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RESEARCH OF CHARACTERISTICS OF ELECTRICAL DISCHARGES IN WATER MEDIUM UNDER THE ACTION OF HIGH-VOLTAGE PULSES

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Abstract- In this article, the characteristics of high-voltage impulse discharges in water (discharge delay time, water-breakdown time, distribution of potential and field strength in the discharge gap, etc.) are investigated when treated medium is exposed to effect of short duration-high pulsed voltage. It is shown that parameters of energy source (pulse amplitude, polarity, electric field intensity) and treated medium itself (electrical conductivity) effect on discharge characteristics in water, such as leader's occurrence time, their rate and energy released in channel, In article measuring technique of characteristics of electric field (potential distribution at the head of leaders, field intensity) by special probes is presented. It is established that at low voltages, due to sharp distortion of electric field around "pin" electrode as a result of electrolysis processes on negative pulse polarity, leader's occurrence time is less than on positive one. It is shown that with increase in positive pulse amplitude in comparison with negative one, because of amplification of electric field in whole interelectrode distance, high-speed processes of various nature in water medium are taken place.

Keywords: High Voltage Pulse, Water, Discharge, High-Speed Process, Breakdown, Leader's Occurrence Time, Electric Field Intensity, Energy.

I. INTRODUCTION

In recent decades, large-scale fundamental explorations of discharge processes in liquid mediums under influence of pulsed high voltages have been carried out. There are known works by numerous authors on use of discharges in water for cleaning alloys, metal products from various kinds of hard-to-remove contaminants, etc. [1-3]. Among them are author's works on disinfection of liquid mediums from various pathogenic organisms [4-7]. In spite of above works, physical phenomena in liquid mediums, accompanied by high-speed processes (more than sound speed in water) under influence of high pulsed voltages of anomalous amplitude still remain quite unexplored. Large energy released in this case can be used for various technological operations. But, this requires careful research of different processes in liquid mediums under effect of pulsed high voltage, which is necessary for development of technological equipment for specific purpose.

This article is devoted to fundamental research of breakdown processes in water mediums, formation of high-conductivity leader channels, resulting in pulsed electric breakdown of treated medium.

II. EXPERIMENTAL PART AND DISCUSSIONS

Source of pulsed energy is nanosecond pulsed generator developed at Institute of Physics of Azerbaijan National Academy of Sciences with an output voltage ~100 kV. Generator is assembled according to Arcadyev-Marx scheme on capacitive energy storage devices. Pulse repetition rate was ~100 Hz. Pulses of microsecond duration (t_i= 100 ns) are effected on water gap at "pin-plane" electrode system at inter-electrode distance l÷50 mm. Polarity of potential electrode is varied. When high electric pulsed fields are effected on water medium, high-speed physical, electrochemical and mechanical processes are occurred with subsonic or supersonic speed, depending on voltage amplitude.

A. Definition of Discharge Parameters and Analysis of Physical Processes

At low voltages (up to 20 kV) in water medium, electrolysis process and formation of gas inclusions as result of liquid boiling is realized. Increase of field strength nearly gas inclusions and presence of free electrons make possible avalanche processes in liquid and formation of highly conducting leader channels. Most authors believe that in water there can be photoionization, shock ionization processes. Ionization process, as in gas breakdown one, can be stepped. Thermal ionization takes place in leader channels.

Ionization conditions in liquid are very different from conditions in breakdown of gases. Thus, high electrical conductivity of water is associated with large number of free ions by both polarities. It is known that energy of vapor's single ionization is 12.6 eV, and the first excitation potential is 7.6 eV. Vapor is an electronegative gas (affinity to electron is 3 eV). In liquid phase due to interaction of molecules, these values are much lower.

Thus, ionization heat of water at 250 °C is ~12.34 kkal/g mole, which corresponds to 0.6 eV. Probably, energy of electron exit from cathode or gas inclusion is same decreased. Despite the short length of electron's free run in water compared to gases, at some electrical field intensities in water (~10^5-10^6 V/cm) avalanche processes and formation of leader channels is become possible. This is facilitated by low values of ionization energy and output one. In absence of reliable quantitative data on microstructure of water, concentration and mechanism of charges motion, it is not possible to calculate breakdown intensity of water. Therefore, main attention in article was paid to accumulation of experimental data on leader breakdown and qualitatively explain obtained results.

Leader's occurrence time, their rate, influence of pulse polarity was determined experimentally. Potential distribution in investigated gaps and electric field intensity nearly leader's head is measured. Leader's occurrence time depends on pulse polarity and its amplitude, field's intensity, and electrical conductivity of water medium.

On initial field intensities 36 kV/cm < E < 45 kV/cm this time is close to calculated value that necessary for water heating to boiling point. With voltage increase leader's occurrence time is become shorter. Average speed of leaders also depends on voltage polarity and amplitude. We obtained experimental results on measurement of leaders occurrence time t_1 and leaders speed v for different voltages at "+ pin - plane" and "- pin + plane" electrode systems on inter-electrode distance range l=1÷20.5 cm and radius of curvature of "pin" electrode r=0.2 cm. Both t_1 and v have statistical spread and are weakly dependent on inter-electrode distance.

Occurrence time of negative leaders is less (up to 25 kV) than positive ones. This seems to be due to difference in value of gas inclusion formed as result of electrolysis process. Speed of negative and positive leaders is little differed to voltages ~25 kV with rectangular voltage wave. Speed of leaders less than 5×10^3 cm/s is not observed. With increasing voltage, leaders' speed is also growing (particularly positive ones). At voltages 90÷100 kV speed of positive leaders is on 10^2 greater than negative ones, which is consistent with data of other researchers.

Somewhat overestimated rates of positive leaders in some experiments are explained by using of electrodes with very small exposed surface and therefore large field inhomogeneity coefficient. Water breakdown process includes the following features: large leader's occurrence time, small differences in rates of positive and negative leaders at low voltages, the most increase of positive leaders speed with voltage growth, slower increase of negative leaders speed at voltages >60 kV, large statistical spread of leader's occurrence time and their speed, emergence of leaders on boundary of insulation and metal electrode and development of leaders in different directions and even from opposite electrode.

B. Experiments and Measurement of Electric Field Parameters

For clarification the reasons of some features, measurements of potential's distribution in water gap and field intensity nearly leader's head were made. Since such measurements are difficult, let us consider in more detail accepted measurement technique. In the case of water breakdown, we are dealing with high conduction currents (tens and hundreds Ampere).

Therefore, when investigating water breakdown, it is impossible to use measurement technique elaborated for research of breakdown processes in long air gaps. However, conductivity and distribution of electric field in water gap, determined by its conductivity, makes possible to investigate potential's distribution and change of field intensity in leader channels by means of probes. Using by some researchers large bare surface in probe by diameter ~3 mm and Ohm voltage divider did not allow them to reveal features of field distribution nearly leader's head. Introduction of such probe effects on field's picture because streamer is constantly attracted to the probe. Basic requirements to probe are reduced to minimum possible field's distortion by its inserting and good resolution in time, since when leader is approached to probe potential can change very quickly. In our investigations we used probe-dividers, sketches of which are shown in Figure 1 (a),(b).

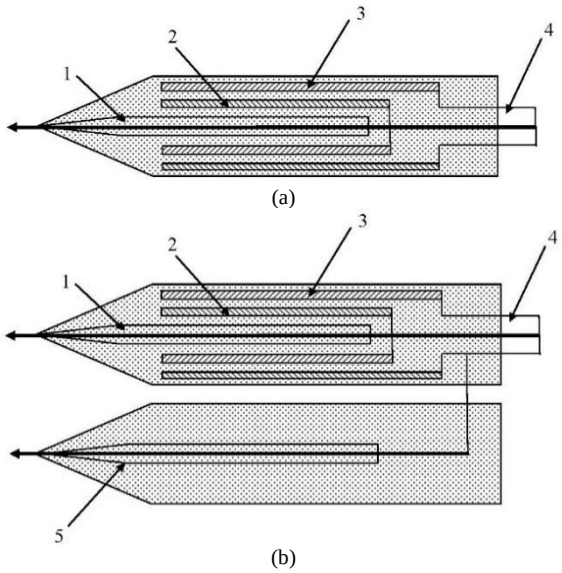

Figure 1. Sketches of probe-dividers for measuring potential, (a) in water gap and electric field intensity, (b): 1- first electrode of probe; 2- tube; 3- screen; 4- cable; 5- second electrode

Electrode 1 of probe is copper wire by diameter ~0.68 mm. Wire end is sharpened and insulated along entire length, except edge with radius ~0.1 mm. Wire with tube 2 is high-voltage divider capacitor. Low-voltage capacitance is formed between tubes 2, 3 and connecting cable 4. Tube 3 is grounded and ensures constant capacitance of high-voltage divider. To prevent crown discharge, ends of electrode and tube are rounded, and insulation does not contain air inclusions and has high resistivity.

When measuring potential, probe is placed in discharge gap and signal proportional to potential difference between probe tip and grounded electrode is transmitted to oscilloscope. Length of connecting cable influences on division factor. However, field's intensity cannot be accurately determined from measured potential distribution in gap, since potential difference at near points is commensurate with error in determining potential. Therefore, probe with additional electrode 5 was used to measure electric field's intensity (Figure 1(b)). Circuit was grounded through electrode 5. To reduce effect of charger's capacitance on ground, circuit contains resistances *R*.

Discharge circuit is compact and has small capacitance relative ground. So, charging of this capacitance when spark discharger is short-circuited does not cause ionization processes in water at electrode 5. Distance between electrodes 1 and 5 is ~0.5 mm, so measured field intensity is averaged over this distance. Let us estimate resolving power of probes in time. Capacitance of electrode 1 is ~5 pcF. Water resistance between electrode 1 and ground electrode when measuring potentials is approximately 100 kΩ. Constant time of probe at water's electrical conductivity 2.5×10^{-4} $\Omega^{-1}cm^{-1}$ will be $\tau=RC=10^{5}\times5\times10^{-12}$.

This means that after time less than 10^{-6} s switching potential of probe electrode will correspond to potential in liquid. Constant time of probe for intensity measuring will be even less, since resistance between electrodes 1 and 5 is smaller Insertion of probe causes some distortion of electric field in water gap. For its evaluation, potential measurements were made at "wire-plane" electrode system. Wire's radius is ~0.34 mm. It is known that radius of leader's head and channel is almost same.

Therefore, we can assume that probe measures true potential at distances between leader channel and probe >0.5 mm. At smaller distances, electric field's distortion, occurred by probe is observed. Described probes have significant drawback due to low capacitance of high-voltage part. To provide required division factor, capacitance of low-voltage part is several hundred pcF. Experiments show that leaders in gap, depending on voltage amplitude, have curved shape and different germination directions.

Therefore, there are difficulties in determining of potential distribution by probe in gap with leaders, since potential at fixed point will depend on random position of leader at this time voltage drop in leader channel is small and it can be modeled as thin wire. At "+ pin - plane" electrode system with length ~20 mm and radius of curvature r=1 mm, potential distribution was measured at different leader's length - thin wire. Potential of "pin" electrode is assumed to be zero. It should be noted that distribution of electric field in conducting liquid is very different than in air. There are significant potentials in areas remote from "plane" electrode. Potential gradient on insulation boundary with metal electrode is approximately same that nearly edge of "pin" one. This explains appearance of leader channels and luminescence not only at the end of "pin" electrode, but also at the boundary with insulation.

Lengthening leader causes slight decrease in field's intensity nearly "pin" electrode. Therefore, each leader is developed independently and does not effect on others rate. This is confirmed by measuring. Close to leader model, there are significant radial intensities, which are cause coronation processes. These intensities should cause conduction currents into leader's channel. Current in leader channel is not same in its length and has the greatest value at the "pin" electrode, and the smallest one at the leader's head. Leader's current is much greater than current of space charge near the head of leaders. Conduction current causes heating and shock expansion of leader's channel.

Emergence of leader is accompanied by sharp increase of field intensity near the head. As leader moves and approaches the opposite "plane" electrode, it's intensity is maximizes. This explains final jump, and at "- pin + plane" electrode system - emergence of leaders, developing from "plane" electrode. Direct measurement of electric field's intensity nearly leader's head by probes requires many experiments and selection of those at which leader touches both probe electrodes. Often leader passes near electrodes or touches one of them. In these cases, it is not possible to process obtained data, since trajectory of leader is unknown.

Determination of leader's position is possible using microscopic attachment and shadow method. Negative leader, when touching both probe electrodes, has higher speed than positive one. Contact time of the first probe electrode and passage distance between them is less. Under indicated conditions of conducting experiments at distance ~3 mm positive leaders slows down. For negative and positive leaders averaged field's intensity and voltage values at distance ~0.5 mm near the leader's head is ~120 kV/cm, ~11 kV and 100 kV/cm, ~10kV respectively. These values correspond to calculated ones when leader is replaced by thin wire. Field's intensity near the leader's head is much greater than in discharge gap. Therefore, experimental fact becomes clear - weak dependence of leader germination rate on geometry of water gap and on leader's position at the given moment (excepting region near the opposite electrode where final jump is taken place).

Leader's speed is determined by potential of its head (voltage in gap minus voltage drop in leader's channel) and excess space charge distorting field nearly it. When leader moves deeper into the gap and small voltage drop in channel, leader's rate depends on pulse wave. Experiments show constancy of speed in rectangular wave or with slow voltage decrease. With increasing voltage, speed of leaders is also increased. As voltage decreases in time, leader's speed is decreased to zero. In this case, we will have an incomplete discharge. Weak change in electric field intensity in gap away from leader's channel and its head can be explained development of parallel, spaced apart leaders at high voltages between electrodes. Each leader is developed in direction of field lines regardless of progress of neighboring leaders.

Even when gap is closed by one or several leaders, if there is no voltage drop across gap (at high power and low internal inductance of energy source), remaining leaders continue to develop, which leads to formation of parallel discharge channels Results obtained for average leader's speed, it's occurrence time and minimum voltage on rectangular pulse wave is differed from another wave one. In wide range of pulse's steepness, it turns out that initial voltage of starting leader processes at "- pin + plane" electrode system is always greater (~2 times) than at "+ pin - plane" one. For rectangular pulse wave with small amplitudes, inverse relation holds. Speed of leaders is also very different.

Thus, for nonrectangular wave speed of negative leaders is increased with steepness growth and at values ~400 kV/μs it is approached to rate of positive ones. With rectangular wave, rate of negative leaders increases slowly with voltage increasing. It is not clear what causes this difference: different electrical conductivity of water and sensitivity of measuring devices or voltage waveform. However, analysis of obtained results shows that rates of positive leaders coincide at close pulse waves, but different electrical conductivities and methods of speed determination.

Therefore, we can assume that wave's form is main factor. To test this assumption, minimum initial voltage value on starting leader processes in same water gaps at inter-electrode distance ~20 mm and radius of curvature of "pin" electrode ~0.5 mm were determined. With steep front wave and 50% drop in time ~250 ns, minimum voltage amplitude at negative polarity is ~8 kV, and at positive one ~9 kV. For waves with steepness ~2 kV/μs, this values are changed and at negative polarity to be greater than for positive one (30 and 24 kV). With increasing wave's steepness, this difference is increased. Explanation of this should be sought in features of elementary processes during water breakdown.

C. Research of Breakdown Time Structure

If the initial strength of the electric field is insufficient to ionize the water, then from effect of high pulsed voltage on treated medium to formation of high-conductivity leader channels, there passes some time - t_1, which is called the delay time [8]. During this time, ions move to the electrodes, neutralization and formation of gaseous oxygen at the anode and hydrogen near the cathode, i.e. a conventional electrolysis process is carried out. In addition to it, water is heated up and boiled in places with the highest current density (at the tip of the "pin" electrode or at the boundary of the insulation-metal electrode). Therefore, the formation of gas inclusions as a result of pore formation is possible. In gas inclusions, the field strength can become sufficient for an independent discharge in them. If the occurrence of an independent discharge in gas inclusions does not cause a local increase in the strength in a liquid sufficient for ionization, then the breakdown is effected by an increase in the zone of gas inclusions. Discharge in gas inclusions can lead to a sharp local increase in the electric field strength, sufficient for the ionization processes in water and the formation of the leader.

Time before the formation of the leader (the delay time) can be determined as the sum of the delay time - t_1 and the discharge time in the gas inclusions - t_2. The leader stage of the discharge ends with a final jump-an increase in the germination rate of the leader near the opposite electrode. Leader's formation time is made up of its "normal" development time - t_3 and the final jump - t_4. If we denote the time of the reverse discharge - t_5, then the breakdown time of the water gap (before the formation of the discharge channel) will be:

$$t = t_1 + t_2 + t_3 + t_4 + t_5 \quad (1)$$

The components of the breakdown time vary depending on the type of the gap, its length, voltage, electrical conductivity of water and a number of other reasons. In addition, there is a statistical spread of the duration of the individual stages. Therefore, the determination of the exact time values of the individual stages of the breakdown requires a large number of experiments. Based on the results of the conducted studies of the process of water breakdown, one can obtain only a qualitative idea of the duration of individual stages of breakdown. In the investigated ranges of the lengths of gaps and voltages, the times of the final shock and reverse discharge in tap water are small in comparison with the duration of the other breakdown stages. In this case the breakdown time will be equal to:

$$t = t_1 + t_2 \quad (2)$$

In short intervals $t_2 << t_1$, so the breakdown time is determined mainly by the delay time. In the voltage range from U_1 to U_2, the breakdown time will be:

$$t = t_1 + t_2 + t_3 \quad (3)$$

At voltages greater than U_2:

$$t = t_1 + t_3 \quad (4)$$

In long intervals, the delay time can be neglected and the breakdown time can be taken equal to the time of the leader stage.

D. Description of Mechanism of Water Breakdown

Currently, there is not enough materials about water structure. Some authors are considering water as crystal. Also there is opinion that water structure is complex and with many anomalies (depending on external conditions, prehistory and especially on impurities content). In water under normal conditions there is crystal lattice of ice-tetrahedron or an ice-like frame with voids by various shapes that are filled with water molecules, which have hydrogen bonds among themselves. There are practically no free H_2O molecules in water (less than 1%), because hydrogen bonds between water molecules in framework cavities are thermodynamically more favorable than other states.

Therefore, water can be considered as crystal or polymer compound $(H_2O)_n$. Available data on so-called magnetic treatment of water, as well as on change in dielectric constant with water motion in magnetic field, prolonged preservation of "new" water properties after its termination indicate that water structure is probably close to crystalline.

In breakdown of crystals, not only shock ionization-interaction of free electron with electron in lattice and transition of lattice electron to conduction band or formation of holes in normal zone can occur, but also so-called electrostatic ionization (tunneling effect) - transition of electrons without expenditure of energy for sufficiently large field intensities that cause slope and widening of energy bands of lattice.

With electrostatic ionization, current build-up near the cathode occurs in conduction band due to increase in electrons, and at anode in normal zone due to its emptying. Breakdown process is an occurrence of avalanches leads to destruction of crystal lattice. When shock or electrostatic ionization occurs in avalanche, free electrons and positive ions are formed. With negative electrode, some electrons leave near-electrode area, forming in gap negative space charge when colliding with molecules of medium or settling on crystal lattice defects.

Magnitude of space negative charge distributed in gap depends on intensity of avalanches and rate of its neutralization. In water, this charge is likely to be neutralized quickly. With positive polarity near the electrode there will be positive space charge, since electrons leave electrode. With rectangular voltage close to leader's formation one, avalanche intensity is small and, therefore, influence of negative space charge can be neglected. Negative electrode will have more favorable conditions for leaders emergence, since field distortion at cathode due to gas generation is greater than on anode.

Therefore, minimum voltage for leader's formation on negative polarity is less than on positive one. With voltage growth, intensity of avalanches increases, volume charges increase and their influence on emergence and movement of leader channels. On other voltage waves, ionization rate increases with time, and space charge accumulates in ionization zone. Therefore, explanation of difference in initial voltage value for leader process and their speed at different polarities seems convincing.

However, for small wave steepness, voltage ratio of beginning of leader process for different polarities can change and become same as for rectangular pulses or constant voltage. Voltage wave front on rectangular pulses with amplitude close to initial voltage value probably does not matter, since accumulation of charge occurs from moment of reaching certain minimum intensity at which avalanche processes can take place. Time to reach required intensity usually considerably exceeds front duration.

Thus, in water breakdown, leader's occurrence time is determined by distortion of electric field that occurs during electrolysis, and also by accumulation rate of space charge [9]. If field intensity is high enough, formation of gas inclusions, as a slow process, will not have time to significantly distort electric field during leader's occurrence time. Time in this case will depend on mobility and neutralization mode of ions. At certain duration of pulse wave, breakdown of short intervals will occur at different voltages, depending on dissolved salts (at sufficient concentration of solution).

At low concentrations, ions of dissolved solution are insignificant in comparison with water ones, so breakdown process does not depend on properties of dissolved substance. Decisive (at low voltages) is only value of electrical conductivity. Experience shows that higher leader's speed, greater its brightness and less channel diameter. At low voltages, when rates of negative and positive leaders are little differed, their brightness and channel diameter are approximately same and reaches ~1-2 mm. With voltage growth brightness of positive leaders is increased, since their diameter is much smaller than negative ones (~0.1÷0.2 mm at 80 kV).

Brightness of leader channel is determined by current density and its duration. Leader's current is mainly determined by conduction current flowing not only near the leader's head, but also along entire length of channel. If consider some element of leader channel, we will have increasing in time current value. Rate of current increase is determined by germination rate of leader. Allocation of energy in leader's channel proves sufficient for its rapid heating. Usually, heating is accompanied by explosive expansion of leader's channel with formation of shock waves in liquid. Rate of that expansion is determined by dissipated energy in channel and physical properties of treated medium.

With rapid introduction of energy (high rate of leader's germination), due to medium inertia, leader's channel does not have time to expand rapidly. Therefore, we will have in this case large current density in leader's channel, temperature and brightness. It is known that brightness of leaders' channels depends on electrical conductivity of water medium. In breakdown of distilled water, brightness of leader's glow is comparatively small. With growth in electrical conductivity brightness of leader's channel is strongly increased while rates of leader's germination are slightly dependent on its value. Thus, it can be concluded that in the breakdown of tap water energy parameters of leader's channel are mainly determined by conduction currents.

III. CONCLUSIONS

Thus, in presented article, physical processes in water mediums under influence of high electromagnetic pulsed fields were investigated, methods for measuring parameters (potential distribution and field's intensity), characteristics of formed high-speed leader channels were considered. It was found that such discharge characteristics as leader's occurrence time, their rate and energy released in channel depend on pulse amplitude, its polarity, and parameters of treated medium.

It is revealed that at low voltages and negative pulse polarity, leader's occurrence time is less than for positive one. This is explained by sharp distortion of electric field around potential "pin" electrode due to electrolysis processes. With increasing voltage amplitude, processes with positive pulse polarity (in comparison with negative one) become more active and, due to high amplification of electric field intensity in whole interval, speed of leader channels sharply increases due to decreasing the leader's occurrence time and rapid input of source energy into the channel. This, in turn, leads to formation of various high-speed processes in water medium which are of high scientific interest.

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BIOGRAPHIES

Elchin Jalal Gurbanov was born in Kurdamir, Azerbaijan on February 12, 1963. In 1980, he graduated from school No. 151 in Baku, Azerbaijan and entered in Faculty of Electronic Equipment, Moscow Power Engineering Institute, Moscow, Russia. In 1986, he successfully graduated that institute by specialty "Electronic devices" and start to work in High Voltage Laboratory in Physics Institute, Azerbaijan National Academy of Sciences, Baku, Azerbaijan. In 1995, he successfully defended a candidate dissertation regarding the high voltage treatment of compositional materials and received a scientific Ph.D. degree in physics and mathematics sciences. In 2006-2010, he studied in doctorate level in high voltage department of Moscow Power Engineering Institute (Technical University). From 2013, he works in Science Department of "Azersu" Open Joint Stock Company, Baku, Azerbaijan. He published more than 90 scientific articles in different journals, 1 author certificate and 2 patents.

Arif Mamed Hashimov was born in Shahbuz, Nakhchivan, Azerbaijan on September 28, 1949. He is a Professor of Power Engineering (1993); Chief Editor of Scientific Journal of "Power Engineering Problems" from 2000; Director of Institute of Physics of Azerbaijan National Academy of Sciences (Baku, Azerbaijan) from 2002 up to 2009; Academician from 2007; the First Vice-President of Azerbaijan National Academy of Sciences from 2007 up to 2013; and Director of Azerbaijan Research Institute of Energetics and Energy Design from 2014 till now. He is laureate of Azerbaijan State Prize (1978); Honored Scientist of Azerbaijan (2005); Cochairman of International Conferences on "Technical and Physical Problems of Power Engineering" (ICTPE) and Editor in Chief of International Journal on "Technical and Physical Problems of Engineering" (IJTPE). Now he is a High Consultant in "Azerenerji" JSC, Baku, Azerbaijan. His research areas are theory of non-linear electrical Networks with distributed parameters, neutral earthing and ferroresonant processes, alternative energy sources, high voltage physics and techniques, electrical physics. His publications are 300 articles and patents and 5 monographs.

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