realistic to transport energy to very long cosmic distances by means of a neutrino? Namely, the answers to these questions are the main purpose of the presented work.

At first, we calculate the differential probability for the scattering of sufficiently low-energy neutrinos at transversely polarized electrons

$$\nu_i + e^- \to \nu_i' + e^{-\prime}, \tag{1}$$

in a constant homogeneous magnetic field in the framework of the Weinberg-Salam electroweak interactions theory where $\nu_i = \nu_e,\ \nu_\mu,\ \nu_\tau$ are the three flavours of neutrinos in the initial state, $\nu_i' = \nu_e',\ \nu_\mu',\ \nu_\tau'$ are the three flavours of neutrinos in the final state. Knowing the differential probability of the considered processes we calculate the average energy of the scattered neutrinos.

We use the Feynman diagram technique [1] and the exact wave function method [2] for the calculation of the differential probability of the considered processes.

## 2. The physical conditions

We assume that electrons in the initial and final states are ultra-relativistic

$$\varepsilon^2 \gg m_e^2, \qquad \varepsilon'^2 \gg m_e^2 \tag{2}$$

where $\varepsilon = \gamma m_e$ , $\gamma = \sqrt{1 + 2fn + (p_z/m_e)^2}$ , $p_z$ and $n$ are the energy, relativistic factor, $z$-component of the momentum and the number of the Landau energy level belonging to the electron in the initial state, respectively. The primed quantities $\varepsilon' = \gamma' m_e$, $\gamma' = \sqrt{1 + 2fn' + (p_z'/m_e)^2}$ , $p_z'$ and $n'$ belong to the electron in the final state. $f$ is the dimensionless field parameter characterizing the external magnetic field $f = B/B_0$ where $B$ is the magnitude of the magnetic field vector $\vec{B}$ that is directed along the $z$-axis and $B_0 = m_e^2/e \cong 4.414 \times 10^{13} G$ is the Schwinger field strength in the system of units $c = \hbar = 1$. $B$ is assumed to be $B \ll B_0$ ( or $f \ll 1$). We also assume that electrons in the initial and final states possess large transverse momenta

$$p_\perp = (2eBn)^{1/2} = m_e (2fn)^{1/2} \gg m_e, \tag{3}$$

$$p_\perp' = (2eBn')^{1/2} = m_e (2fn')^{1/2} \gg m_e. \tag{4}$$

The assumptions $\varepsilon^2 \gg m_e^2$, $\varepsilon'^2 \gg m_e^2$ , $p_\perp \gg m_e$, $p_\perp' \gg m_e$ and $f \ll 1$ mean that the main contribution to the differential probability of the process comes from the electron states occupying high Landau levels ($n,\ n' \gg 1$). In this case motion of the electrons in the initial and final states are semiclassical. We consider the case when the longitudinal momentum of the electron in the initial state is zero: $p_z = 0$.

Within the considered physical conditions we can neglect the mass of a neutrino and we can apply the massless neutrino model. Let the incident low-energy neutrino fly along the $z$-axis (along the magnetic field direction) and its energy is in the range $\omega_{min} \ll \omega \ll m_e$, (or $f/\sqrt{\gamma^2 - 1} \ll \omega/m_e \ll 1$) where $\omega_{min} = eB/p_{\perp}$.

### 3. The differential probability of the processes

We obtain the following general formula for the differential probability of the processes $\nu_i e^- \to \nu_i' e^{-\prime}$:

$$dw = \frac{G_F^2 m_e^2}{4\pi^{3/2}} \frac{1}{V} \left[ A\Phi_1(z) - B \left(\frac{\chi}{u}\right)^{2/3} \Phi'(z) - C \left(\frac{\chi}{u}\right)^{1/3} \Phi(z) \right] \frac{u\,du}{(1+u)^4} \tag{5}$$

where

$$A = \frac{\kappa}{2u} [g_L^2(1+u)^2 + g_R^2 + 2g_L g_R \zeta\zeta'(1+u)] - g_L g_R (1+\zeta\zeta')(1+u), \tag{6}$$

$$B = g_L^2(1+u)^2 + g_R^2 + 2g_L g_R \zeta\zeta'(1+u), \tag{7}$$

$$C = g_L^2 \zeta'(1+u)^2 - g_R^2 \zeta + g_L g_R (\zeta - \zeta')(1+u), \tag{8}$$

$$\chi = \frac{B}{B_0} \frac{p_{\perp}}{m_e} = [f^2(\gamma^2 - 1)]^{1/2} \tag{9}$$

is the field parameter,

$$\kappa = \frac{2\omega\varepsilon}{m_e^2} \tag{10}$$

is the kinematical parameter, $u$ is the invariant spectral variable

$$u = \frac{\chi}{\chi'} - 1 = \frac{p_{\perp}}{p_{\perp}'} - 1 \simeq \frac{\omega'}{\varepsilon - \omega'}, \tag{11}$$

the field parameter $\chi'$ belongs to the electrons in the final state,

$$\Phi(z) = \frac{1}{2\sqrt{\pi}} \int_{-\infty}^{+\infty} dt exp\left[ i \left( zt + \frac{t^3}{3} \right) \right] \tag{12}$$

is the Airy function depending on the argument

$$z = \left(\frac{u}{\chi}\right)^{2/3} \left(1 - \frac{\kappa}{u}\right), \tag{13}$$

$\Phi'(z) = d\Phi(z)/dz$, $\Phi_1(z) = \int_z^{\infty} \Phi(y)dy$, $G_F$ is the Fermi constant, $\zeta(\zeta')$ is the projection of the spin of the electron in the initial (final) state onto the $z$-axis, $g_L = 0.5 + \sin^2\theta_W$ and $g_R = \sin^2\theta_W$ for the

$\nu_e e^- \to \nu_e{}' e^-{}'$ process, $g_L = -0.5 + \sin^2\theta_W$, $g_R = \sin^2\theta_W$ for the $\nu_\mu e^- \to \nu_\mu{}' e^-{}'$ ( or $\nu_\tau e^- \to \nu_\tau{}' e^-{}'$) process.

## 4. The average energy of the scattered neutrino

Using the general formula (5) for the differential probability and the formula for the average energy

$$\langle\omega'\rangle = \frac{\int_0^\infty \omega' dw}{\int_0^\infty dw} \tag{14}$$

we obtain the asymptotic formula for the average energy of the scattered neutrino in the limiting case $\chi \gtrsim 10^2$, $\kappa < 1$ that corresponds to the case $\eta \gg 1$ when the field effects are sufficiently essential:

$$\langle\omega'\rangle_{\nu e^-} = \frac{1}{3}\varepsilon \frac{2g_L^2 + \frac{5}{27}g_R^2 + \frac{8}{9}g_L g_R \zeta\zeta'}{g_L^2 + \frac{5}{27}g_R^2 + \frac{2}{3}g_L g_R \zeta\zeta'}. \tag{15}$$

## 5. Discussion and numerical estimations

The analysis of the formulae (15) shows that the average energy of the scattered neutrino is proportional to the energy of the electron in the initial state: $\langle\omega'\rangle_{\nu_i e^-} \sim \varepsilon$ . It means that the average energy taken away by the scattered neutrino is in order of the energy of the electron in the initial state. In fact, the energy is transferred from the electron in the initial state to the neutrino. This happens at the expense of the anti-Stokes transition that is realized when the condition

$$\mathrm{B} \gg \mathrm{B}_0 \frac{\omega \mathrm{m_e}}{\varepsilon^2} \tag{16}$$

is satisfied.

Using the relation (2) and the unitarity limit ($\sqrt{s} \approx 600\ GeV$) for the neutrino-electron scattering [3] we can determine the following range for the energy of the electron in the initial state

$$m_e \ll \varepsilon \lesssim 600\ GeV \tag{17}$$

and the range for the average energy of the scattered neutrino

$$10^5 eV \ll \langle\omega'\rangle_{\nu_i e^-} \lesssim 10^2\ GeV\ . \tag{18}$$

This result enables us to realize the amplification of the energy of very low-energy neutrinos, including cosmic relic neutrinos up to energies $\sim 10^2 GeV$ and the transportation of energy over a long (cosmic) distance by means of neutrinos.

The dependence of $\langle\omega'\rangle_{\nu_i e^-}$ on the structural constant $g_L$ shows that the average energy transported by the scattered neutrino is sensitive to the neutrino flavour and the polarization of the spins of the electrons in both initial and final states. Sensitivity of the average energy of the scattered neutrino to the neutrino flavour in case of $\zeta = +1$ and $\zeta' = -1$ is given in the Table 1.

Table 1.

Neutrino flavour dependence of the average energy transported by the scattered neutrino

| Reaction | $\langle\omega'\rangle_{\nu_i e^-}$ |
| --- | --- |
| $\nu_e e^- \to \nu_e' e^{-\prime}$ | $0.72\ \varepsilon$ |
| $\nu_\mu e^- \to \nu_\mu' e^{-\prime}$ | $0.57\ \varepsilon$ |
| $\nu_\tau e^- \to \nu_\tau' e^{-\prime}$ | $0.57\ \varepsilon$ |

For realization of the amplification of the energy of a cosmic relic neutrino we need the electrons accelerated up to energies $\sim 10^2\ GeV$ and sufficiently strong magnetic fields. The strength of any permanent magnets in the terrestrial conditions is not more than $\sim 10^5\ G$. However, when ultra-relativistic electrons pass through the single crystal possessing strong internal electrostatic field $\vec{E}$ (eg, tungsten $W$, diamond $C$) along its crystal axis or plane, the passing electrons experience the action of an extended effective magnetic field according to the formula $\vec{H}_{ef} = [\vec{E}\vec{\beta}]/\sqrt{1-\beta^2}$, where $\vec{\beta} = \beta\vec{n}$, $\beta = v/c$ [4-7]. The strength of this magnetic field by orders of magnitude exceeds that of any permanent magnets.

The simple scheme of the proposed experiment is given by the Fig. 1. The single crystal is placed so that the accelerated electrons enter the single crystal in the direction perpendicular to the internal crystalline electric field $\vec{E}$ as shown in Fig 1. We assume that there are always relic neutrino beam passing along the effective magnetic field direction. We must take into account that the single crystal should be cooled permanently and the related experiment should be performed under the ground of the depth $\sim km$ (to avoid the undesirable background effects).

It should be noted that the neutrinos in the final state scatter at the extremely small angles with respect to the plane that is perpendicular to the effective magnetic field direction.

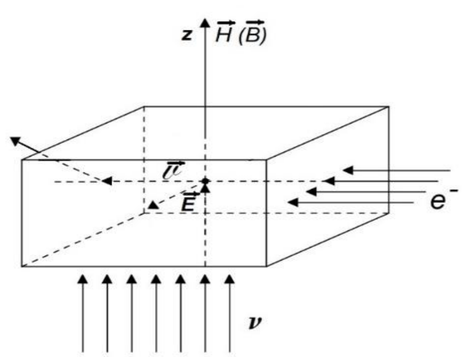


Figure 1. The proposed experiment

Let us perform numerical estimations on the free path of the scattered neutrinos. If the energy of the accelerated electrons in the initial state is $\varepsilon = 5.5 \times 10^2 GeV$, then the energy of the scattered neutrinos will be $\omega' = 0.72\varepsilon = 3.96 \times 10^2 GeV$. The cross section for the scattering of a high-energy neutrino at the target electron that are at rest is calculated according to the formula [3]

$$\sigma = \frac{2G_F^2 m_e \omega'}{\pi} \approx 1.68 \times 10^{-41} \frac{\omega'}{GeV} cm^2.$$

For the energy $\omega' = 3.96 \times 10^2 GeV$ we obtain $\sigma \approx 6.65 \times 10^{-39} cm^2$. Knowing the electron concentration in ordinary substances (eg, $n \cong 3 \times 10^{23} cm^{-3}$) we can calculate the mean free path of the scattered neutrinos according to the formula $\lambda = 1/(\sigma n)$: $\lambda \approx 5 \times 10^9 km$. This distance is approximately equal to the distance from the Earth to the outer-known planet (Neptune) of the solar system which is equal to $(4.3 - 4.7) \times 10^9 km$. It means that the scattered neutrinos with the energy $\omega' = 3.96 \times 10^2 GeV$ will collide with the electrons of the target situated at the distance $R \gtrsim 10^9 km$ in the solar system or beyond its boundaries (i.e., in our Galaxy and outer galaxies) and transfer their energies to the target electrons definitely. The time interval which is required for the transportation of energy to the indicated distance is about $4.72\ h$.

Calculation of the numerical value of the cross section for the relic neutrino-electron scattering is performed according to the formula [8, 9]

$$\sigma = \frac{7G_F^2}{4\pi} \omega^2.$$

For the relic neutrino energy ($\omega \cong 1.677 \times 10^{-4}\ eV$) the cross section is $\sigma \sim 10^{-63} cm^2$. For the electron concentration of an ordinary substance the related mean free path is

$$\lambda_r \sim 10^{34} - 10^{35}\ km \sim 10^{21} - 10^{22} ly.$$

We see that at the expense of the amplification of the energy of relic neutrinos their mean free path decreases at least $10^{24}$ times.

## 6. Conclusions

It is shown that when the ultra-relativistic electrons accelerated up to energies $500 - 600\ GeV$ pass through the single crystal possessing sufficiently strong internal electrostatic field along its crystal axis or plane, the influence of the external effective magnetic field of the single crystal on the low-energy neutrino-electron scattering becomes essentially and it leads to the amplification of the energy of very low-energy neutrinos, including cosmic relic neutrinos up to energies $\sim 10^2 GeV$. The possibility of the amplification of the energy of very low-energy neutrinos, including cosmic relic neutrinos up to energies $\sim 10^2 GeV$ enables us to realize the transportation of energy to the distances $R \gtrsim 10^9 km$ in the solar system or beyond its boundaries (i.e., in our Galaxy and outer galaxies) by means of neutrinos.

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## NEYTRİNOLAR VASİTƏSİLƏ ENERJİNİN KOSMİK MƏSAFƏYƏ ÖTÜRÜLMƏSİ

**Vəli A. Hüseynov, Rəsmiyyə E. Qasımova**

**XÜLASƏ**

Biz sabit bircins maqnit sahəsində kifayət qədər aşağı enerjili neytrinoların eninə polyarlaşmış elektronlardan səpilməsini tədqiq edirik. Baxılan proseslər üçün diferensial ehtimalı və səpilən neytrinoların orta enerjisini hesablayırıq. Müəyyən edilmişdir ki, $500-600\,QeV$ enerjiyə qədər sürətlənmiş ultrarelativistik elektronlar kifayət qədər güclü daxili elektrostatik sahəyə malik olan monokristaldan onun kristal oxu və ya müstəvisi boyunca keçdikdə, monokristalın xarici effektiv maqnit sahəsinin aşağı enerjili neytrino-elektron səpilməsinə təsiri əhəmiyyətli dərəcədə olur və bu, çox aşağı enerjili neytrinoların, o cümlədən kosmik relikt neytrinoların enerjisinin $\sim 10^2 QeV$ enerjiyə qədər artmasına gətirib çıxarır. Çox aşağı enerjili neytrinoların, o cümlədən kosmik relikt neytrinoların enerjisinin $\sim 10^2 QeV$ enerjiyə qədər gücləndirilməsinin mümkünlüyü neytrinolar vasitəsilə enerjinin Günəş sistemində və ya ondan kənarda (yəni bizim Qalaktikamızda və kənar qalaktikalarda) $R \gtrsim 10^9 km$ məsafələrə ötürülməsini həyata keçirməyə imkan verir.

Professor **Vali Allahverdi Huseynov** is the head of the Laboratory for Physics of Cosmic Ray Sources of the Institute of Physics, Baku, Azerbaijan, graduated from the Lomonosov Moscow State University (MSU), has a PhD from the MSU and Doctor of physical and mathematical sciences from the Baku State University. Prof. Huseynov is the Correspondent Member of the Azerbaijan National Academy of Sciences and is a specialist on Theoretical Particle Physics and Astrophysics. He investigates the lepton processes with participation of neutrinos and antineutrinos in an external magnetic field, the spin asymmetries, the polarization and field effects arising in these processes. The new theoretical methods suggested by him enable the experimentalists to detect neutrinos and antineutrinos and to distinguish their flavours. The scientific results obtained by Prof. Huseynov enable astrophysicists to explain a number of possible reasons for the positron excess encountered in the structure of cosmic rays. His recent investigations are devoted to the questions connected with the cosmic rays, amplification of neutrino (antineutrino) energy and detection of relic neutrino background.

Associate Professor **Rasmiyya Eldar Gasimova** is a leading researcher at the Department of Theoretical Astrophysics and Cosmology of the Shamakhy Astrophysical Observatory, Baku, Azerbaijan. She has a PhD degree from the Baku State University and is a specialist on Theoretical Physics and Astrophysics. She investigates electroweak processes with participation of neutrinos (antineutrinos) and polarized charged leptons proceeding in the magnetized media like neutron stars, magnetars, white dwarfs, supernovae etc. Her recent investigations are devoted to the questions connected with the cosmic rays, amplification of neutrino (antineutrino) energy and detection of relic neutrino background.

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# CONCEPTUAL MODEL OF A NANOSATELLITE WITH LASER BEAM TRANSMISSION AND ITS IMPORTANCE IN RENEWABLE ELECTRICAL POWER HARVESTING

**Mehman H. HASANOV, Nadir A. ATAYEV**

## ABSTRACT

The concept of placing huge solar-powered satellite systems (SPS) in space represents one of several new technology options that could provide large-scale, green base power to terrestrial markets. NASA has already launched the multi-megawatt SSP systems and wireless power transmission (WPT) for government missions and commercial markets (in space and on the ground). As a result, an initial conceptual model of the new generation low earth orbit nanosatellite with solar power harvesting to laser beam conversion and transmission sub-system was developed with an estimated solar radiation harvesting calculus, part selection along with the structural scheme and its working principle have been proposed.

**Keywords:** Solar-powered satellite systems (SPS), Nanosatellite, CubeSat, System, Space.

# КОНЦЕПТУАЛЬНАЯ МОДЕЛЬ НАНОСПУТНИКА С ЛАЗЕРНОЙ ПЕРЕДАЧЕЙ И ЕЕ ЗНАЧЕНИЕ ДЛЯ СБОРА ВОЗОБНОВЛЯЕМОЙ ЭЛЕКТРОЭНЕРГИИ

**Мехман Х. ГАСАНОВ, Надир А. АТАЕВ**

## АБСТРАКТ

Концепция размещения в космосе огромных спутниковых систем, работающих на солнечной энергии (SPS), представляет собой один из нескольких вариантов новых технологий, которые могут обеспечить крупномасштабную экологически чистую базовую электроэнергию для наземных рынков. НАСА уже запустило многомегаваттные системы SSP и беспроводной передачи энергии (WPT) для правительственных миссий и коммерческих рынков (в космосе и на земле). В результате была разработана первоначальная концептуальная модель низкоорбитального наноспутника нового поколения с подсистемой сбора солнечной энергии для преобразования и передачи лазерного луча с оценочным расчетом сбора солнечного излучения, выбором деталей, а также структурной схемой.

**Ключевые слова:** Спутниковые системы на солнечной энергии (СЭС), наноспутник, CubeSat, система, космос.

## INTRODUCTION

Huge amounts of solar energy are continuously available in outer space in the form of light and heat. Therefore, the use of satellites aimed primarily at collecting solar energy and transmitting it back to Earth is being considered. No need for expensive storage devices when the sun is not visible. Only a few days on the day of the spring and autumn equinoxes, the satellite will be in the shadow. Unused heat is radiated back into space. Energy can be channeled to where it is needed and there is no need to invest in a grid as big as the grid [1].

Electricity makes up the majority of the energy consumed. On the one hand, the main loss of control occurs during transmission from generating stations to end users. Wire resistance in a power distribution system results in a loss of 26% to 30% of the generated power. So the losses mean that our current power transmission system is between 70% and 74% efficient. On the other hand, generation is predominantly based on fossil fuels, which will not last long (say, by 2050).

The solar energy collector converts solar energy into DC electricity. DC to microwave converter. Large antenna array for transmitting microwave power to the ground. A means of receiving energy from the earth is through microwave antennas. The cosmic part will be in free fall, in a vacuum environment, and will not need to support itself against gravity, other than relatively weak tidal loads. The main advantages of SBSP are that they do not pollute the environment, they 100% replacement of fossil fuels shortly, no power lines, overhead lines, and cables since electricity can be sent to a specific point around the world. No air or water pollution is created during generation Figure 1 [4].

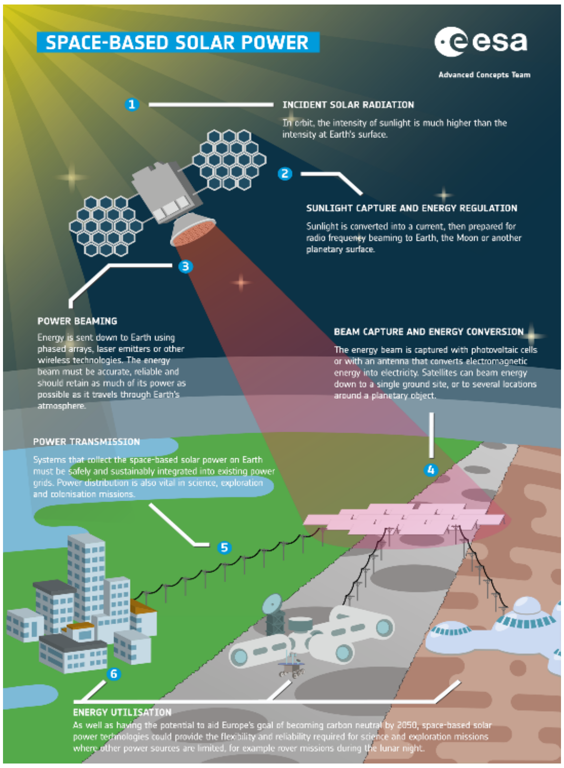


**Fig. 1.** Illustration of Space-Based Solar Power

Looking at the statistics of satellite platforms launched into orbit over the past decade, we can see that Nano Satellite space systems are in high demand compared to other small and mostly large satellite platforms. In short, Nano Satellite platforms mean any 1 kg to 10 kg and 1U (Unit) 10x10x11cm range satellites. The brightest group member of them is CubeSat satellites. The following are the main factors in the high-trend design of CubeSat platforms [1]:

- Relatively low pricing of CubeSat purchase, transport, and launch;

- The possibility to use the off-the-shelf parts;
- The standard-sized shape, size;
- Low level of difficulty with development based on standardized (U) structure, etc.
- With that regard SPS platforms are much more convenient with using Nanosatellite platform representative CubeSat's based on their pros mentioned earlier.

## RESEARCH OBJECTIVES

The initially designed CubeSat prototype model has a structure and functionality designed to perform all the necessary tests and procedures.

As shown in Figure 2, the 2U CubeSat platform consists of a series connection of two electromechanical 1U parts. These include 1 - 2U mechanical subsystem with active and passive components, 2 - Active transponder and data exchange/communication subsystem, 3 - Altitude and position determinant subsystem, 4 - Microcontroller-based on-board computer subsystem, 5 - Electricity generation, power supply, and control subsystem, 6, 7 - Two-plane laser beam optical Nano wave transponder, 8, 9 - Two-plane laser beam controlled 3D optical switch, 10 - Solar panels.

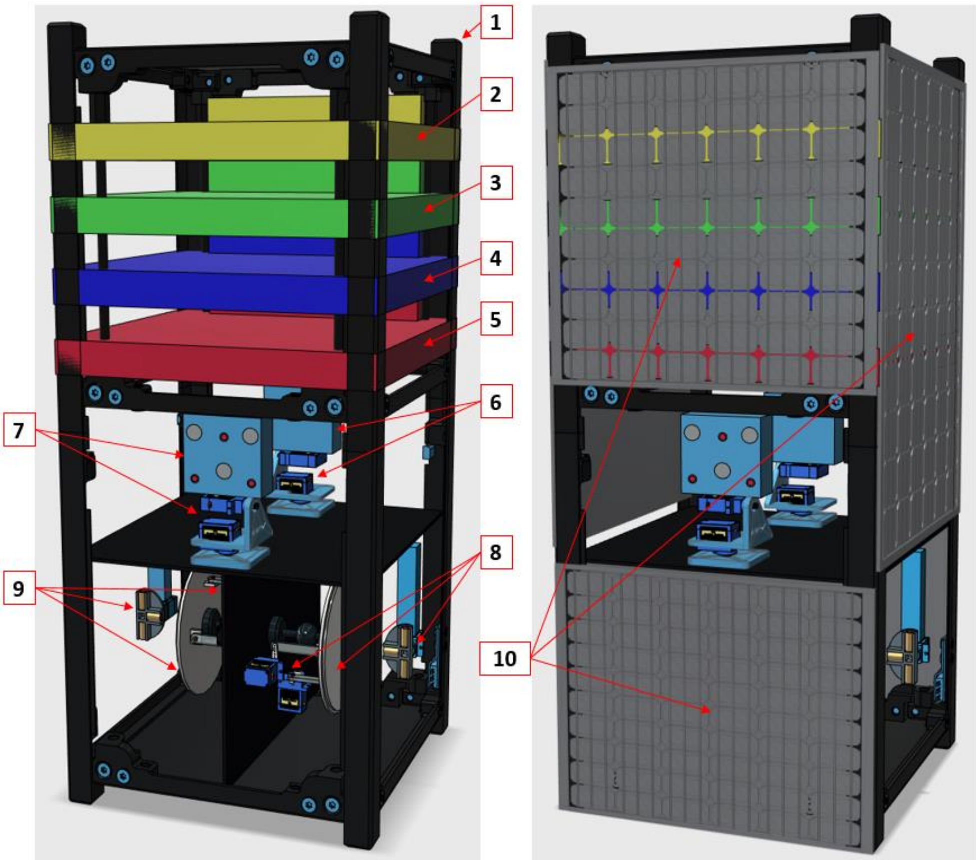


**Fig. 2.** A simplified view of the prototype model of the 2U CubeSat platform.

Figure 3 shows the functional block diagram of the previously presented subsystems of the 2U CubeSat platform. In short, the circuit is divided into two (1U and 2U) subsystems, and the corresponding operating processes can be described as follows.

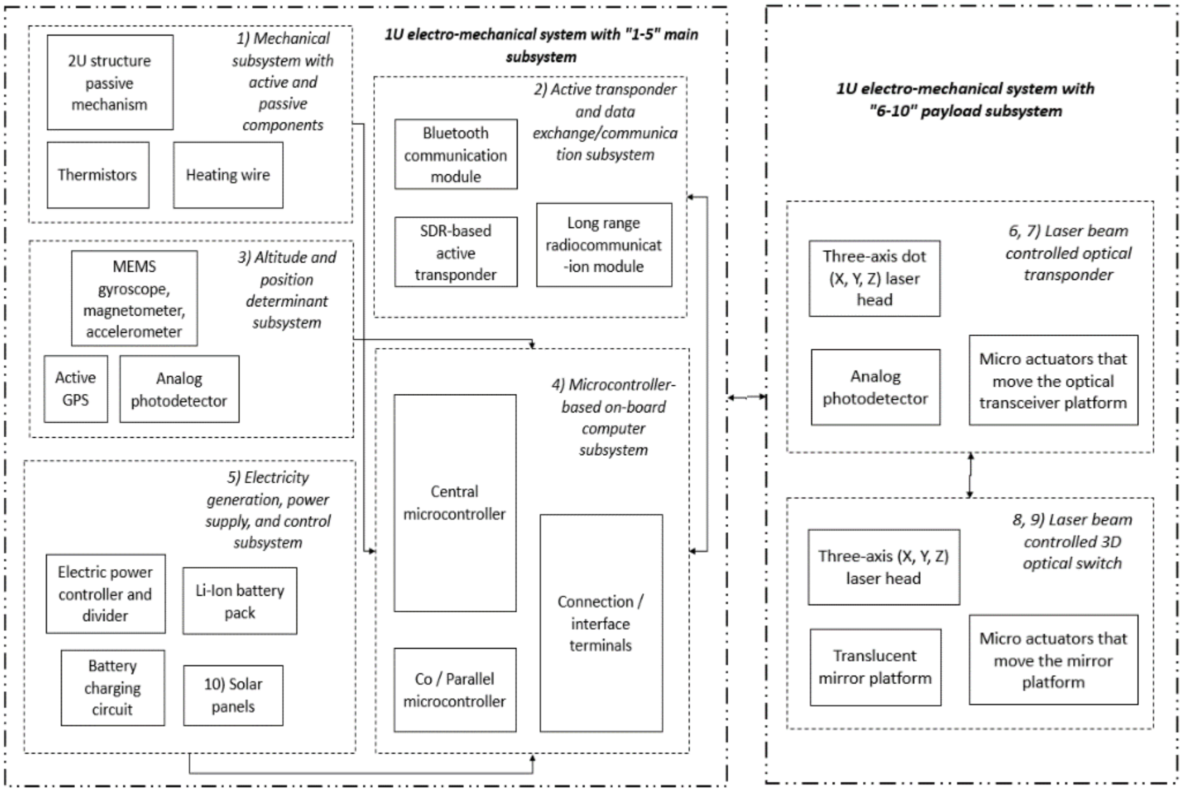


**Fig. 3a and 3b.** 3a Electro-mechanical structural diagram of the first U part of the 2U CubeSat platform; 3b Figure 4. Electro-mechanical structural diagram of the second U part of the 2U CubeSat platform.

A. *Mechanical subsystem with active and passive components*

By providing a secure system structure within a single body, protecting it from external interference sources, determining the internal thermal performance of the platform with thermistors, and ensuring the stability of operation with heating wires.

B. *Active transponder and data exchange/communication subsystem*

As an important communication subsystem of the CubeSat platform, it is equipped with a long-distance radio communication module and a Bluetooth module to perform necessary tests on the desktop. In addition, it is planned to integrate a Software designed Radio (SDR) device due to the active radio transponder functionality of the platform.

C. *Altitude and position determinant subsystem*

A gyroscope, accelerometer sensors, GPS module, and photo detectors were used to determine the platform's position in a free environment and determine the geographical position coordinates.

D. *Microcontroller-based on-board computer subsystem*

It performs the function of central control with an external connection interface/terminal, with functions such as the reading of data packets provided by all subsystems, and execution of appropriate autonomous and managed commands.

E. *Electricity generation, power supply, and control subsystem*

For autonomous power supply of the whole platform, from the second type of solar-electric converter panels "10) Solar panels" from a set of Li-Ion batteries as a constant power source, from these two parts power control and distribution, as well as circuit to charge batteries for desktop tests.

F. *Laser beam-controlled optical transponder and Power generation SA design*

Unlike the active radio communication transponder, and in addition, this optical transponder subsystem consists of a three-axis point (X, Y, Z) laser-headed nanovawe transmitter and microwave directional power transmittion antennas.

## RESULTS

As for the EPS and direct power transmission, the incidence or absence of solar radiation drives the selection criteria for each component, which utilises converted solar energy during the presence of the sun in orbit (light time) and uses batteries to supply power during eclipse periods (shadow time). The amount of power generation depends on the available energy at the observation location. The total solar irradiance at 1AU distance between sun and earth could harvest up to ~1353 $W/m^2$ of electrical power by solar cells, but this estimation follows geometrically driven with $1/r^2$ so, between sun and moon of 1.003 AU could ideally deliver up to ~1339 $W/m^2$ power generation [6].

For COTS selection some units are known as:

$WSS$ = 1.1$W$ (2.5$V$, 0.44$A$) - power harvesting by one GaInP/GaAs/Ge substrate 30% efficient triple- junction solar cell; $kSP$ = 99% - sun irradiance efficiency between sun and moon; $\eta MPPT$ = 0.85, $\eta REG$ = 0.85, $\eta SW$ = 0.95, $\eta BAT$ = 1 – various power generation and conversion efficiency by each power parts; $Torbit$ = 2.64$h$.

After determining load power consumption of $Pload$ = 30 $W/h$ (with worst case margin) period durations of the worst case at ~30% of light and shadow times can be determined as [5],

$$T_{shadow} = T_{orbit} * 30\% = 0.79h \tag{1}$$

$$T_{light} = T_{orbit} - T_{shadow} = 1.84 \tag{2}$$

By defining the above orbital change variables, power, capacity, max. Depth of discharge for the battery pack, appropriate solar cell/panel power number, and power can be calculated.

$$P_{SA} = \frac{\frac{1}{T_L*\eta_{MPPT}}*\left(\frac{W_{BAT}}{\eta_{MPPT}}+\frac{P_{Load}*T_L}{\eta_{Reg}*\eta_{Sw}}\right)}{k_{SP}} = 63.07\ W \tag{3}$$

$$W_{BAT} = \frac{P_{Load}*T_{shadow(h)}}{\eta_{REG}*\eta_{SW}} = 29.4\ W \tag{4}$$

$$C_{BAT} = \frac{W_{BAT}}{3.7V} = 7.9\ A/h \tag{5}$$

$$N_{SS} = \frac{P_{SA}}{W_{SS}} = 57.33\ \approx 60\ W \tag{6}$$

Based on the calculated values, EPS parts including solar cells/panels, Li-ion battery pack, and available

Control/distribution for Battery & Solar panels can be selected, among the available COTS on the market [2].


**Fig. 5.** Functional solar cell configuration schematic in array and panels structure

Besides the above results, there are still some essential points that must be considered for the right choice, which are described below [4, 7]:

*Solar cells/panels:*

- Selected solar panels for both sides of the solar tracking array consist of 2 panels, each having 15 SC. As illustrated in Fig. 1. an array of “1-2” and “3- 4” panels are connected in series (25V, 1.3A, 32.5 W/h) and “1-2; 3-4” connected parallel (25V, 2.6A, 65 W/h) and B array is the same configured as A array but each array rotates in one axes reverse to each other for maximizing solar power harvesting of the CubeSat during different sun incidence and orbit plane changes around the North Pole of the Moon;
- All 4 sides of the satellite has 8 SC, along with zenith, nadir ones having 4 cells. Here 2 cells of each panel are connected in series (5V, 0.45A, 2.25 W/h), and the left cells are connected in parallel for higher capacity. These cells will be used when there sufficient light radiation is hit on them and will get in series contact with A and B arrays generating 30V, 4.4A, and 132 W/h to meet extra maneuver capability which would have been required by propulsion during orbit maneuvering and decommissioning;
- One of the future improvements for sustaining high efficiency and triple junction GaAs SC used on the panels would be to apply a backside coating layer for use in harsh radiated space solar applications.

*Li-ion battery pack:*

- Featuring 135 W/h, 28V electrical, and 0.7U, <815g of mechanical parameters within highly effective and radiation tolerant Li-Ion batteries. Built-in battery interface electronics provide storage inhibits in battery voltage and current fault protections.

*Control/distribution for Battery & Solar panels:*

- The “Ibeos SmallSat Electric Power System” as a battery and solar panels unit and converter.
- Featuring 150 W/h solar panel input power, MPPT system, and different voltage outputs, with additional built-in battery electrical and 0.3U, 140g of mechanical parameters this EPS board is radiation tolerant and fully compatible with a selected battery pack.

G. *Laser beam-controlled 3D optical switch*

As the most important subsystem of the CubeSat platform, this subsystem combines the new application direction of previous scientific and practical research (New Generation 3D Optical Switch).

As a brief recall, the studied 3D optical switch offered three main advantages over other existing optical switches for creating high-speed and efficient communication transitions in optical communication networks [8 - 10]:

- Compact assembly of lenses, depending on the number of beam sources, the arrangement of light sources in one way or another on a 360-degree rotation head, thereby reducing the size, amount of material consumed, and the financial cost of the final device;
- Multiply the switching time of the incoming optical signals by controlling the laser heads in the final device via two high-precision microactuators and by controlling the movement of the translucent mirror in the switching direction;
- Possibility for constant control of the switch and effective diagnostics of the problems through the integrated electronic control and measuring system.

These points will pay for themselves on the designed CubeSat platform, allowing the effective exchange of high-volume and fast optical information between two or more satellites on the level of interlink satellite batch (the inter-satellite link between satellite constellations).

## CONCLUSION

The concept of space solar energy (SCSE) is attractive in that it is much more profitable than ground-based solar energy. Based on current research, space solar power should no longer be viewed as requiring an unimaginably large upfront investment. Moreover, space solar power systems appear to offer many significant environmental benefits over alternative approaches to meeting growing terrestrial energy needs, including the need for a much smaller land area than terrestrial solar power systems.

Such as in this article a new-generation 2U CubeSat satellite platform model prototype was developed, combining the advantages of existing RF and OC communication technologies of the NanoSat satellite system, as well as 3D laser beam control, nanowave transponder, and SDR-based RF active transponder subsystems with a 3D optical switch, and its structural scheme, as well as a simplified working principle, are given.

At the same time, the 2U nano-satellite can harvest up to 60W of renuvable solar irradiance and transmit it in both laser nanowave and microwave with directional active antennas.

A nanosatellite (CubeSat) suitable for a final flight can be developed and sent to low earth orbit (LEO, 1000-2000km) and can be applied in the following areas:

- Ensuring high-volume and high-speed full optical beam data exchange between an orbiting nano-satellite and full-suplex transmittion with GS;
- By establishing SPS platforms with CubeSat constellation the amount of efficent could increase significantly.

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# ENERGY EFFICIENCY – AZEBAIJANIAN EXPERINCE

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**Abstract.** Enhancing energy efficiency creates the basis for the effective implementation of programs for the long-term development of the entire economy, including the energy sector of the Republic of Azerbaijan. The national policy and legal framework of the energy efficiency strategy in the energy complex of the Republic of Azerbaijan are analyzed, as a result of which adequate recommendations are given on the use of energy efficiency potentials.

**Key words:** Energy efficiency, GDP, Energy Intensity, green technology, diversification, distribution, renewable energy sources.

The necessary conditions for enhancing the energy security of Azerbaijan are ensuring the technical availability of energy for a developing economy, keeping the cost of energy within the economic affordability for all consumer groups. [1,2]. One of the important sources of increasing the technical availability of energy are sources that are formed through energy efficiency measures.

Azerbaijan has one of the largest technical energy efficiency potentials in the world, representing more than 30% of energy consumption. In absolute terms, this is roughly estimated at 2 billion cubic meters (1.7 Mtoe) per year [3,4].

The energy efficiency resource should be considered as one of the main energy resources for future economic growth.

Obviously, energy efficiency is one of the strategic directions of science and technology in all countries of the world. This is primarily due to the limited conventional energy resources (CER), the continuous growth of their cost and, finally, global environmental problems. It should be emphasized that energy efficiency is also the most efficient way to increase generating capacity.

Energy efficiency is a complex multi-criterion problem, which can be solved using various organizational, scientific and technical methods.

Energy efficiency must be achieved in different ways. Firstly, it is the reduction of energy losses at all stages of its transformation - from primary sources to end users, it is a breakthrough in technology based on the achievements of scientific and technological progress, the creation of energy-saving equipment and devices, the replacement of obsolete equipment at power plants and power grids with highly economical and environmentally reasonable, as well as more qualified operation of power facilities, improving the quality of their design and building, etc.

Secondly, it is the restructuring of the energy balance through the development of renewable energy sources (RES) - wind, sun, energy of rivers and sea tides, earth heat, biomass, etc.

The redistribution of the components of the energy balances of many regions and entire countries due to the growth in the use of RES is not only the most important direction of energy-efficiency policy, but also plays a significant role in the strategy of curbing climate change, since the production of energy and heat using RES is accompanied by minimal emissions compared to conventional installations into the greenhouse gas atmosphere.

Energy efficiency, as well as the efficient use of energy in general, is not an end in itself, but is aimed at achieving a common economic effect.

It is clear that obtaining the maximum effect from energy-efficiency measures requires the modernization of the energy complex.

As is known, among such CIS states as Russia, Kazakhstan, etc., the Republic of Azerbaijan also belongs to the group of rapidly developing and self-sufficient countries in terms of energy resources (Fig 1). Therefore, in order to maintain the annual GDP growth in the Country, new efficient elements of electricity production and transmission are needed in combination with the implementation of appropriate energy-saving measures.

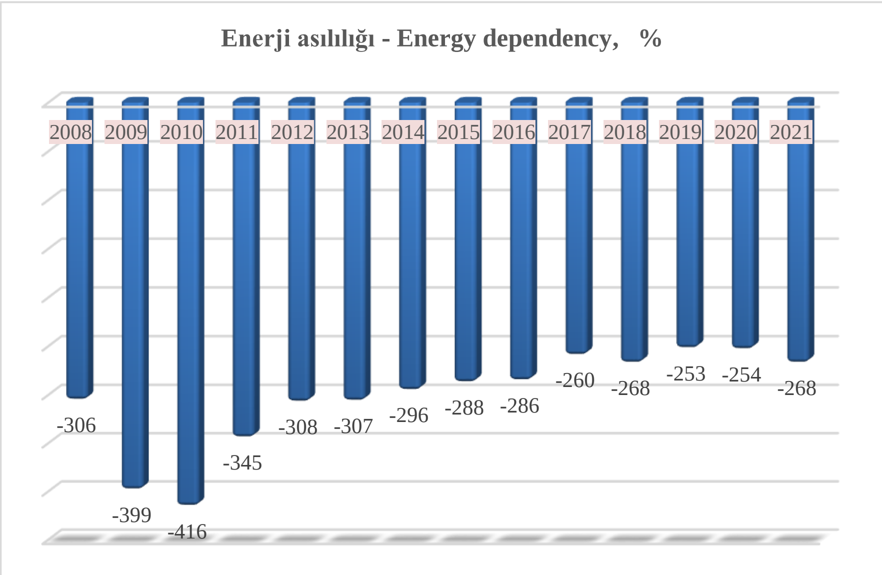


Figure 1.

It is also known that the cost of saving 1 kW of energy is several times (4-5) cheaper than the cost of one newly installed.

The economy of Azerbaijan has entered a phase of sustainable economic development. Behind the crisis and the post-crisis period of recovery. In recent years, there has been a positive trend in macroeconomic indicators (Fig. 2).

Since the oil crisis 2015 the government of Azerbaijan has been making a lot of efforts to develop its non-oil sector that resulted in the increase of non-oil-gas share of economy in GDP from 38% in 2008 to 58 % in 2021. In 2021, Azerbaijan's GDP grew by 5.6 %, while the non-oil sector recorded a 7.6 % increase [5].

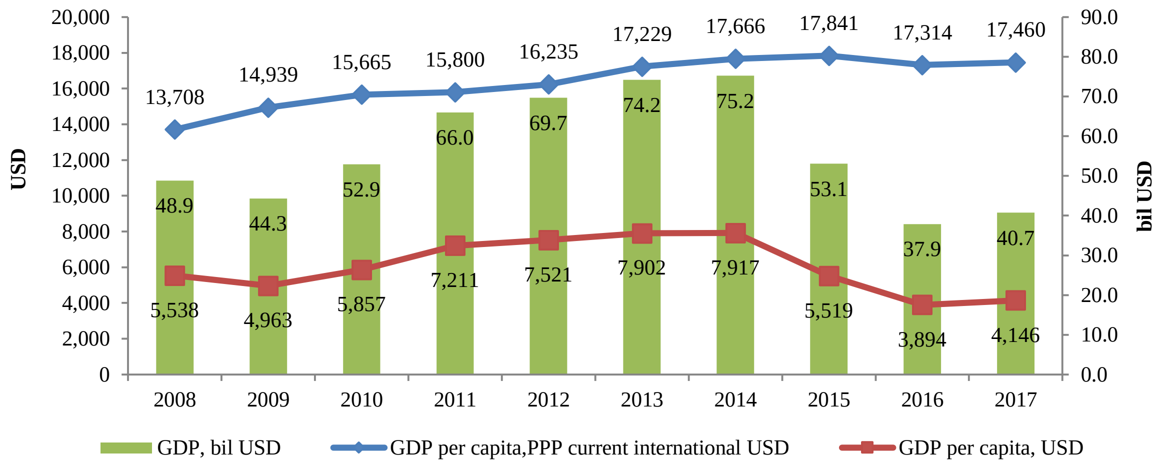


Figure 1. Dynamics of GDP (bil USD) and GDP per capita (USD) in 2008-2017 [6]

Due to energy-saving measures, positive dynamics also takes place in other macro indicators: energy intensity (Fig. 2).

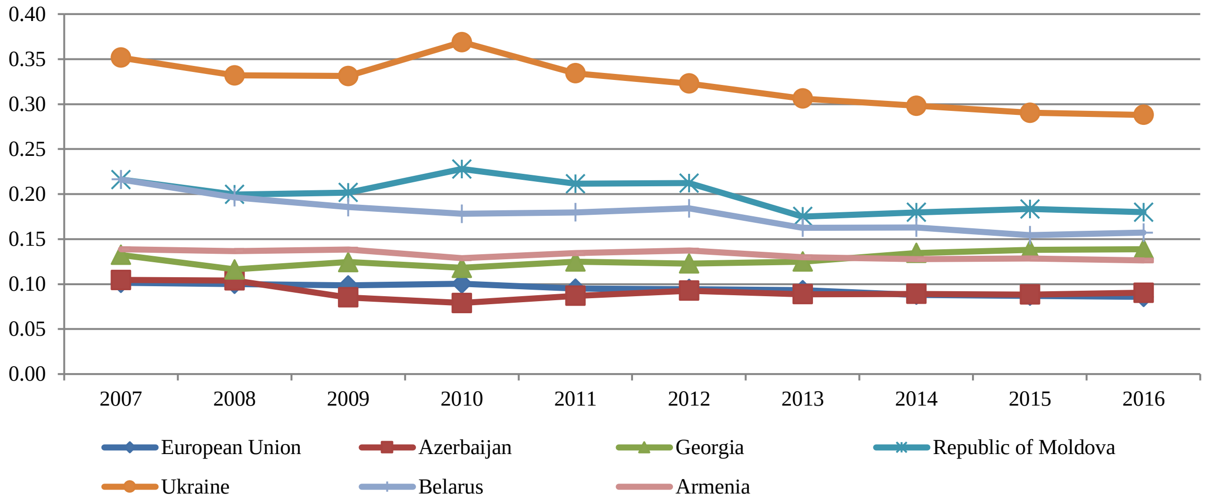


Figure 2. Energy Intensity – TPES/GDP, 2007-2016, toe per thousand 2011 USD PPP [6]

The energy intensity of Azerbaijan decreased by 14% or from 0.105 to 0.090 tonnes of oil equivalent (toe) per thousand 2011 USD PPP during 2007–2016 and followed almost the same dynamics as the energy intensity of the EU (Fig 2) [7].

As can be seen, all indicators indicating the degree of efficiency of the economy and the efficiency of the use of energy resources, including electricity tends to decrease.

At the same time, energy intensity analysis alone does not reflect the overall performance of a country. Figure is depicted in the figure //// compares per capita energy consumption (Fig…). Thus, despite that the energy intensity of Azerbaijan is almost at the same level as in the EU, the average consumption per capita in the 28 EU countries in 2021 was 2.1 times higher than in Azerbaijan. [8].

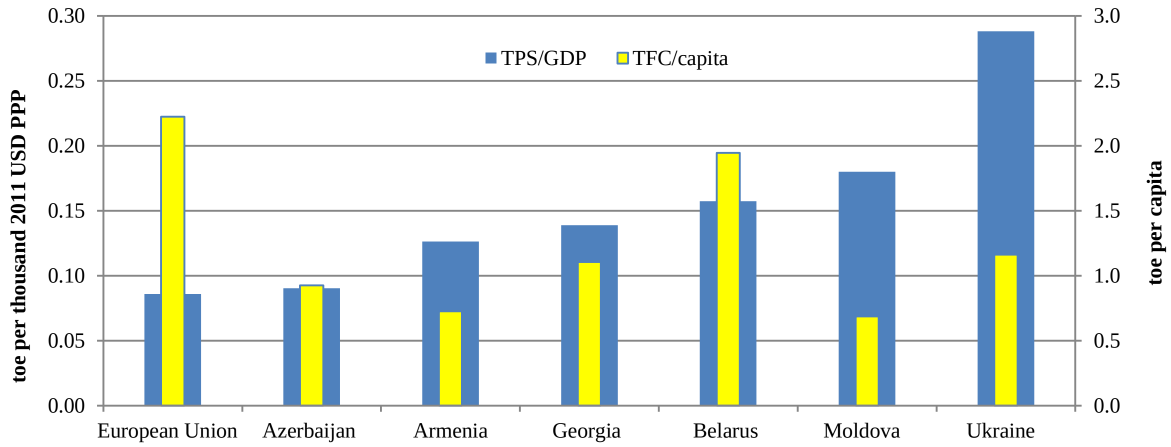


Figure 3. Comparison of energy intensity and TFC per capita in Eastern Partnership countries and the EU in 2016 [7]

The total primary energy supply (TPES) in Azerbaijan has slightly increased 6.5% from 14,495 ktoe in 2008 to more than 16 ktoe in 2011 (Fig. 4). Liquid and gaseous fuels are forming 98% of the TPES.

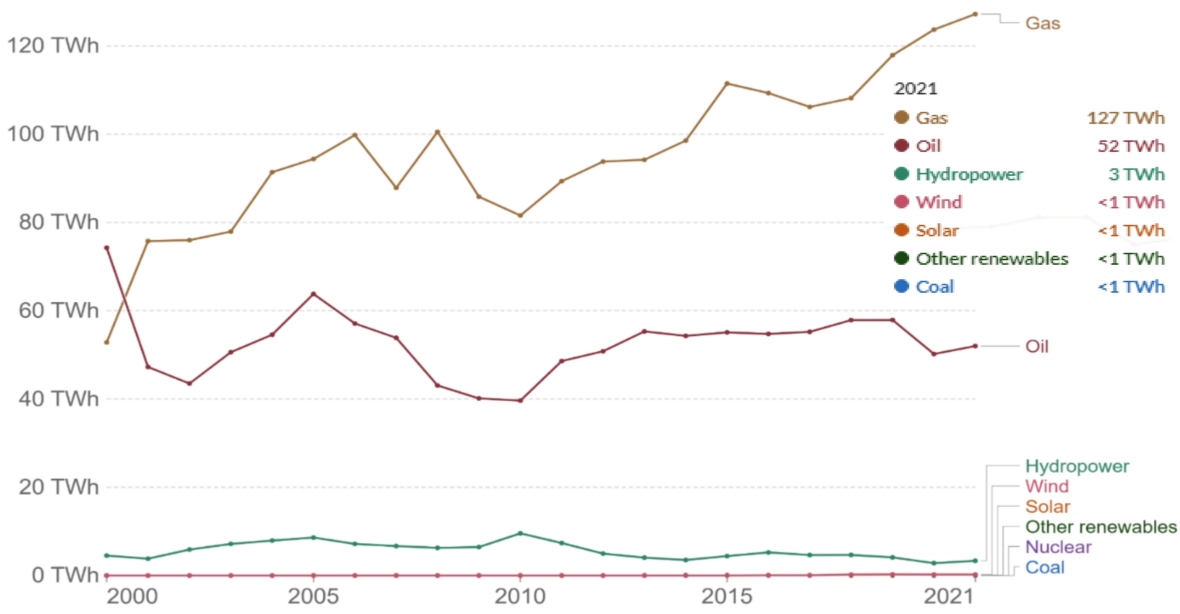


Figure 4. Total primary energy consumption by source [9]

The total final consumption (TFC) of Azerbaijan has increased by 12% over the last decade (Fig. 5). During 2008-2017 the highest growth of energy consumption was recorded in non energy use and transport sectors and resulted in 68% and 56% increase, correspondingly. Consumption in services increased by 48% and in agriculture sector by 42%. While, the energy consumption decreased by 27% in industry and by 9% in household sector. The residential and transport sectors were the dominant energy consumers for the last decade and in 2017, their TFC shares were of 37% and 28%, respectively.

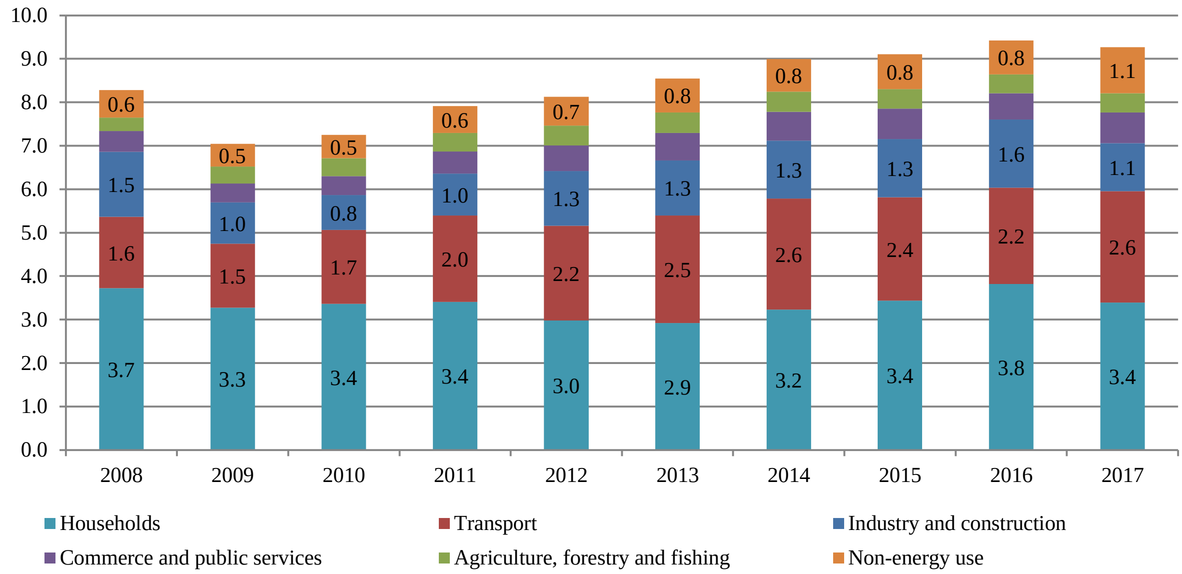


Figure 5. Total final consumption by sectors, 2008–2017, Mtoe [9]

Similar trends can be observed when analysing the final electricity consumption. Meanwhile substantial changes occurred in the electricity consumption by three major sectors over the last decade:

- In total household’s sector consumptions went down by 6,9 % during 2008-2021;
- In total the consumption by commerce and public sector increased by 55,3 % during 2008-2021;
- The consumption by industry and construction sector increased by 66,5 %;
- The energy industries own use increased by 3,6 % during 2008-2021.

Under these conditions, the electric power industry is subject to the highest requirements for all components of energy efficiency: efficiency, environmental friendliness, reliability.

The strategy of the State of the electric power grid (PG) is reflected in a number of State Programs and Documents, which not only ensure the energy balance at certain stages of economic development (2005-2010-2015-2020), but also take into account the criteria and principles that meet the requirement of energy efficiency.

It is known that one of the most important principles that ensure the efficiency of the development and functioning of PG in modern conditions is the principle of diversification.

Even before 2000, there were functioning only two types of energy generating plants in the PG – Steam (ST) and Hydro turbines (HT), and more than 80% - ST with an efficiency factor of about 32 %. As of the end of 2021, the total installed capacity of the country was 7,965 GW including the following:

- Electric and CHP plants working with fuel - 6,649 GW (+3.9 GW during 2000–2021);
- Renewables - 1,316 GW (+81.4 GW during 2008–2021);

The principle of distributed generation, which makes it possible to bring electricity to the end consumer in the shortest possible way, with construction in a short time, was reflected in a special State Decree, in accordance with which, in the short term of 2006-2009, 6 power plants with a total capacity of 860 MW were built, based on 34SG gas-fueled engines and 50DF dual-fuel generating sets (Wärtsilä), and located in various regions of the republic [10-12].

Along with this, in the period 2018-2021, the reconstruction of the old 300 MW blocks of Azerbaijan TPP and Mingecheur HPPs with their capacity increased to 2640 (against 2400) and 420 (against 360) MW, respectively, a number of uneconomical, outdated capacities have been decommissioned, and at the same time, positive development dynamics has been maintained.

At the end of 2022, there are no more energy blocks with worn-out and uneconomical equipment with a high specific fuel consumption in the power system.

The implementation of the strategy has led to an improvement in the technical and economic indicators, as well as indicators of the energy security of the system.

The efficiency of the power plant increased from 30% in 2008 to 47% in 2021, the specific fuel consumption over that period decreased from 400 to 260 g/kWh, losses in the electrical network from 15 to 8.1%. A number of indicators of energy security and environmental friendliness indicators have also received positive dynamics.

For the first time in 2007, a positive balance (export) of electrical energy appeared.

Thanks to the implemented projects, the energy system is already redundant and ready, as before, to play a dominant role in the South Caucasus region. The export potential of the Azerbaijan Power Plant today is 4-5 billion kWh and will increase by another 2-3 billion kWh in the near future.

It should be noted that the export potential of the Azerbaijan PG was formed due, on the one hand, to the commissioning and modernization of generating capacities, and on the other hand, the introduction of energy-saving measures in the consumer sector.

One of the priority areas of development to improve the energy efficiency of the energy system, the Republic of Azerbaijan considers the expansion of interstate power lines with the PG of neighboring states (Fig. 6).

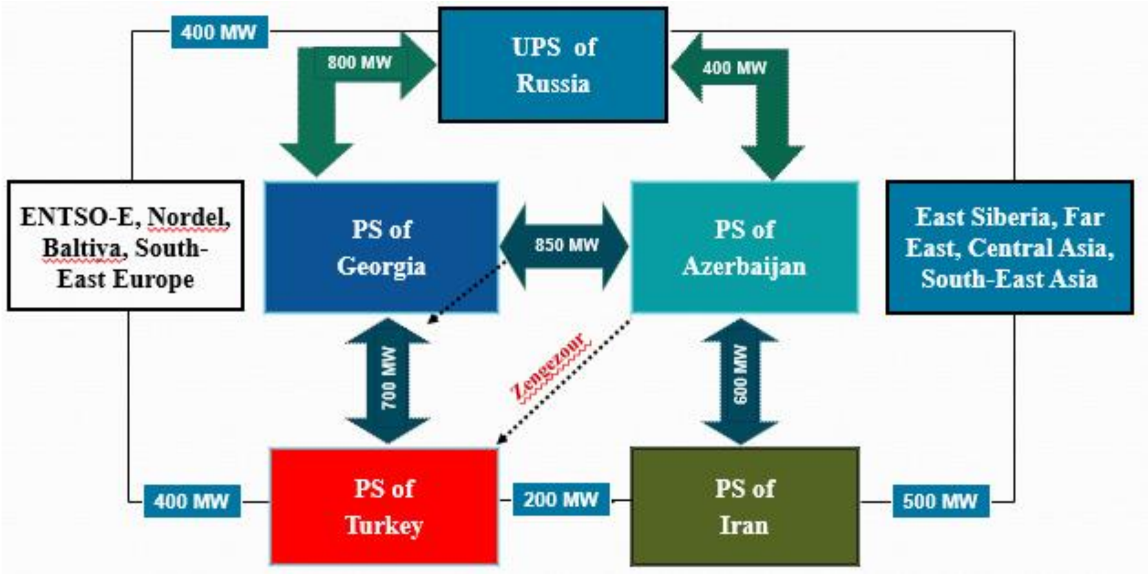


Figure 6. **Block diagram of the interstate links [13]**

Commissioning of the substation "Khachmaz" with a voltage of 330/110 kV in the north of Azerbaijan with the "entry-exit" of the interstate line 330 kV Derbent, significantly improved the reliability of the energy modes of transit "Russia-Dagenergo-Azerbaijan’s PG".

In the southern direction, the commissioning of substations and power lines of 330 and 220 kV (with a total length of about 340 km) created the technical possibility of increasing energy exchange between Iran and Azerbaijan from 240 to 600 MW with an annual volume of about 4 billion kWh electricity.

One of the important projects, the implementation of which not only provided significant economic benefits, but also raised the power industry of the countries of the region to a qualitatively new level, can be called the project of large-scale export of electricity from the Republic of Azerbaijan to Turkey "Azerbaijan-Georgia-Turkey energy bridge". The growth rate of the electric power complex in the Republic of Azerbaijan may allow the export of electricity to Turkey in the amount of up to 3.5-4.0 billion kWh per year with the capacity of 600-700 MW [14-15].

At present, after the liberation of the part of the Azerbaijani territories occupied by Armenians, the construction of a high voltage power line (330/400 kV) in the Zangezur corridor has been updated, which will ensure the synchronous operation of the entire system of Azerbaijan, as well as increase the export potential of electricity to Turkey, for further transmission to European countries.

An important factor in energy efficiency and an element in the development of the electric power industry, as noted above, is the utilize of renewable energy sources. This type of energy resources in the Republic has been sufficiently studied, namely, the potential of solar energy, wind energy and small hydropower plants. The economic potential of small HPPs, which can be included in the power balance until 2025, is 4.5-5 billion kWh, about the same from solar and wind power plants. Currently, the construction of solar and wind power plants has begun with an installed capacity of almost 500 MW and active work on the feasibility study and preparation of design of new capacities [10].

The foregoing indicates a lot of work to develop the PG in the republic, increase its energy efficiency in terms of economy and environmental friendliness.

Meanwhile, it is necessary to note that, there is no National Energy Efficiency Action Plan (NEEAP) in Azerbaijan. However, adopted (President degree dated 20 August 2021 under No. 1433) the new Law on Energy Efficiency (EE) is required the development of a five-year NEEAP. İn 2015, there were also attempts to develop state EE programmers, but neither document was adopted. The Law on Energy Efficiency defines the following main objectives of the state policy in the field of energy efficiency and energy saving:

- Ensuring the reliability and security of the energy system of the Republic of Azerbaijan;
- Ensuring competitive economic development through efficient use of energy resources;
- creating an enabling environment conducive to the efficient use of energy resources, promoting investment in energy efficiency measures and high-performance technologies;
- Strengthening the interaction between producers, transmission, transport, distribution, suppliers and consumers of electricity, as well as state bodies (institutions) and local governments.

The results in terms of practical energy saving and energy efficiency increase largely depend on the activities of the executive authorities of the Azerbaijan Republic.

The institutional framework for energy efficiency includes multiple stakeholders and the Ministry of Energy is the leading responsible authority for the development and implementation of energy policies related to energy efficiency, renewable energy and environmental protection. However, there is a lack of coordination of EE-related activities in industry, buildings and transport sectors.

## Conclusion

1. Accelerate the development and approval of a long-term energy strategy. Such a strategy should include ambitious but realistic long-term quantitative targets and achievable energy efficiency and demand management targets, and should recognize the principle of "Energy Efficiency First" as a priority to meet and reduce future energy demand, increase energy export revenues. and other benefits from achieving long-term EE goals.
2. Prioritize the approval of the draft EE law and the timely adoption of the NEEAP and other legislative acts envisaged by the law. Continue ongoing efforts on the development of an energy-related legislative framework according to the Presidential Decree on “The Acceleration of Reforms in the Energy Sector of Azerbaijan”.
3. Establish a clear baseline, management information and benchmarking system in the EE field.
4. Conduct further reforms supporting functional unbundling and the development of electricity market, taking into consideration EE. Introduce competition in the electricity generation market and develop an efficient regulatory framework, incentivizing optimal capacity distribution among power plants in Azerbaijan in order to ensure the most reliable and efficient balance of electricity demand and supply.
5. Prioritize the reduction of specific fuel consumption and power plants’ own use. Introduce incentives for the management and the staff of the plant to improve overall plant efficiency and reduce fuel consumption. Increase transparency and regularly publish data on key performance indicators of the power-generating sector.
6. Introduce specific long-term targets aimed at improving the efficiency of energy transformation, the reduction of losses in electricity, natural gas and heat networks.

7. Enhance the procurement of renewable energy.
8. Develop and implement a grid (connection) code with standards for variable renewable energy integration.
9. Azerbaijan still has a sizable energy subsidy system in place. The cost of the energy subsidy was equivalent to almost 3.4% of GDP in 2016, with an average energy subsidy estimated at USD 130 per capita. The total value of subsidies almost doubled in the period between 2014 and 2016 from USD 751 million to USD 1 269 million. In 2015 and 2016, more than half of the subsidies were provided to the electricity sector through support to oil and gas energy sources, while subsidies to renewable energy were negligible.
10. Maintain efforts to improve national energy statistics.

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# Estimation of critical parameters of the states of the power system with renewable energy sources at random shutdowns of its main elements

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The paper proposes a method and algorithm for estimating the maximum, according to the conditions of voltage stability, the limit of transmitted power in a power system with renewable energy sources (RES) in case of random failures of its main elements (power lines and generating plants). The method is based on the analysis of the weighted states of the system, created by increasing the power values of sources (generators of power plants). The model of the state of the system in limiting modes is described in the form of dependences of the maximum transmitted power on the values of the generation powers. The effectiveness of the method is being investigated on IEEE test circuits.

**Keywords:** power system, renewable energy sources, voltage stability, limit of transmitted power, random failure of power system elements.

## Оценка критических параметров состояний энергосистемы с возобновляемыми источниками энергии при случайных отключениях ее основных элементов

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В работе предложен метод и алгоритм оценки максимального, по условиям устойчивости напряжения предела передаваемой мощности в энергосистеме с возобновляемыми источниками энергии (ВИЭ) при случайных отказах ее основных элементов (линии электропередачи и генерирующих установок). Метод основан на анализе утяжеляемых состояний системы, создаваемых путем увеличения величин мощностей источников (генераторов электростанций). Модель состояния системы в предельных режимах описывается в виде зависимостей предельной передаваемой мощности от величин мощностей генерации. Эффективность метода исследуется на тестовых схемах IEEE.

**Ключевые слова:** энергосистема, возобновляемые источники энергии, устойчивость по напряжению, предел передаваемой мощности, случайный отказ элементов энергосистемы.

## Bərpaolunan enerji mənbəli enerjisistemin əsas elementlərinin təsadüfi açılmaları zamanı onun kritik vəziyyət parametrlərinin qiymətləndirilməsi

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Məqalədə bərpa olunan enerji mənbələri (RES) olan enerjisistemdə onun əsas elementlərinin (elektrik veriliş xətləri və generasiya qurğuları) təsadüfi imtinaları halında, gərginliyin dayanıqlılıq şərtlərinə uyğun olaraq, ötürülən gücün maksimal həddini qiymətləndirmək üçün üsul və alqoritm təklif olunur. Üsul, mənbələrin (elektrik stansiyalarının generatorları) güclərinin qiymətlərinin artırılması yolu ilə yaradılan sistemin ağırlaşdırılmış vəziyyətlərinin analizinə əsaslanır. Sərhəd rejimlərində sistemin vəziyyətinin modeli sərhəd ötürülən gücün generasiya güclərinin dəyərlərindən asılılığı şəklində təsvir edilmişdir. Üsulun effektivliyi IEEE test sxemlərində tədqiq olunur.

**Açar sözlər:** enerjisistem, bərpaolunan enerji mənbələri, gərginliyə görə dayanıqlıq, ötürülən güc həddi, enerjisistemin elementlərinin təsadüfi imtinası.

## Introduction

In recent years, emergency shutdowns (failures) of their main elements - generating units, power lines and transformers - have occurred in modern energy systems, as a result of limited opportunities for the transit of large capacities through transmission networks, lack of generation capacity, equipment wear and the impact of other factors. During frequent failures of these components, especially in maximum consumption modes, it leads the power system with RES to a state close to the border of voltage stability violation, and the subsequent state can lead to a complete “blackout” of its most part [1-3]. Taking into account the formed existing state of the power system with RES and frequent emergency failures of its elements, there is a need to tighten the requirements for ensuring voltage stability.

Other important factors leading to the violation of voltage stability are the configuration of the electrical system, the characteristics of RES, other generating devices and loads.

The practical implementation of a large number of proposed methods for determining the limit of static stability of an electric power system leads to the analysis and control of successive weighting modes of electric networks up to the maximum transmitting power. Typically, weighting is done by controlling the power generated by the generators or the power consumed by the loads.

In the paper under consideration, a method is proposed for weighting the regime to the optimal critical value using the source model. The proposed methodology makes it possible to determine the load limit as a function of the generation power change. This method creates the possibility of reaching the network load limit with the participation of all generating sources in the process of mode weighting.

## 1. Methods of weighting the system mode with an increase in the power consumed by the loads

The essence of these methods is to identify the share of each source for a given increase in load and cover the losses that occurred during the transmission of this power through the electrical network. For example, $K_{Gi}$ is an indicator of the growth of the generated active power of the $i-$th generator, and $P_{Gi,0}$ is the base (nominal) generated power of this source. In this case, $P_{Gi}$ the generation power at the point following the increase in power will be as follows:

$$P_{Gi} = P_{Gi,0}(1 + K_{Gi}), \quad i = 1,2,...,n \qquad (1)$$

The value $K_{Gi}$ indicates the degree of participation of the $i-$th generator in violation of the voltage stability limit. Below is an analysis of existing methods to determine the number of generators involved in maintaining voltage stability.

*Traditional approach.* Usually in the system, generation, as in the case of planning in accordance with the existing reserve of rotation, exceeds the specified value [4]. After increasing the load, the power of the $i-$th generator can be represented as follows:

$$P_{Gi} = P_{Gi,0}\left(1 + K_{Gi}\right) = P_{Gi,0} + \Delta P_{Gi} \tag{2}$$

$$\sum_{N} \Delta P_{Gi} = \Delta P_D + \Delta P_n \tag{3}$$

where $P_{Gi}$ – is the generated power of the generator $i$; $P_{Gi,0}$ – $i-$th generator power at rated load; $\Delta P_{Gi}$ – increase in the power of the $i-$th generator; $\Delta P_D$ – load increase; $\Delta P_n$ – increase in power loss; $N$ – number of generators.

*Method for selecting the limiting voltage value in the electrical networks of the power system.* This method allows you to determine the maximum value of the weighting - the load limit, as a function of the active powers of the generating units. The practical implementation of this method can be carried out in the following three stages:

1st stage. The dependence of the load limit $P_{H\max}$ is determined depending on the magnitude of the increase in the power of each generator. Not taking into account the basic, boundary value of the load is determined by the curves $P-U$ built for a series of corresponding generators $P_{Gi}$. Then the dependency curve $P_{H\max}(P_{Gi})$ is approximated as the following polynomial [5]:

$$P_{HM(j)} = B_{j,0} + B_{j,1}P_{G,j} + \ldots + B_{j,n}P_{G,j}^{n} = B_{j,0} + \sum_{p=1}^{n} B_{j,p}P_{G,j}^{p} = B_0 + P_{Hm1j} \tag{4}$$

where $P_{HM(j)}$ – the polynomial approximating the curve $P_{HM}$ in the case of two generators (basic generator and another generator associated with the node $j$; $B_{ij}$ – are the coefficients of the approximating polynomial; $n-$ the number of coefficients; $P_{HM1}-$ if the constant (constant) $B_0$ is not taken into account, is equal to $P_{HM}$.

2nd stage. The surface $P_{H\max}$, approximated for the multidimensional case (the case when more than 2 generating units are involved in maximizing the load limit of the network), was based on the condition of possible division. In the case of participation of all units, $P_{H\max}$ it is determined by the following formula:

$$P_{H\max} = B_0 + \sum P_{H\max 1j} \tag{5}$$

Equation (5) describes the surface $P_{H\max}$ for all possible generators that exist in the power system. Data for this can be obtained from combinations of all polynomial equations in the form (4).

3rd stage. The last step of the proposed method consists of determining the best vector $P_{G,i}$ providing the best surface value $P_{H\max}$. This value can be determined by maximizing expression (5) within the following limits:

$$\sum P_{Gj} = 1, \quad 0 \le P_{Gj} \le 1$$

Research at the first stage, consisting of determining the dependence of the transmitted power limit $P_{np}$ on the amount of generated power of each generator for the cases of the most probable emergency failures of individual elements of the system, is carried out using an industrial calculation program for the existing probabilistic power distribution.

Thus, when carrying out computational experiments, for each case of an emergency failure "$j$", one can obtain a series of dependences $P_{np}^{j}$ on the power of an individual $i-$th generator $P_{Gi}^{j}$:

$$P_{np}^{j} = F\left(P_{Gi}^{j}\right) = b_0^j + \sum P_{np} \tag{6}$$

For each case of an emergency failure, the global maximum of the parameter $P_{np}^{j}$, reflecting the effect of changing the powers of all sources on $P_{np}^{j}$, is determined by the extreme value of the function (6). To do this, you can use one of the traditional methods.

**2. Оценка максимального предела устойчивости системы при различных состояниях элементов сети и генерирующего агрегата**

2. Estimation of the maximum stability limit of the system for various states of the network elements and the generating unit

In accordance with the proposed method, the limiting state of the system is estimated until the maximum of the curve $P-U$ is reached for various values of the increase in load and power of generating sources. The size of the spatial state of the system in power coordinates is determined by the number of sources selected for the operational dispatch control of the power system. The number of sources involved in operational control for the 14-node IEEE test circuit is 4. First, the effect of 2, 3, and 4 generators in series on voltage stability is investigated. The powers of the sources connected to nodes 1, 2, 3, 8 are 150, 78, 40 and 40 MW, respectively, and the total power consumption is 260 MW.

In dual oscillator control, the simulation considered paired oscillators associated with the following buses: 1 and 2 (G1-2), 1 and 6 (G1-6), 1 and 8 (G1-8). In all variants under study, the generator connected to bus 1 was taken as a balancing one.

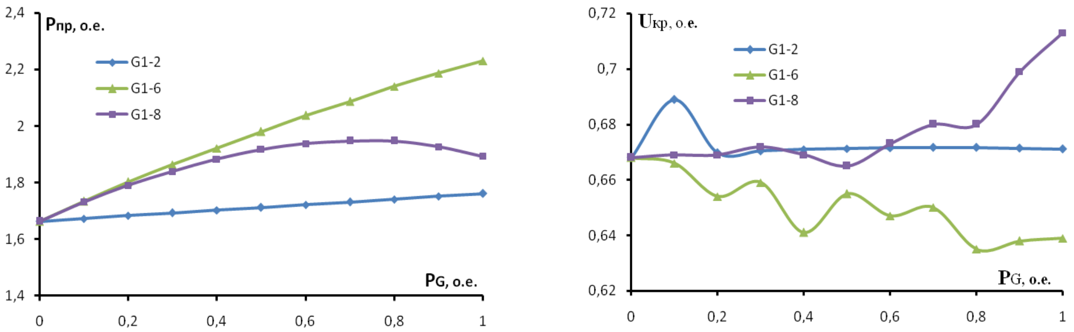
On fig. 1,a shows the characteristic of changing the limit of the transmitted power of the line 1-2. These curves were built on the basis of calculations of the voltage stability limit during the change in the power of generators 2, 6, 8. It should be noted that the overall effect obtained from all pairs of generators is estimated as follows:

$$P_{G,1} + P_{G,2} = 1; \quad P_{G,1} + P_{G,6} = 1; \quad P_{G,1} + P_{G,8} = 1.$$

This means that, for example, if G2 compensates for 20% of the loads, then the balancing source compensates for the remaining 80%. On fig. 1b shows graphs of changes in the critical voltage limits in the cases of the considered pair generators.

As can be seen from Fig. 1, during various pair options of generators involved in power regulation, the boundary parameters ($P_{np}$, $U_{kr}$) have a different pattern of change. Approximating dependencies $\left(P_{np}\right)_i = f\left(P_{G,i}\right)$ are presented in Table 1.

As can be seen from fig. 1, the largest value of the transmitted power limit is formed with an increase in output, respectively, in generators 6 and 8. For example, in the 8th generator, a power increase of only 0.6 (p.u.) can provide a limit to the maximum power in the network.




а) б)

Fig. 1. Curves of changes in the limit of transmitted power (a) and critical voltage for the option of 2 generators dedicated to regulation

Table 1. Coefficients of approximating dependencies $\left(P_{np}\right)_i = f\left(P_{G,i}\right)$

| Coefficients | G1-2 (j=2) | G1-6 (j=6) | G1-8 (j=8) |
|---|---|---|---|
| $b_{j,0}$ | 1,663 | 1,663 | 1,663 |
| $b_{j,1}$ | 0,0984 | 0,6518 | 0,7668 |
| $b_{j,2}$ | -0,0011 | 1,3101 | -0,9968 |
| $b_{j,3}$ | 0,000609 | -9,5352 | 2,3964 |
| $b_{j,4}$ | | 27,3342 | -4,4472 |
| $b_{j,5}$ | | -39,3054 | 3,1079 |
| $b_{j,6}$ | | 27,9063 | -1,1972 |
| $b_{j,7}$ | | -7,7942 | |

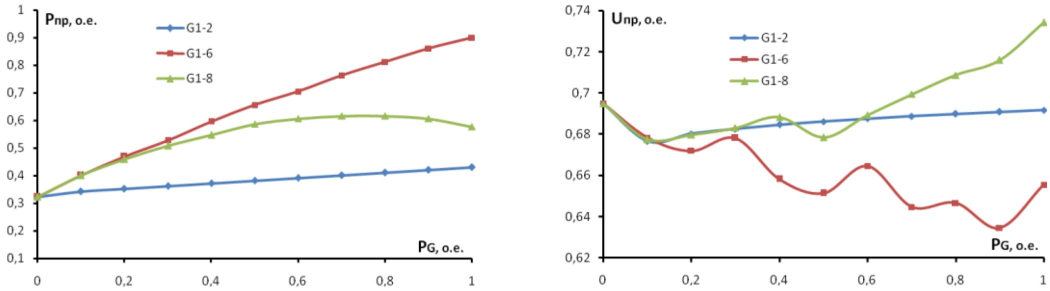
The values of the coefficients of the approximating polynomials, which are given in Table 1, express the curves in Fig. 1 in the following form:

$$P_{np(2)}\left(P_{G,2}\right) = B_0 + \sum_{p=1}^{3} B_{2,p} P_{G,2}^{p}, \quad P_{np(6)}\left(P_{G,6}\right) = B_0 + \sum_{p=1}^{7} B_{6,p} P_{G,6}^{p}, \quad P_{np(8)}\left(P_{G,8}\right) = B_0 + \sum_{p=1}^{6} B_{8,p} P_{G,8}^{p}$$

These polynomials are used to describe the surface of the spatial state of the system in the case of 3 and 4 generators involved for subsequent control of the power balance mode in the system. On fig. 2 shows the curves of changes in the power limit and critical voltage in the system for the options for the participation of paired generators 1-2; 1-6; 1-8 in the regulation of the total load transmission mode in the event of an emergency failure of one of the lines (case N-1).

In the case of a paired generator 1-8, the maximum transmit power limit is reached at $0{,}6P_{np(n-1)}$, which $P_{G,8}=0{,}65$ means that the likely value of the transmit power limit is reduced to $1{,}8P_{np}/0{,}6P_{np(n-1)}=3$. Accordingly, during the failure of one of the lines in the system, the indicators that determine the magnitude of the critical voltage deteriorate. The equations approximating the curves in Figs. 2, and their coefficients are presented in table 2.

$$P^{(2)}_{np(n-1)}=B_0+\sum_{p=1}^{7}B_{2,p}P^{p}_{G,2}\,,\ P^{(6)}_{np(n-1)}=B_0+\sum_{p=1}^{6}B_{6,p}P^{p}_{G,6}\,,\ P^{(8)}_{np(n-1)}=B_0+\sum_{p=1}^{8}B_{8,p}P^{p}_{G,8}$$




a)

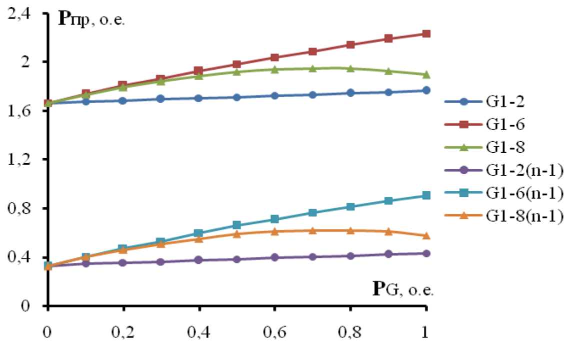
b)

Fig. 2. Change in the limiting state of the system in the case of one control source and emergency failure of one element
a- is the limit of the transmitted power; b-critical stress

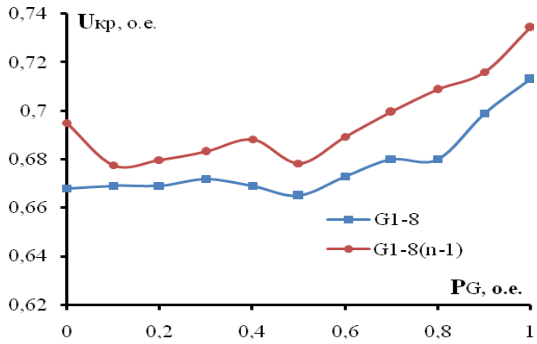
Table 2. Coefficients of approximating dependences in the case control source 2 and emergency failure of one element

| Coefficients | G1-2 (j=2) | G1-6 (j=6) | G1-8 (j=8) |
|---|---|---|---|
| $b_{j,0}$ | 0,3228 | 0,3228 | 0,3228 |
| $b_{j,1}$ | 0,3129 | 0,9175 | 0,9044 |
| $b_{j,2}$ | -1,7408 | -1,18446 | -1,1935 |
| $b_{j,3}$ | 6,9375 | 6,3475 | -1,1513 |
| $b_{j,4}$ | -15,1973 | -11,5674 | 12,9309 |
| $b_{j,5}$ | 18,461 | 10,086 | -28,649 |
| $b_{j,6}$ | -11,6961 | -3,362 | 25,9782 |
| $b_{j,7}$ | 3,0103 | | -8,5654 |

The following analysis was carried out on the basis of the results of computational experiments for the previously considered schemes and modes of the power system, but taking into account emergency failures of lines and sources. On fig. 3 shows the dependence curves and the surface of the limit of the power transmitted from the network in the case of options with a different number of generators involved in power regulation.




a)




б)

Fig. 3. Curves of changes in power limits (a) and critical voltage (b) in cases of regulating source 2 and emergency failure of one element

## CONCLUSIONS

1. Methods of system mode weighting with an increase in load power consumption were studied and it was determined that these methods make it possible to determine the number and power of sources involved in mode weighting, but cannot be used in multi-machine systems.

2. Calculations of the probabilistic power distribution in case of accidental outages of lines and generators were carried out according to standard IEEE schemes. Based on the results of the calculations, deviations of the critical voltage $U_{kr}$ in the nodes and the most critical nodes according to the stability condition were determined by the value of the maximum power flows in the lines $P_{\max}$. The effects of individual random shutdowns on critical parameters $U_{kr,i}$ and $P_{\max,i}$ are determined. The results obtained make it possible to establish rational measures for the operational control of modes and determine the most critical modes in various states of the power system.

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*UOT 536.77:547.442*

# AZƏRBAYCANIN XAÇMAZ RAYONUNUN "XAÇMAZ" TERMAL SUYUNUN (p, ρ, T) XASSƏLƏRİNİN TƏDQİQİ

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## XÜLASƏ

Azərbaycanın Xaçmaz rayonunun "Xaçmaz" termal suyunun (p,ρ,T) xassələrinin tədqiqinin aparıldığı təcrübə laboratoriyası T=293,15 K daimi temperaturda iqlimləşdirilmişdir. Su, toluol və NaCl (m=2,96661 mol·kg$^{-1}$) sulu məhlulu üçün alınmış nəticələrin müxtəlif ədəbiyyatlarda verilmiş məlumatlarla müqayisəsi aparılmışdır. Alınmış nəticələr qrafiki şəkillərdə göstərilmişdir.
***Açar sözlər:*** *sıxlıq, təzyiq, temperatur, termal sular.*

# ИССЛЕДОВАНИЕ (p, ρ, T) СВОЙСТВ ТЕРМАЛЬНОЙ ВОДЫ "ХАЧМАЗ" ХАЧМАЗСКОГО РАЙОНА АЗЕРБАЙДЖАНА.

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## *АННОТАЦИЯ*

*Экспериментальная лабораторная установка, в которой исследуются (p,ρ,T) свойства термальной воды «Хачмаз» Хачмазского района Азербайджана, акклиматизирована при постоянной температуре T=293,15 K. Результаты, полученные для водного раствора воды, толуола и NaCl (m=2,96661 моль•кг$^{-1}$), были сравнены с литературными данными приведенными в различных источниках. Полученные результаты представлены графически на рисунках.*
***Ключевые слова:*** *плотность, давление, температура, термальные воды.*

# THE INVESTIGATION OF THE PROPERTIES OF THERMAL WATER "KHACMAZ" (p, ρ, T) IN KHACMAZ DISTRICT, AZERBAIJAN

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## ABSTRACT.

The experimental laboratory, in which the properties of thermal water "Khachmaz" (p,ρ,T) in Khachmaz district, Azerbaijan were investigated, was air-conditioned at a constant temperature of T=293.15 K. The results obtained for the aqueous solution of water, toluene and NaCl (m=2.96661 mol·kg$^{-1}$) were compared with the data given in various sources. The obtained results are presented graphically in the figures.

***Keywords:*** *density, pressure, temperature, thermal waters.*

## INTRODUCTION.

There are various geothermal technologies in the world with different levels of development, which are widely used in district heating systems, greenhouses and other applications. The technology of generating electricity from naturally high-conductivity hydrothermal tanks is also considered reliable. The majority of the geothermal power plants currently in operation in the world are based on dry steam turbines or "flash" devices (single, double and triple) and are used at 180 °C above hot water sources. Furthermore, new technologies are presently being developed, such as Enhanced Geothermal Systems (EGS)

Another option for a geothermal power plant uses natural geothermal resources, such as, water heated to a high temperature as a result of natural processes. However, the scope of such resources is limited. For example, in Russia, Kamchatka and Caucasian mineral water regions are among them. Otherwise, as a result of high geological pressure, water itself freely rises through a specially dug hole. This is a general operating principle that is applicable to almost all types of geothermal power plants.

Also, the substantial work is being carried out in this direction in Azerbaijan. By decision of the Republic of Azerbaijan dated October 21, 2004, the Ministry of Energy was instructed to ensure the implementation of the provisions of the State Program on "the Use of Alternative and Renewable Energy Sources". The State Program reflects the applications of energy sources that are convenient for our republic in this area, such as the use of wind energy, solar energy, geothermal waters, hydroelectric power of mountain rivers, canals, as well as the use of biomass energy. There are also fundamental possibilities of using the internal heat from the Earth's subsoil. According to the temperature, water or steam-water mixture can be used for hot water supply and heat supply, for the production of electrical energy, or for all of these purposes simultaneously.

High-temperature heat of near-volcano areas and hot dry rocks are preferably used to generate electricity and heat. The potential total operating capacity of global geothermal power plants lags behind that of most other power plants using renewable energy sources. However, the high energy intensity of individual geographical regions where fuel and minerals are not available or relatively expensive, as well as government programs are developing in this direction.

From 1950 to the present, the works of all researchers in Azerbaijan contain a lot of diverse and valuable information about the sources of mineral waters in different regions of the republic. Also, many questions of their formation and genesis are still insufficiently worked out and require in-depth study. This issue depends on solving the problems of prospecting and rational use of hydro-mineral resources. In hydrochemical and hydrodynamic approaches, the transition zone from less mineralized water to saline water, which is of greater interest in terms of the detection of different types of mineral waters, has not been studied yet.

The temperature of the mineral waters of Azerbaijan fluctuates between 4-65$^0$C. This applies only to natural water sources. At the same time, water with a temperature of 95°C is extracted from the bowels of the earth in Azerbaijan.

The investigated thermal waters were taken directly from their exit zones and prepared for experimental purposes by various chemical processing methods. These areas are rich in nitrogen and hydrogen sulfide thermal and cold mineral springs. Sodium (Na) constitutes the majority of the chemical elements of the “Khachmaz” geothermal power resource in Khachmaz district, Azerbaijan. It accounts for approximately 72.41÷90.12% of all chemical substances of the “Khachmaz” geothermal power resource in Khachmaz district, Azerbaijan.

Before conducting the main experiments, the operating capacity of the experimental device to be used was confirmed by conducting verification experiments with materials that have high-quality experimental data. Since this vibrating tube method needs to be calibrated with at least two substances, water and aqueous NaCl solutions, methanol, ethanol and toluene were chosen as the main substances used for the calibration for this purpose. The process of calibration was analyzed. After the calibration procedure, the calibrated items were repeatedly measured and the average error of the comparisons was analyzed. In a number of cases, the experiments were repeated 4-5 times at the same temperatures, and the operating capacity of the device was checked at different times, regardless of its charging difference and the experiment. The laboratory where the experiments were conducted was air conditioned at a constant temperature of T=293,15 K. The comparison of the results obtained for the aqueous solution of water, toluene and NaCl (m=2,96661mol·kg$^{-1}$) with the information given in the literature is shown in figures 1, 2 and 3.

As shown in the figures below, the difference between the newly obtained density data and the data given in the literature does not exceed the estimated errors of the measurements on this device. Bi-distilled water was obtained in various laboratory facilities. NaCl, methanol and other reagents were purchased from Merck company (Germany). The results were always close to each other with small errors. All this testifies to the high accuracy of the developed experimental device.

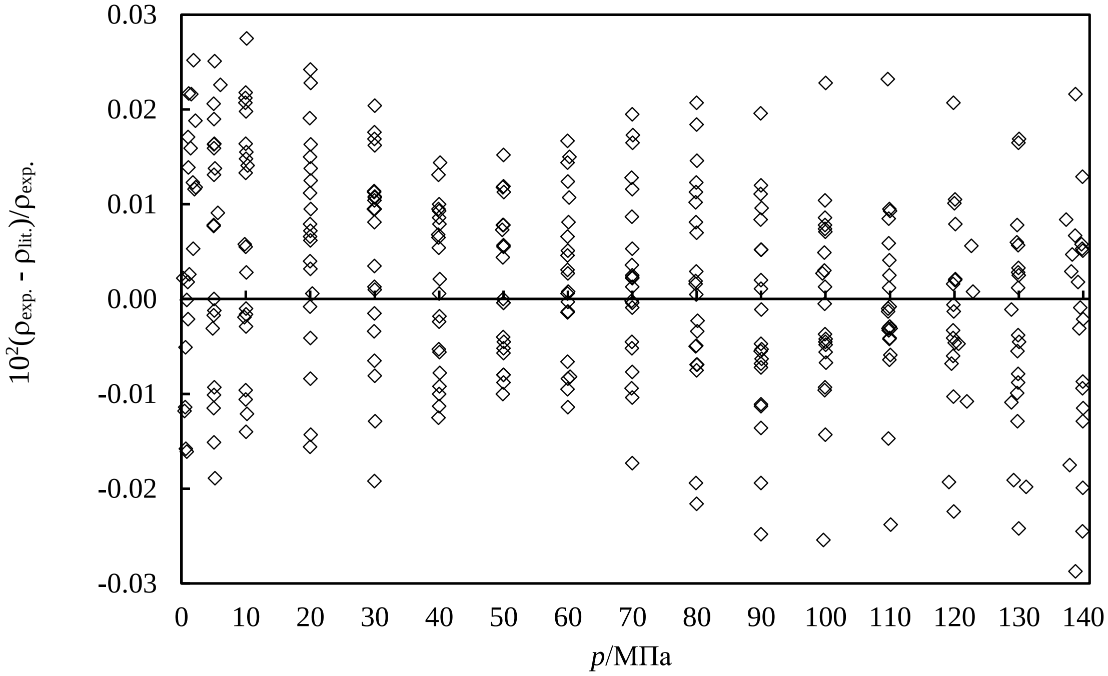


**Figure 1.** Dependence of measured water density on pressure at temperature T=(278,15-468,15) K and difference from literature data IAPWS 95

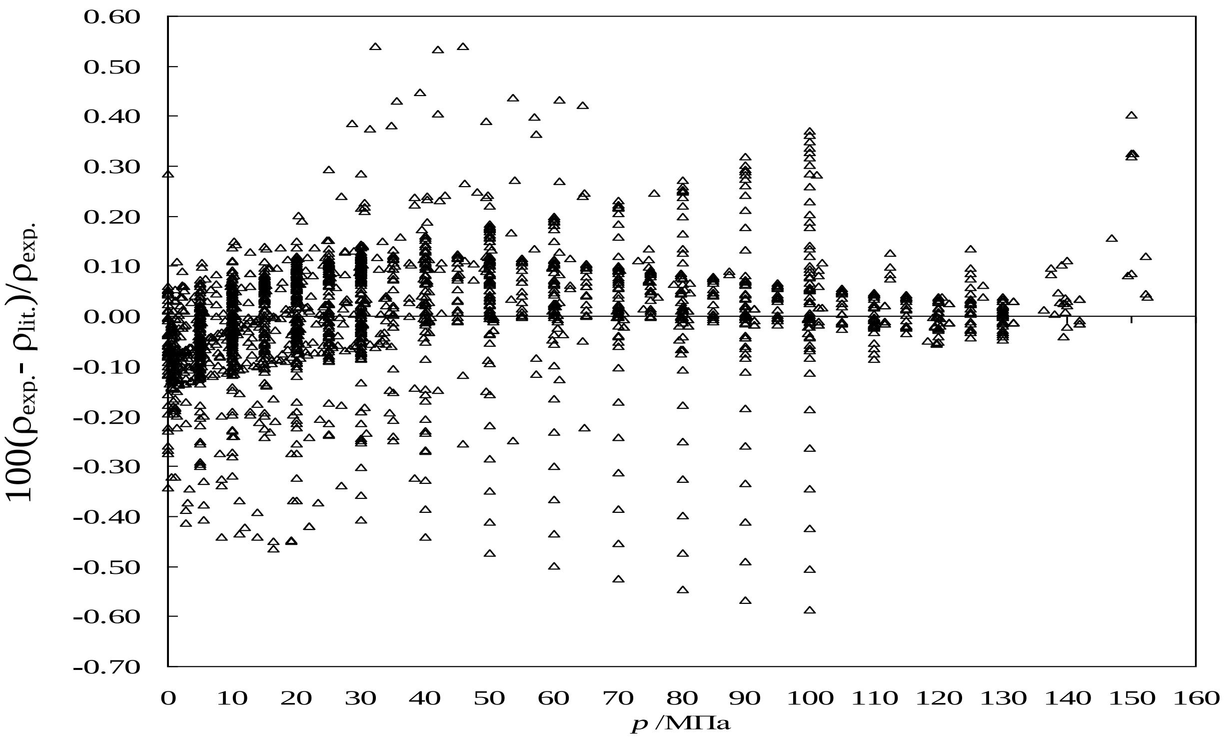


**Figure 2.** Dependence of the measured density of toluene on pressure at a temperature of T=(278,15-468,15) K and the difference with data from various literature (data up to 2000).

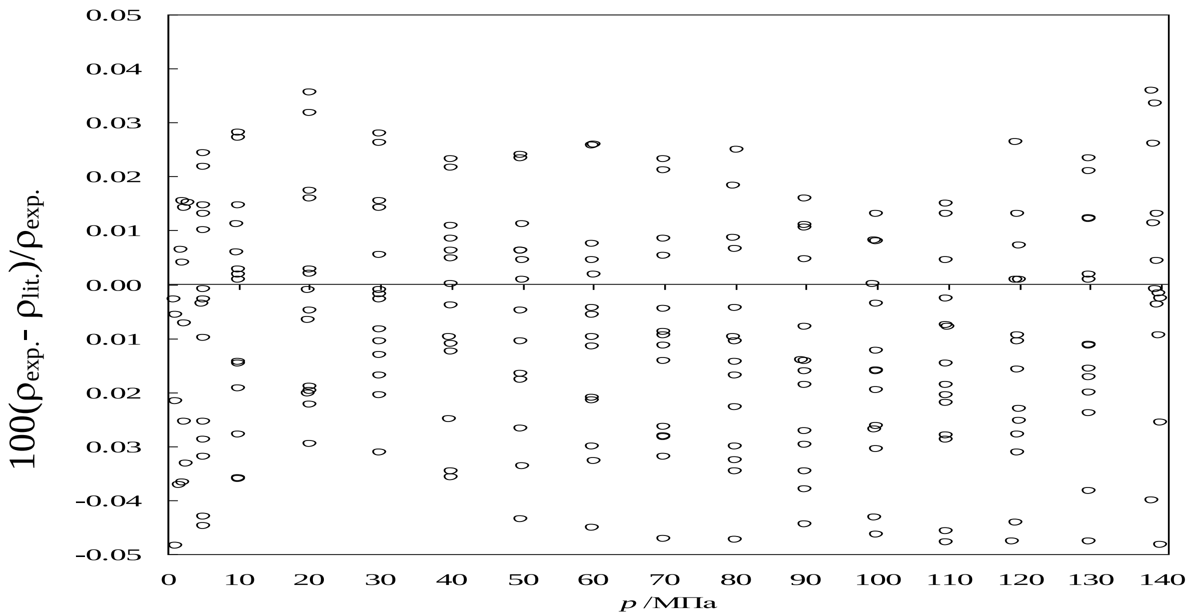


**Figure 3.** Dependence of the measured density of aqueous NaCl solutions (m=2,96661 mol·kq[1]) at temperature T=(278,15-468,15) K and difference with data from different literature (data up to 2000).

After testing water, NaCl, methanol, ethanol and toluene (p, ρ, T), dependences (p, ρ, T) of thermal water in Khachmaz district of Azerbaijan, as well as high pressure and experimental device where vibration tube method is implemented at different temperatures were measured.

When measuring the dependences (p, ρ, T) in each equilibrium state, it was sought to create as low pressure values as possible in order to obtain highly accurate density values using graphical extrapolation at atmospheric pressure, which were compared with the values of density measured on the DMA 4500 device. The data obtained by these different methods are in good agreement within ±0.02%. Each isotherm experiment was performed with pressure intervals of approximately 5 MPa. Researches for all studied objects were conducted at temperatures starting from T=(278.15÷373.15) K and pressures up to p=40 MPa. The obtained experimental parameters (p, ρ, T) are given in table 1.

*Table 1.*

**Experimental values of the density of thermal water “Khachmaz” in Khachmaz district, Azerbaijan at various pressures and temperatures**

| $\frac{p}{MPa}$ | $\frac{\rho}{kg \cdot m^3}$ | $\frac{T}{K}$ | $\frac{p}{MPa}$ | $\frac{\rho}{kg \cdot m^3}$ | $\frac{T}{K}$ |
|---|---|---|---|---|---|
| 0.624 | 1004.04 | 278.15 | 1.160 | 989.32 | 328.02 |
| 5.004 | 1006.21 | 278.15 | 5.024 | 990.99 | 328.04 |
| 10.023 | 1008.65 | 278.16 | 10.079 | 993.00 | 328.17 |
| 15.012 | 1011.05 | 278.15 | 15.576 | 995.38 | 328.18 |
| 20.035 | 1013.43 | 278.14 | 19.985 | 997.22 | 328.19 |
| 25.036 | 1015.76 | 278.15 | 25.527 | 999.61 | 328.17 |
| 30.054 | 1018.07 | 278.15 | 30.023 | 1001.50 | 328.14 |

| | | | | | |
|---|---|---|---|---|---|
| 35.124 | 1020.37 | 278.14 | 35.513 | 1003.58 | 328.12 |
| 40.021 | 1022.56 | 278.15 | 39.978 | 1005.37 | 328.06 |
| 0.539 | 1002.59 | 288.14 | 0.846 | 981.22 | 343.15 |
| 5.006 | 1004.66 | 288.16 | 5.097 | 983.06 | 343.16 |
| 9.855 | 1006.87 | 288.17 | 9.967 | 985.17 | 343.14 |
| 15.151 | 1009.25 | 288.17 | 15.525 | 987.55 | 343.15 |
| 20.064 | 1011.43 | 288.17 | 20.000 | 989.45 | 343.15 |
| 25.121 | 1013.64 | 288.16 | 25.586 | 991.82 | 343.14 |
| 30.103 | 1015.79 | 288.16 | 30.045 | 993.68 | 343.16 |
| 35.111 | 1017.92 | 288.16 | 35.514 | 995.98 | 343.15 |
| 40.145 | 1020.04 | 288.15 | 40.050 | 997.87 | 343.15 |
| 1.025 | 1000.15 | 298.27 | 0.846 | 974.29 | 354.24 |
| 5.079 | 1002.02 | 298.22 | 5.097 | 976.23 | 354.25 |
| 9.818 | 1004.22 | 298.22 | 9.967 | 978.33 | 354.27 |
| 15.593 | 1006.61 | 298.17 | 15.525 | 980.63 | 354.27 |
| 20.018 | 1008.46 | 298.13 | 20.000 | 982.58 | 354.27 |
| 25.104 | 1010.69 | 298.13 | 25.586 | 984.92 | 354.27 |
| 30.155 | 1012.85 | 298.12 | 30.045 | 986.83 | 354.28 |
| 35.089 | 1014.82 | 298.13 | 35.514 | 989.17 | 354.27 |
| 40.040 | 1016.88 | 298.13 | 40.050 | 991.07 | 354.27 |
| 0.898 | 995.52 | 313.08 | 1.626 | 962.02 | 372.90 |
| 4.995 | 997.25 | 313.10 | 5.059 | 963.59 | 372.90 |
| 9.972 | 999.20 | 313.15 | 10.042 | 965.73 | 372.96 |
| 15.563 | 1001.65 | 313.17 | 15.525 | 968.08 | 372.97 |
| 20.008 | 1003.42 | 313.20 | 20.014 | 970.00 | 372.99 |
| 25.534 | 1005.80 | 313.18 | 25.596 | 972.31 | 373.00 |
| 30.057 | 1007.65 | 313.19 | 30.001 | 974.44 | 372.90 |
| 35.586 | 1009.82 | 313.17 | 35.576 | 976.79 | 372.91 |
| 39.970 | 1011.52 | 313.15 | 40.013 | 978.53 | 372.92 |

Isotherms are plotted in p-ρ coordinates in the pressure range of 0,1-40 MPa (Figure 4).

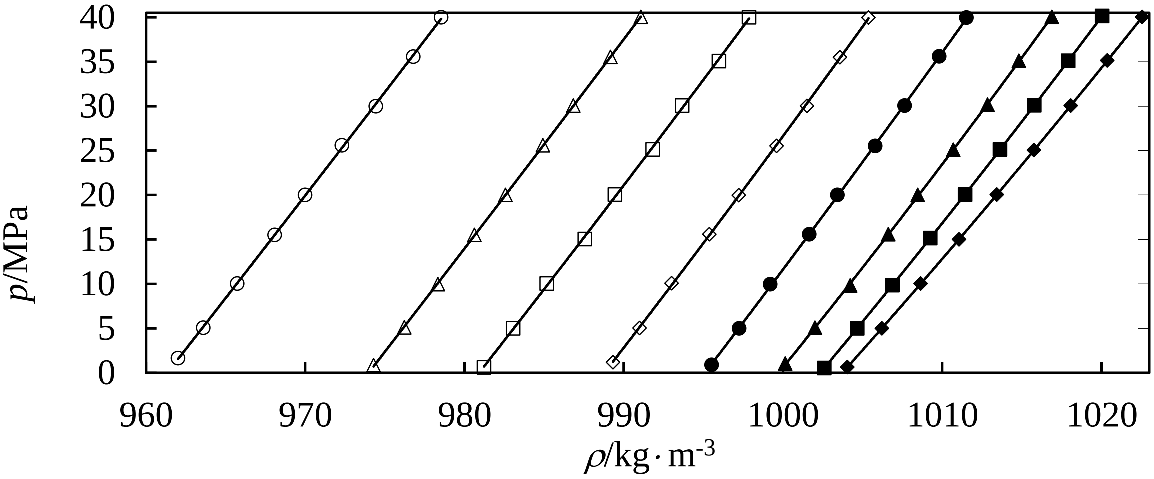


**Figure 4.** Dependence of pressure (p) on density (ρ) of thermal water "Khachmaz" in Khachmaz district, Azerbaijan, calculated according to formulas 1-2:

♦, 278,15 K; ■, 288,16 K; ▲, 298,17 K; •, 313,18 K; ◊, 328,18 K;□, 343,15 K; Δ, 354,27 K; ○, 372,96 K.

The measured density of thermal water “Khachmaz” in Khachmaz district, Azerbaijan was also calculated on the DMA 5000M device at atmospheric pressure with an accuracy of 0.01% (more precisely than at high pressures). This device allows accurate measurements at temperatures up to T = 363,15 K. The results obtained are written by the following equation of state:

$$p = A\rho^2 + B\rho^8 + C\rho^{12} \qquad (1)$$

It is proved that with an increase in the third limit of the Akhundov-Imanov equation, the error in the description of experimental data decreases to $\Delta\rho/\rho=\pm(0.001\div0.003)\%$. The coefficients A(T), B(T) and C(T) depend on temperature in polynomial form:

$$A(T) = \sum_{i=1}^{3} a_i T^i,\ B(T) = \sum_{i=0}^{2} b_i T^i,\ C(T) = \sum_{i=0}^{2} c_i T^i \qquad (2)$$

The values of the coefficients $a_{ij}$, $b_{ij}$ və $c_{ij}$ in equation (2) are given in table 2.

*Table 2.*

| | | |
|---|---|---|
| $a_1$= -3.9508587 | $b_0$= 8322.6444921 | $c_0$= -6583.286607275 |
| $a_2$= 0.019210690563 | $b_1$= -56.828468335 | $c_1$= 45.23492762848 |
| $a_3$= -0. 3685081337·$10^{-4}$ | $b_2$= 0.103286734291 | $c_2$= -0.07893862924 |

Equation (1) makes it possible to write down the experimental values of the dependence of thermal water “Khachmaz” (p, ρ, T) with an average error of 0.007%, taking into account the values of the coefficients A(T), B(T) and C(T).

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Nabiyev Nofal Dunyamaly oglu held positions of teacher, dispatcher, chairman of the “Automotive” subject unification committee, head of the department at Baku Industrial - Pedagogical College over the years. In 2016, he worked as the head of Education Department, deputy director for Educational and Scientific Affairs and director at “Baku College of Management and Technology”. From 20.09.2018 to 05.06.2020, he worked as a senior lecturer at the Department of “Thermal Power Engineering” of Azerbaijan Technical University, and also worked on a voluntary basis as the deputy dean for Scientific Affairs of the Faculty of “Electrical Engineering, Power Engineering and Automation”. He is currently working as a senior lecturer at the Department of “Energy Efficiency and Green Energy Technologies” of Azerbaijan Technical University, and a deputy dean of the Faculty of “Energy and Automation”. In 2012, he received the degree of Ph.D. in Technical Sciences. Nabiyev Nofal is the author of 65 scientific works (including 1 textbook, 1 monograph, academic programmes for sub-bachelor, bachelor’s and master’s degrees, scientific articles published in the USA, Germany, Russia and Kazakhstan). He is a member of the Academic Council of the Faculty of “Power Engineering and Automation” of Azerbaijan Technical University.

Bashirov Mahir Majnun oglu worked as a mechanic and head of the workshop of the “Motor Transport Enterprise No. 5” in 1981-1984, in Barda, Azerbaijan. He defended his Ph.D. thesis in 1987, and his doctoral thesis in 2004. Since 1987, he has been working in various positions at Azerbaijan Technical University, working as an assistant, then as an assistant professor at the Department of “Heat and Cold Engineering”. From 2008 to the present time, he has been working as a Professor at the Department (currently called the Department of “Energy Efficiency and Green Energy Technologies”). From 9.06.2008 to 8.10.2019, he worked as the dean of the Faculty of “Electrical Engineering and Power Engineering” at Azerbaijan Technical University. Since 02.04.2021, he has been the Head of the Department of “Magistracy and Doctoral Studies” of Baku Engineering University, and since 29.09.2021, he has been a Professor at the Department of “Automatics and Electroenergetics” of Baku Engineering University.

In 2005 and 2009, M.M. Bashirov underwent an internship for the exchange of scientific experience at the University of Duisburg-Essen, Germany, through the German Academic Exchange Service (DAAD). In total, he is the author of more than 210 scientific works, including more than 90 national ones, 66 articles (40 of which have an impact factor) published in international journals, 9 textbooks and manuals, 6 monographs, more than 50 academic programmes, 1 invention (authorship certificate).

# PLC-BASED MODERN PROTECTION SYSTEM OF ELECTRIC MOTORS

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**ABSTRACT**

In the past, simple protection systems of electric motors based on components such as timers, contactors, electromagnetic switches, and voltage and current transformers were slow and inaccurate, as well as low sensitivity. However, the production of PLCs and their application in this field eliminated the mentioned problems. Extensive operation of motors, being the main executive equipment in the field of application, requires the creation of modern automated protection systems to ensure their reliable and stable operation.

Today, PLCs are continuously evolving and striving to be the best choice for various industrial automation applications. Since the PLC-based protection system is a reliable, fast, high-precision system, modern protection systems based on PLC of electric motors are researched in the article.

**Keywords:** PLC, protection system, fault analysis, electric motor, reliability

# ELEKTRİK MÜHƏRRİKLƏRİNİN PLC ƏSASINDA MÜASİR MÜHAFİZƏ SİSTEMİ

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**XÜLASƏ.**

Əvvəllər elektrik mühərriklərinin taymer, kontaktor, elektromaqnit açarı, gərginlik və cərəyan transformatoru kimi komponentlərin əsasında qurulmuş sadə mühafizə sistemləri yavaş və qeyri-dəqiq olmaqla yanaşı aşağı həssaslığa malik idilər. Lakin PLC-lərin istehsalı və bu sahədə tətbiqi qeyd olunan problemləri aradan qaldırdı. Mühərriklərin geniş şəkildə istismarı, tətbiq olunduğu sahədə əsas icraçı avadanlıq olması, onların etibarlı və dayanıqlı iş rejiminin təmini üçün müasir avtomatlaşdırılmış mühafizə sistemlərinin yaradılmasını tələb edir.

Günümüzdə PLC-lər davamlı olaraq inkişaf edir və müxtəlif sənaye avtomatlaşdırma tətbiqləri üçün ən yaxşı seçim olmağa səy göstərir. PLC əsaslı mühafizə sistemi etibarlı, cəld, yüksək dəqiqliyə malik bir sistem olduğundan, məqalədə, elektrik mühərriklərinin PLC əsasında müasir mühafizə sistemləri tədqiq olunmuşdur.

**AÇAR SÖZLƏR:** PLC, mühafizə sistemi, nasazlıqların təhlili, elektrik mühərriki, etibarlılıq

# СОВРЕМЕННАЯ СИСТЕМА ЗАЩИТЫ ЭЛЕКТРОДВИГАТЕЛЕЙ НА ОСНОВЕ ПЛК

**ФАРИД ГУСЕЙНОВ, ЭЛЬШАН МАНАФОВ**

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**АННОТАЦИЯ.**

В прошлом простые системы защиты электродвигателей на основе таких компонентов, как таймеры, контакторы, электромагнитные переключатели, трансформаторы напряжения и тока, были медленными и неточными, а также имели низкую чувствительность. Однако производство ПЛК и их применение в этой области устранило указанные проблемы. Экстенсивная эксплуатация двигателей, являющихся основным исполнительным оборудованием в области применения, требует создания современных автоматизированных систем защиты, обеспечивающих их надежную и устойчивую работу.

Сегодня ПЛК постоянно развиваются и стремятся стать лучшим выбором для различных приложений промышленной автоматизации. Поскольку система защиты на базе ПЛК является надежной, быстрой, высокоточной системой, в статье исследуются современные системы защиты на базе ПЛК электродвигателей.

**КЛЮЧЕВЫЕ СЛОВА:** ПЛК, система защиты, анализ неисправностей, электродвигатель, надежность.

## INTRODUCTION.

Electric motors are electromechanical machines used in industry and other fields to convert electrical power into mechanical power. Electric motors are widely used in vehicles, machine tools, presses, cranes, escalators, and elevators. Asynchronous motors used in transport are particularly distinguished from other electric motors by their high reliability, low maintenance requirements and high efficiency.

Motor failures are mainly due to mechanical and electrical stress. Overloading, sudden and sharp load changes in motors cause mechanical stresses resulting in increased temperature, vibration and noise. Electrical stress can cause a short circuit, temperature rise, phase loss, etc. as a result of some other malfunctions. Failure to prevent malfunctions and defects in time leads to motor failure. This is unacceptable in important production areas, as well as in transport. Real-time automatic protection and control of motors are required for the timely detection of abnormal conditions to reduce the number of accidents that lead to long downtimes and high motor overhaul costs. The main difficulty in creating such a protection system is its complex organization. The fact that the main parameters to be protected vary in a wide range depending on the motor load and operating mode directly affects the accuracy of the protection.

## STATEMENT OF THE PROBLEM.

Currently, several methods are used to protect electric motors. The application of traditional protection systems in the protection of motors has some disadvantages. To overcome these shortcomings, modern protection systems should be developed according to the diagnostic status of motors. To overcome the problems of traditional protection systems, PLC (Programmable Logic Control) based protection systems can be applied to motor fault detection and protection.

## SOLUTION OF THE PROBLEM.

Nowadays, system control in energy systems and several large enterprises is carried out based on SCADA. SCADA (Supervisory Control And Data Acquisition) - stands for Dispatcher Control and Data Acquisition. SCADA is a system that collects data from various sensors in industrial and remote facilities, sends it to a central computer, and controls executive equipment based on the received data. The main goals of using a SCADA system are to collect data, display them on the monitor screen in the control room, store the relevant data on the hard disk of the master computer, and create the possibility of controlling field devices (remote or local) from the control room. SCADA systems are equipped to make on-the-fly adjustments to the operating system, which increases equipment life, reduces the need for costly repairs, and reduces downtime. The main element of the SCADA system is the PLC. Considering the scope of use of PLCs, their application in motor protection is prospective. Below is a block diagram for the protection of an electric motor based on PLC.

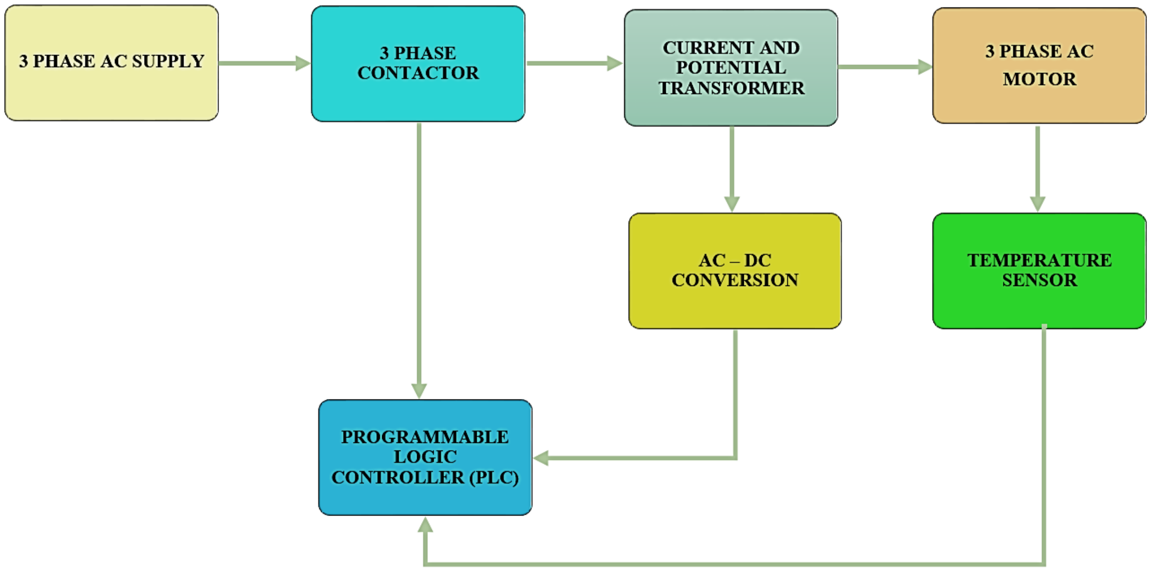



Figure 1. Block diagram for protection of electric motor based on PLC

As shown in the block diagram, CT (current transformer), and PT (voltage transformer) sensors are used to measure current and voltage, and LM35 sensors are used to measure temperature. The output of these sensors is fed to the PLC. In this protection method, online monitoring of the electric motor is carried out and all informative parameters - voltage, current and temperature are monitored. If all parameters are within the normal operating range, the PLC will continuously allow a three-phase power supply to the motor. However, if any abnormal mode is detected, the PLC will stop the induction motor by giving an opening signal to the magnetic contactor and relay according to the programmed conditions.

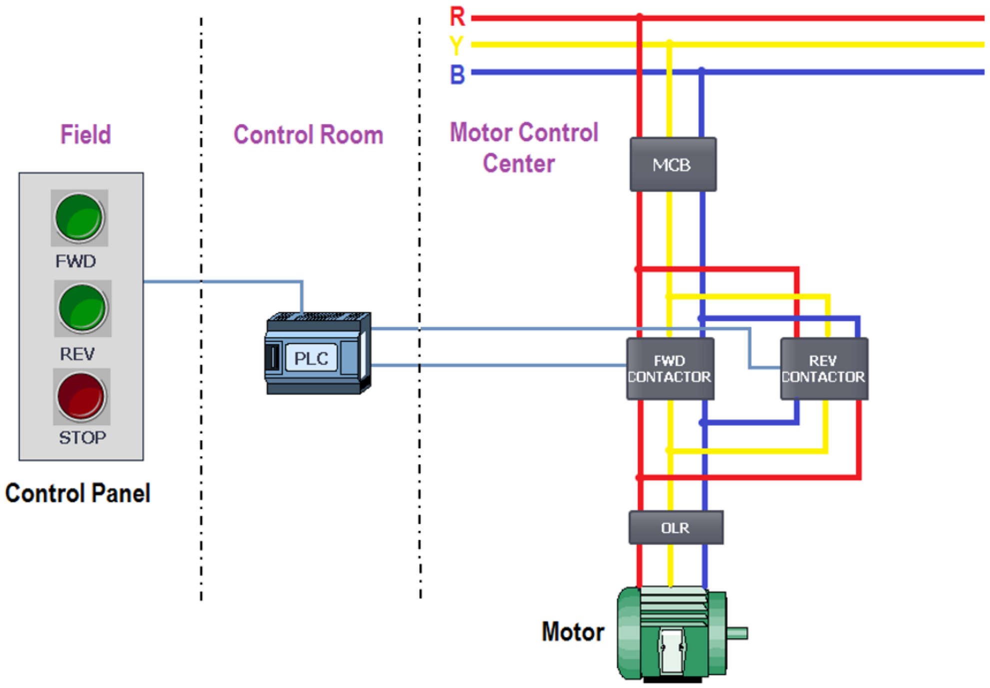
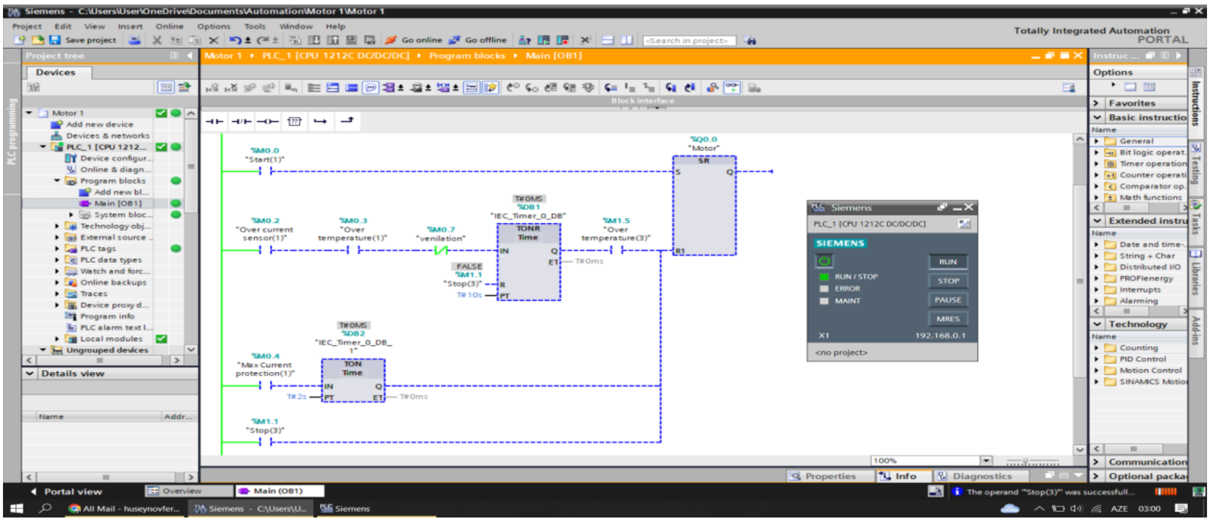
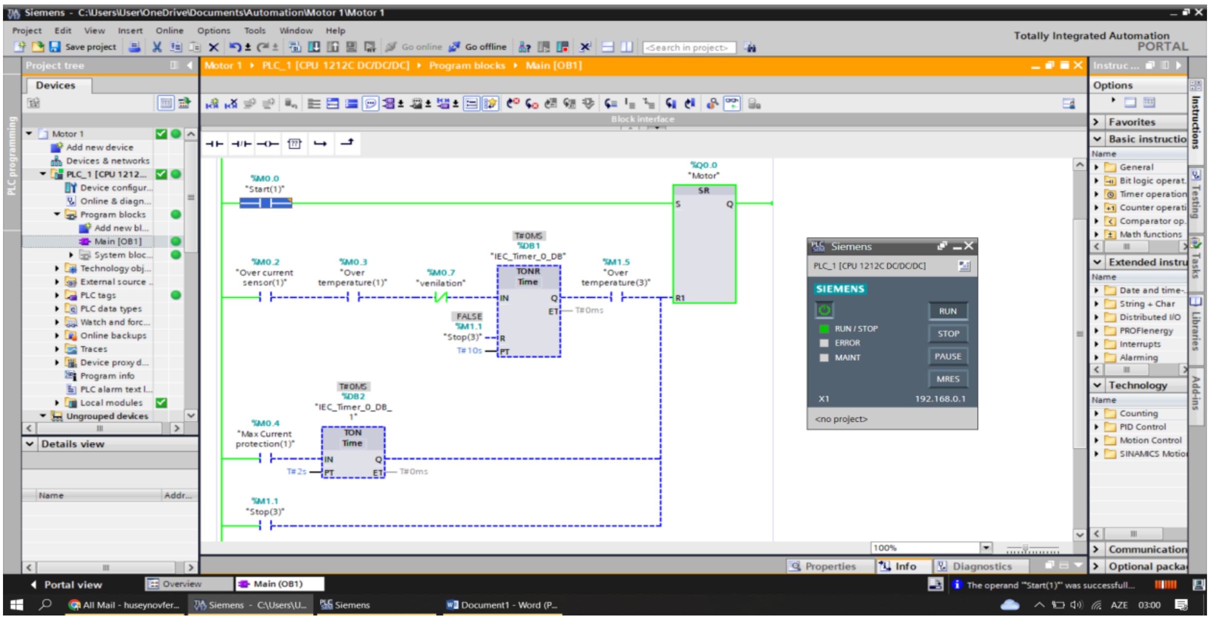


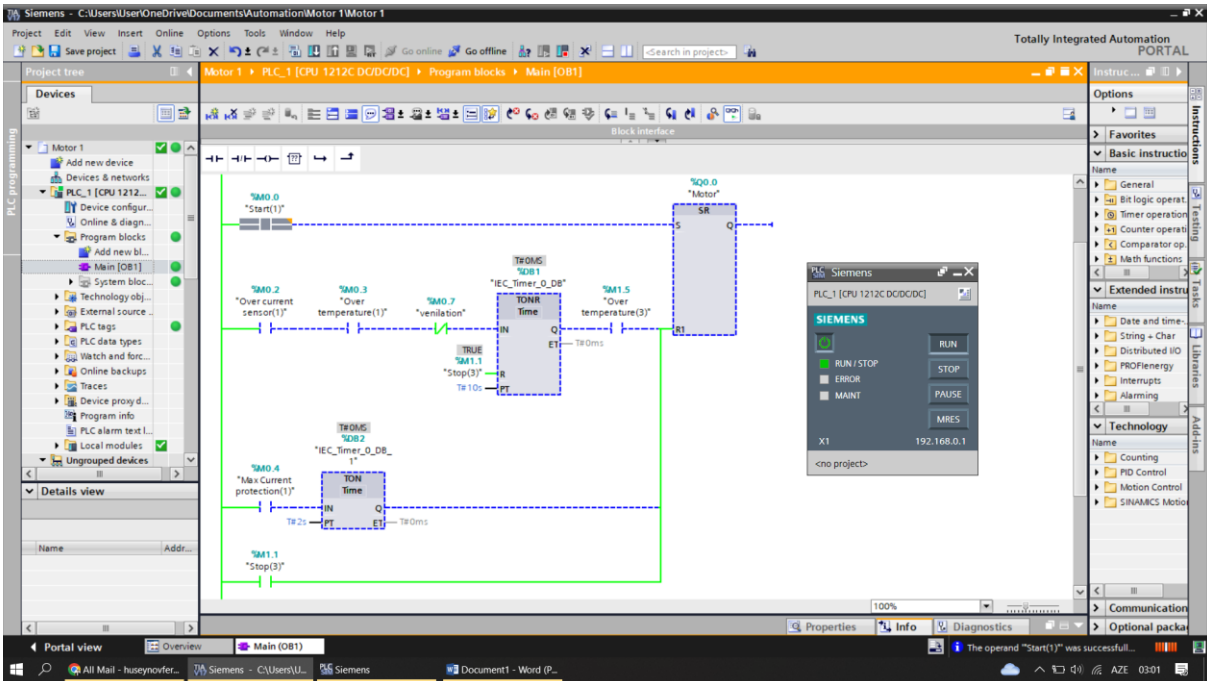

Figure 2. PLC - Motor control circuit

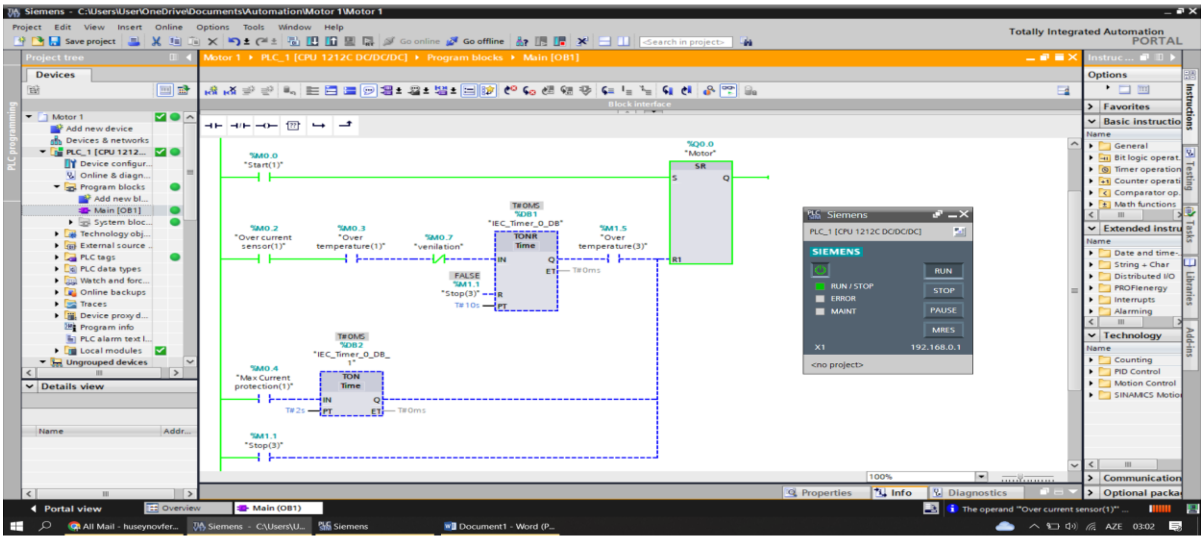
## MODELING.

Modelling of the motor protection system based on PLC was carried out with "TIA Portal" program. In normal conditions, the motor is controlled by the "Start" and "Stop" buttons. The motor's current and temperature protection system is simulated in the program. If the value of the current reaches the maximum limit, the motor will be protected from the maximum current with a waiting period of 2 seconds. Also, if there is an overload in the motor due to the current, then the temperature is measured and, analogously, the auxiliary ventilation is automatically connected. After 10 seconds of fan operation, the temperature is measured again. If the measured temperature is equal to or greater than the previous value, the motor is protected. Otherwise, based on the diagnostic monitoring system, the warning system starts and makes a decision about the real condition of the motor. That is, the obtained informative parameter is compared with other parameters. As mentioned, the proposed modern protection system is implemented according to the diagnostic situation. The structure of the modelling is given in the following Figure 3.

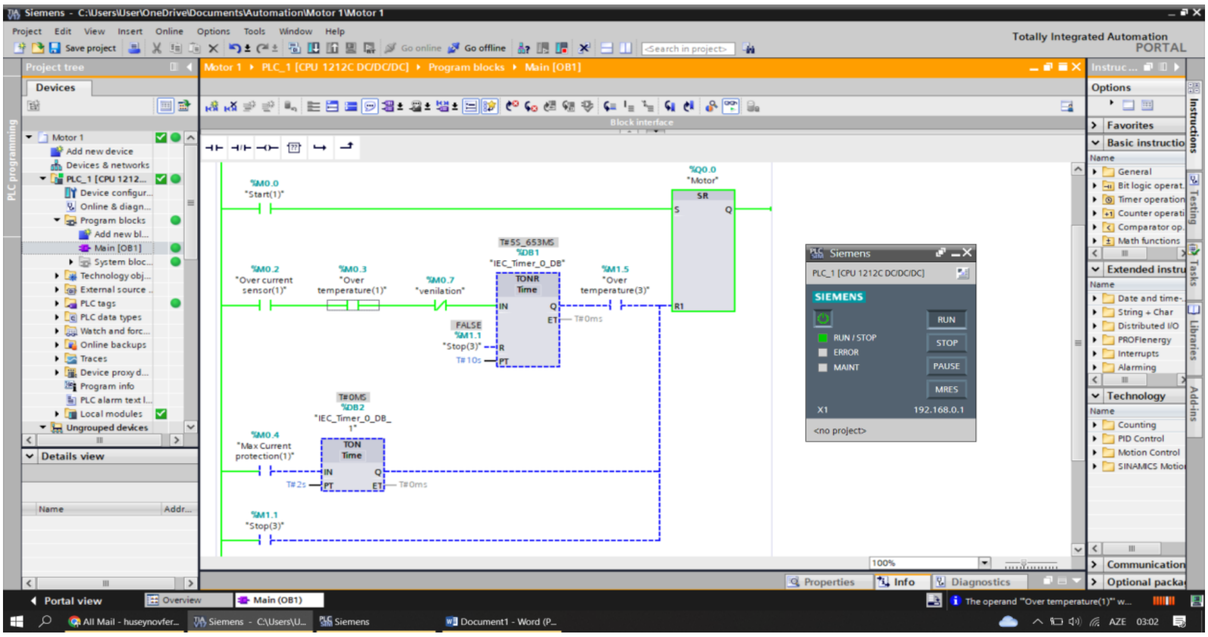

Totally Integrated Automation
PORTAL
Motor 1 ▸ PLC_1 [CPU 1212C DC/DC/DC] ▸ Program blocks ▸ Main [OB1]
%M0.0
"Start(1)"
%Q0.0
"Motor"
SR
%M0.2
"Over current sensor(1)"
%M0.3
"Over temperature(1)"
%M0.7
"venilation"
%M1.5
"Over temperature(3)"
%DB1
"IEC_Timer_0_DB"
TONR
Time
FALSE
%M1.1
"Stop(3)"
T#10s
%DB2
"IEC_Timer_0_DB_1"
TON
Time
%M0.4
"Max Current protection(1)"
T#2s
%M1.1
"Stop(3)"
SIEMENS
RUN / STOP
ERROR
MAINT
RUN
STOP
PAUSE
MRES
a)


Totally Integrated Automation
PORTAL
Motor 1 ▸ PLC_1 [CPU 1212C DC/DC/DC] ▸ Program blocks ▸ Main [OB1]
%M0.0
"Start(1)"
%Q0.0
"Motor"
SR
%M0.2
"Over current sensor(1)"
%M0.3
"Over temperature(1)"
%M0.7
"venilation"
%M1.5
"Over temperature(3)"
%DB1
"IEC_Timer_0_DB"
TONR
Time
FALSE
%M1.1
"Stop(3)"
T#10s
%DB2
"IEC_Timer_0_DB_1"
TON
Time
%M0.4
"Max Current protection(1)"
T#2s
%M1.1
"Stop(3)"
SIEMENS
RUN / STOP
ERROR
MAINT
RUN
STOP
PAUSE
MRES
b)

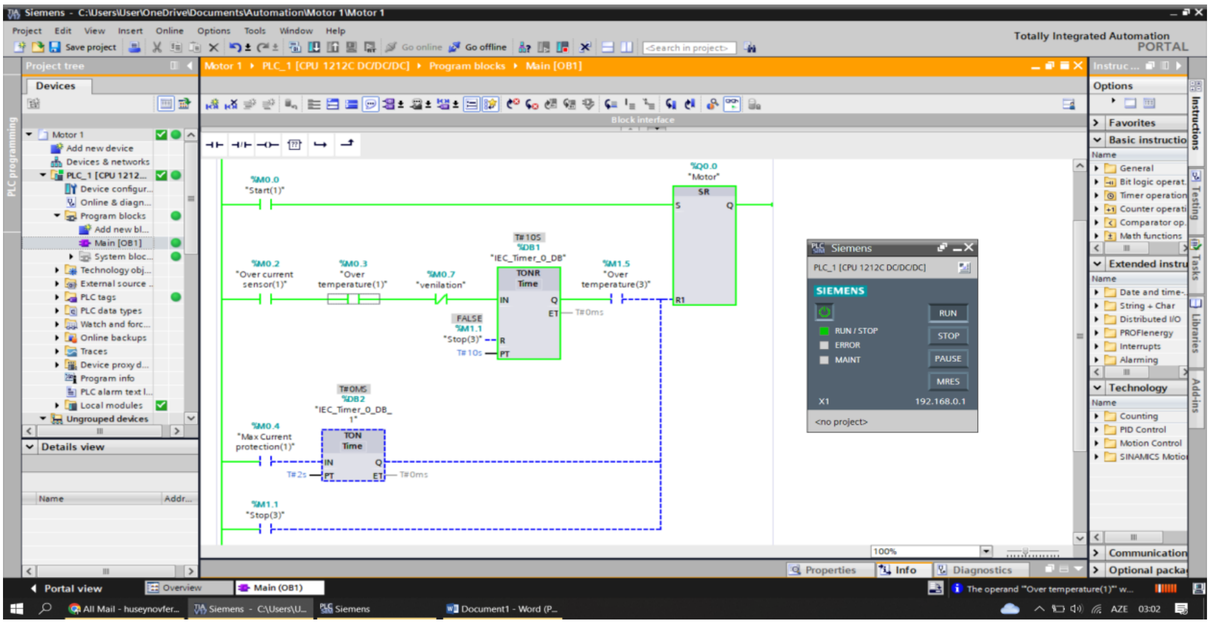

Totally Integrated Automation
PORTAL
Motor 1 ▸ PLC_1 [CPU 1212C DC/DC/DC] ▸ Program blocks ▸ Main [OB1]
%M0.0
"Start(1)"
%Q0.0
"Motor"
SR
%M0.2
"Over current sensor(1)"
%M0.3
"Over temperature(1)"
%M0.7
"venilation"
%M1.5
"Over temperature(3)"
%DB1
"IEC_Timer_0_DB"
TONR
Time
TRUE
%M1.1
"Stop(3)"
T#10s
%DB2
"IEC_Timer_0_DB_1"
TON
Time
%M0.4
"Max Current protection(1)"
T#2s
%M1.1
"Stop(3)"
SIEMENS
RUN / STOP
ERROR
MAINT
RUN
STOP
PAUSE
MRES
c)



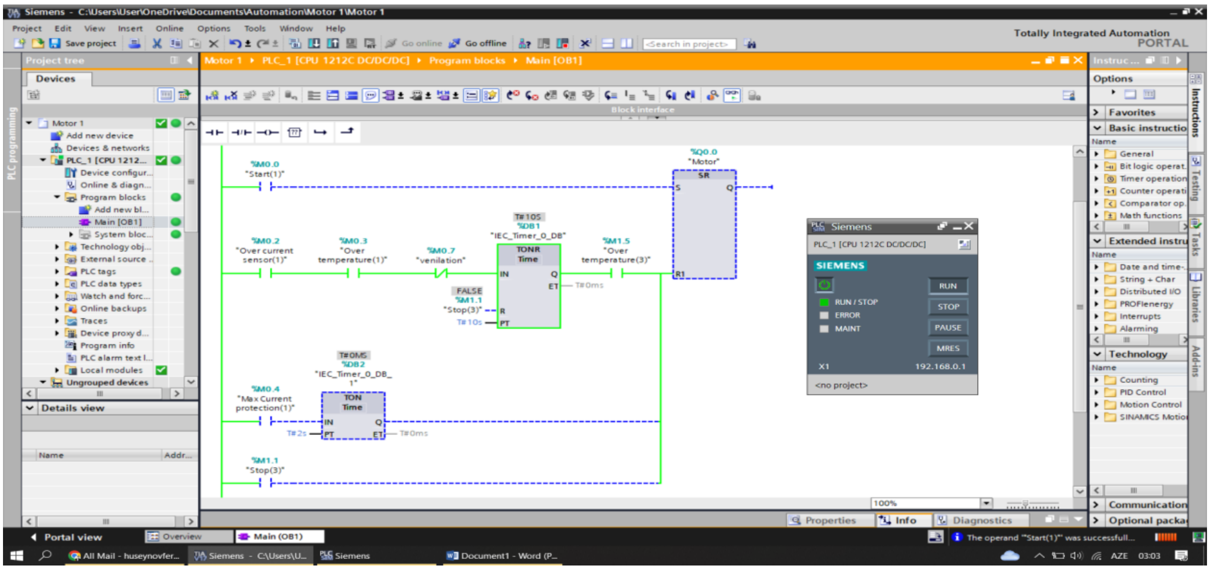
d)



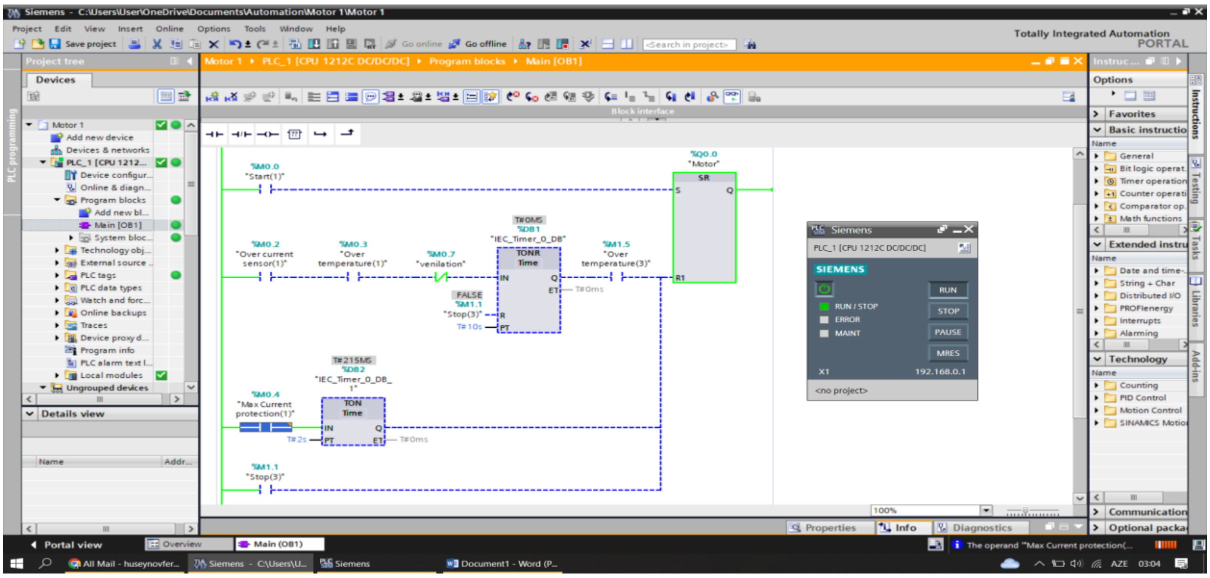
e)



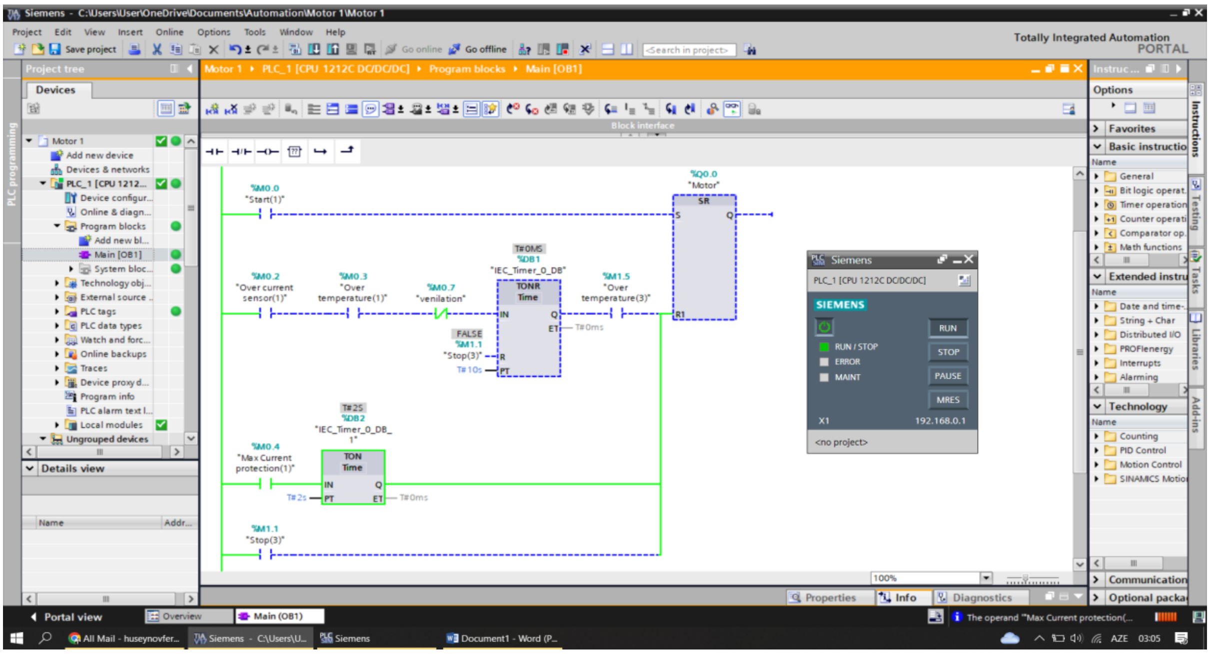
f)



g)



h)



j)

Figure 3. Motor protection simulation based on PLC: a) inactive; b) run; c) stop; d) run and overload; e) overload and temperature increase; f) ventilator operation time; g) re-measurement of temperature and motor protection; h) run and other model of motor protection; j) maximum current protection

## CONCLUSIONS

The protection system of the electric motor was built and simulated using PLC. In addition to voltage, current and temperature parameters, the PLC can provide protection based on other parameters depending on the operating conditions. This is why PLCs are used more than other logic devices in the industry. They are relays, valves, actuators, transmitters, motor starters, etc. have direct interaction with other industrial devices such as

As we know, one of the main elements of the SCADA system is PLC. SCADA (Supervisory Control And Data Acquisition) - stands for Dispatcher Control and Data Acquisition. SCADA is a system that collects data from various sensors in industry and other remote locations, sends this data to a central computer, and controls executive equipment based on the received data. One of the special features of SCADA is the ability to monitor the entire system in real-time. The main purposes of using this system are to collect data, display them on the monitor screen in the control room, store the relevant data on the hard disk of the master computer, and create the possibility of controlling field devices (remote or local) from the control room. SCADA systems are equipped to make instant corrections to the operating system, which increases the life of the equipment, reduces the need for costly repairs, and reduces downtime.

Thus, it is possible to monitor various parameters of the motor in real-time from the SCADA system and to monitor the technical condition of the motor from the computer screen, when necessary, to make changes. As mentioned, new hybrid protection systems should be built according to the diagnostic situation to organize deeper protection of electric motors and increase accuracy.

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