Analysis of operational data on the work of hydro power plant

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Abstract: *Paper focuses on the use of renewable energy sources and in particular the use of water energy. A hydro power plant is a complex of facilities and equipment for converting the energy of the water flow into electrical energy. The advantages of hydro power plants are obvious – a supply of energy constantly renewed by nature itself, simplicity of operation, absence of environmental pollution. Taking into account the growing role of small and medium-sized enterprises in the economic development, both of an individual country and on a global scale, as well as the widespread orientation towards the use of renewable energy sources in the production of electricity, the main goal of the current development is the analysis of the operation of the electrical part of a specific hydro power plant with small power. Statistical processing of operational data on the change of certain variables was carried out. In conclusion, it is summarized that the hydro power plant under consideration has good operational indicators.*

Keywords**:** *RENEWABLE ENERGY SOURCES, HYDROELECTRIC POWER GENERATION, DATA ANALYSIS*

1. Introduction

In order to achieve the set goal, namely the analysis of registered data from the operation, the following tasks have been solved:

- consideration of hydro power plant (HPP) as a source of electricity;
- presentation of the features of the activity of a specific hydro power plant;
- calculation of summary indicators from the processing of registered data, based on statistics.

The energy of water has served man for many millennia. Earth's reserves are colossal. No wonder some scientists believe that it would be more correct to call our planet not Earth, but Water - after all, about three-quarters of the planet's surface is covered with water. It is clear that mankind could not pass through the gigantic reserves of water in its demand for energy. The earliest people learned to use the energy of water. But when the golden age of electricity came, the water wheel was revived, but in a different form, in the form of a water turbine. Electric generators producing energy must rotate, and water can do that quite successfully. Moreover, there is already a centuries-old experience of this. It can be considered that modern hydropower was born in 1891.

Nearly 30% of the electricity worldwide is produced by means of hydroelectric power generation and about 88% of the energy coming from renewable sources is hydroelectric [1].

Each HPP is a complex of facilities and equipment for converting the energy of the water flow into electrical energy. The advantages of a HPP are obvious – a constantly renewable energy supply from nature itself, simplicity of operation, low maintenance costs, their life cycle is very long, absence of environmental pollution. In addition, a HPP can reach its maximum output within a few minutes. In comparison, it takes a few hours for a thermal power plant (TPP). The main disadvantage of hydroelectric power plants is that they cannot always maintain a constant load due to the variability of the intensity of the corresponding energy, in this case water energy.

Hydro power plants range from very small micro-hydro power plants to huge dams that provide electricity to millions of people. The distinction between small, mini- and micro-hydro power plants is conditional, although it is accepted in almost all countries of the world that the classification is based on the available installed capacity. The category of small HPPs includes plants with an installed capacity equal to or less than 10 MW, mini HPPs are called plants with a capacity of 500 to 2000 kW, and micro HPPs – up to 500 kW [2].

A hydraulic turbine (water turbine) is a prime mover that converts the mechanical energy of water (its positional, pressure and velocity energy) into the energy of a rotating shaft. A hydraulic turbine uses the force of gravity of water descending from a certain height, called head. The main parts of the turbine are the impeller located on the rotating shaft and the fixed guide jet device located in front of it. Water, under pressure higher than atmospheric, is directed to this apparatus. When exiting narrow openings, it gains great speed. Inside the wheel, this speed is reduced and its direction changed. The resulting inertial forces create a torque in the wheel which is transmitted to the shaft. The electrical generator, usually located on this shaft (in a horizontal or vertical position), converts the energy of the rotating shaft into electrical energy transmitted to the grid. The set of turbine and generator is called a hydro unit. Hydraulic turbines work under head from 2 to 2000 meters. The amount of water passed through the turbine in one second is called flow rate. It reaches up to 800 m^3/s. The power delivered by the turbine to the shaft is proportional to the head, the flow and the coefficient of useful action (efficiency), which determines the degree of use of the energy of the passing water by the turbine and is usually between 0.75 and 0.94.

Existing turbine systems are divided into two classes: active or impulse (free-jet) and reaction (pressure-jet) turbines. The Pelton turbine belongs to the first, and to the second - radial-axial flow (Francis turbine) and axial-flow, divided in turn into propeller (screw) and with reversible blades (Kaplan turbine). The ability of different turbines at the same head and power to operate with good efficiency. at a different number of revolutions per minute of their wheels is evaluated with a special coefficient called rapidity. It has values from 2 to 5 for the Pelton turbine, from 70 to 400 for the Francis turbine, and from 400 to 1000 for the shafts. The lower the head and the greater the power of the turbine, the higher the rapidity of the turbine should be selected.

Inside the impellers of jet turbines, the water pressure is reduced at the expense of high speeds and becomes less than atmospheric. In such cases, a phenomenon called cavitation sometimes occurs. Depending on the needs of the electrical grid for energy, the unit produces and supplies to the network sometimes more, sometimes less energy. The variation of the load on the unit is achieved by adjusting the turbine. At the same time, the automatic regulator changes the position of some parts of the guide apparatus and feeds into the impeller sometimes a larger, sometimes smaller flow.

A hydro generator is an alternating current (rarely direct) generator set in motion by a hydraulic turbine. Usually, the hydro generator is an salient-pole three-phase synchronous generator, the rotor of which is usually attached to the same shaft as the turbine impeller. Hydro generators are built with capacities from 100 to 100,000 kW and more at rotation speeds from 50 to 500 (rarely 1500) min^{-1} and voltage from 400 to 16,000 V.

The frequency of the induced voltage in the synchronous generator depends on the rotation frequency n, [min^{-1}] and the number of stator pole pairs p:

$$f = pn \quad (1)$$

The frequency of the generated voltage is set in advance by the grid (most often 50 Hz). The rotational frequency depends on the type of turbine. In the case of hydropower turbines, n is a small value, but p – a large one. For the turbines of the TPP, n is a large value, and p – a small one.

Due to the relatively low rotation speeds of the hydro generators, at a frequency of the generated current of 50 Hz they have many poles (120 at 50 min^{-1}) and in terms of size and weight they are significantly larger than other electric machines of the same power.

2. Describing of the considered hydro power plant

Hydropower is the most common form of the renewable energy sources (RES) portfolio and produces around 17% of the world's electricity, but its capabilities are limited, in the sense that where possible, such plants have generally already been built. This energy can be highly competitive with other types of energy from RES, given that there are high water falls in Bulgaria and a large annual water flow.

The efficiency of the conversion of the primary resource energy into electricity is the highest in hydropower plants (85-95%), compared to all other energy technologies (Fig. 1) [3].

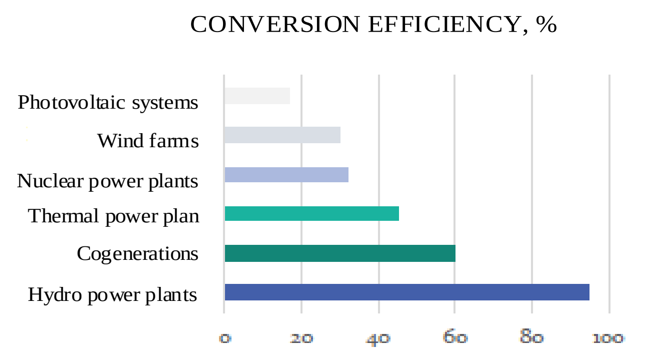

Fig. 1 *The efficiency of the conversion of the primary resource energy into electricity.*

In Bulgaria, over 60% of the renewable energy is produced by hydro power plants, the installed capacities are 3,330 MW, the energy produced by them in 2018 is 5,095,621 MWh, the financial expression of saved CO_2 emissions for 2018 is 10,953,613 BGN million [3].

Out of a total of 92 hydro power plants, more than 2/3 are small, occupying nearly 6% of the installed capacities and 14% of the average annual electricity production in the country. The ownership structure is dominated by privatized small hydropower plants (80.3%), in which a significant part of the installed capacities (92.6%) and the production of the sub-sector (91.9%) are concentrated.

Pursuant to the Law on Energy from Renewable Sources (based on relevant acts of European legislation - directives and regulations, in force from 03.05.2011) a preferential price is set for the purchase of electrical energy produced from renewable sources, including electrical energy, produced by hydroelectric plants with a total installed capacity of up to 10 MW. Hydro power plants with an installed capacity greater than 10 MW are not treated as RES, because other phenomena occur with them - e.g. change of the local climate in the presence of dams, etc. The creation and connection of energy objects for the production of electricity from RES (photovoltaic systems with a total installed capacity of up to 30 kW inclusive, which are planned to be built on roof and facade structures of buildings connected to the electricity distribution network and on real estates attached to them in urbanized territories, HPPs with an installed electrical capacity of up to 1.5 MW inclusive) is under reduced and preferential conditions.

Hydro power plant ‘Enina’ is located to the east of the village of the same name, at a distance of 8 km north of the town of Kazanlak, at the foot of Balkan in Central Bulgaria. The catchment area is in a national reserve. HPP ‘Enina’ is a plant with a capacity of up to 1.02 MW, with three hydrogroups in number. The maximum water quantity (water flow) is 1.3 m^3/s, and the head (water fall) – 101.9 m.

The plant has been in continuous operation since its inception until now. It is the oldest operating plant in Bulgaria, built and put into operation on January 1, 1914, it still functions and produces electricity with the old turbines and generators, as it was created. The city of Kazanlak was supplied with electricity on December 31, 1913, at exactly midnight. The city lights up - all businesses and buildings whose owners have trusted the creators. The rapid development of the city begins. The availability of electricity makes it possible to create modern enterprises and factories, and this attracts a lot of foreign capital. By creating the HPP ‘Enina’, Kazanlak is ahead of cities like Plovdiv, Ruse, Burgas, Sliven and serves as an example to follow. The availability of electricity helps the rapid industrial and cultural rise of the city. In 1937, a new 740 hp hydro generator set was delivered to the plant. On December 25, 1947, the HPP ‘Enina’ was nationalized and from 1947 to 1993 it was state property. At the beginning of 1994, the plant was restituted to the previous owners, who registered the company ‘Pobeda’ Ltd. for the purpose. In 1972, a museum collection was created.

An interesting fact is that the construction of the plant was accompanied by many ups and downs. In addition to problems with the builders, the construction activity had to be suspended for a whole year due to the outbreak of the Balkan War, and then the Inter-Allied War. The locals rise up and start sabotaging the work. The first rumor that is spread in the village of Enina is that the electricity on the water will kill the cows that are at the watering hole. Thus, the village sank into darkness at night for many years, while the town of Kazanlak had electric street lighting through a built power transmission line from the HPP ‘Enina’.

The amount of electricity produced is strongly dependent on the annual water runoff, i.e. the climatic factor is decisive for the income of the company-owner. For a period of 35 years, for which reliable data is available, the following can be established:

- peak annual production of electrical energy – 4111824 kWh;
- minimum annual electricity production – 1384930 kWh;
- average annual electricity production for the last 35 years is 2581000 kWh.

The technical base available to the company is as follows:

- own buildings (machine room, apparatus room and substation);
- facilities - pressure pipelines, high-speed channels;
- power machines - hydrogroups; control panel, measurement, protection, automation and signaling; closed switchgear; transformers – 3 units for each hydro group, 1 unit each; battery with rectifier for excitation of the generators.

The hydrogroups (three numbers) consist of:

- Turbine horizontal, type Francis (1 piece). The power of the turbine is regulated by a guide apparatus. This hydro unit has downtimes due to design imperfections (rolling bearings on the turbine shaft and an intermediate third bearing in the middle of the shaft). Power 540 kW, rotation frequency Nn = 1500 min^{-1}, made in Germany.
- Pelton type turbines (2 pieces) with a power of 240 kW, rotation frequency Nn = 750 min-1, manufactured in 1912 in

Switzerland. The power of each of the turbines is regulated by two nozzles per impeller.

Although the machines are many years old, their technical condition is good and they are excellently maintained, have no significant defects and have a low accident rate and little downtime. These three hydro groups are located indoors, in an machine room. A general view of the machine room is shown in Fig. 2.

Fig. 2 *A general view of the machine room of the HPP 'Enina'.*

The plant does not have a water catchment basin and the power of operation is determined by the amount of water entering the river. This is achieved automatically by a level regulation device that monitors the water level in an apparatus chamber and changes the load on the turbine so as to maintain a constant level. Reaching extreme 'high' and 'low' levels are signaled and operating personnel start or stop the next turbine.

The electric generators are three-phase synchronous, PFL type, manufactured by 'SIEMENS-SCHUCKERT'.

The following can be briefly mentioned about the company 'SIEMENS':
In 1903, 'SIEMENS & HALSKE' bought the company 'Elektrizitäts-Aktiengesellschaft vorm. Schuckert & Co.', merging it with its own power engineering division, thus forming 'SIEMENS-SCHUCKERT-WERKE' GmbH. The aim of the new company is to cover all areas of electrical engineering. The history of 'SIEMENS' is over 170 years old. Since its founding by Werner von Siemens, the company has grown into a global innovation network with more than 400,000 employees in over 190 countries worldwide.

Данни за генераторите :

- Generator 1: apparent power S_n = 640 kVA; rated voltage U_n = 6.3 kV; power factor $cos\varphi = 0.8$;
- Generator 2 and Generator 3: apparent power S_n = 240 kVA; номинално напрежение U_n = 6.3 kV; power factor $cos\varphi = 0.8$.

The original nameplate of one of the electric generators is presented in Fig. 3.

Fig. 3 *Nameplate of one of the operating generators.*

In terms of technological mode, the primary electrical circuit of the HPP 'Enina' is based on the 'generator-cable-transformer block' principle.

Each hydro group comprises a turbine, a synchronous generator, a line, a step-up transformer. Parallel work to the country's energy system is carried out on 20 kV buses.

The frequency of each turbine is maintained by a turbine generator, which is connected to the shaft of the turbo group by two belt gears: one to drive the centrifugal tachometer and the second to drive the oil pump of the regulator for the turbine guide apparatus or the position of the nozzle needles of the turbine. The turbine is stopped by a hydraulic braking system. In order to safely shut off the water flow when the machine is stopped, a wedge valve is installed in front of each turbine. The temperature of the turbine and generator bearings is continuously monitored by a measuring unit.

All the technological and relay protections necessary according to regulations and rules have been built and are in operation, ensuring continuous and safe operation of the HPP 'Enina'.

All employees have a long experience at the HPP 'Enina', i.e. they are highly qualified specialists with the necessary experience. Every year they take aptitude tests and requalifications according to the requirements of regulations in the energy system. The microclimate is good, provides comfortable conditions for workers, ensuring the health of workers and ensuring good self-esteem and high work capacity.

3. Summary indicators for statistical processing of registered data

Mathematical statistics is applied as a tool facilitating the carry out of scientific research and the accumulation of data in the field of technology. In order to be able to use the apparatus of mathematical statistics, the researcher must first of all be able to find some numerical characteristics and draw statistical distributions, with the help of which the necessary conclusions can be done later.

Cumulative data can generally be thought of as measurements of certain properties of objects selected from some large *population*. Information on certain characteristics of the elements is registered by *sampling*. Elements of the population are the so-called *statistical units* [4].

With the help of *samples* by measurements, some statistical indicators are determined, which are used to draw conclusions about some quantitative characteristics or parameters of the source *population* from which the sample was taken. There are an unlimited number of problems, but still some properties of the distribution of population values are particularly often studied. For example, we are usually interested in the mean value of some population characteristic.

Position characteristics

There are several characteristics of the state of the empirical data population. The most common are the *arithmetic mean value* and the so-called the *median*. In short, the arithmetic mean is the value about which the entire empirical distribution can be "balanced". On the other hand, the median is such a value that one half of the sample values are smaller than it, and the other half of the values are larger (the median divides the area of a possibly drawn histogram into equal halves).

For raw (ungrouped) data $x_1, x_2, ... x_n$ the arithmetic mean is,

$$\bar{x} = n^{-1}.\sum_{i=1}^{n} x_i \qquad i = 1,2,......n \tag{2}$$

If the sample size is an even number, for example $n = 2r$, then the median can be thought of as half the sum of two means:

$$M_e = \frac{1}{2}.(x_r + x_{r+1}) \tag{3}$$

As a characteristic of the position, a *geometric mean value* can also be used. In the case of sample volume n, the geometric mean is defined as:

$$\bar{\sigma} = (x_1 x_2 ..... x_n)^{\frac{1}{n}} \tag{4}$$

Another characteristic is the *harmonic mean value*:

$$Q_{mean} = \left(n^{-1}.\sum x_i^{-1}\right)^{-1} \tag{5}$$

Dispersion characteristics

One of the most commonly used characteristics of data dispersion is the *mean square deviation*. First, the square of this quantity, called the *variance*, is determined.

For a sample of ungrouped data, the variance is defined as:

$$s^2 = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1} \tag{6}$$

The *mean square deviation* is defined as the positive square root of the variance. For ungrouped data:

$$s = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}} \tag{7}$$

In the case of ungrouped data, the formula can be converted to a more convenient form:

$$s = \sqrt{\frac{\sum_{i=1}^{n} x_i^2 - \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n}}{n-1}} \tag{8}$$

Another dispersion characteristic is the *standard deviation*:

$$\frac{\sum_{i=1}^{n} |x_i - \bar{x}|}{n} \tag{9}$$

4. Results obtained

A set of recorded data on the generated electrical energy from a specific hydroelectric power plant for a period of 2 years was considered.

This real statistical population of statistical units, which in this case are empirical data for active and reactive energy, has been processed, which allows certain regularities to be established based on analysis. The tables made, including calculation results, are implemented according to the rules of statistics [5].

The so-called scattering meters are presented in tabular form [6], respectively arithmetic mean, median, quadratic mean, geometric mean, harmonic mean.

The registered data were recorded by static electronic electricity meters "Schlumberger" at the terminal (lead) 'Kazanlak' - 20 kV in the HPP 'Enina'. The registered data were obtained after establishing professional contacts with representatives of 'Pobeda' Ltd. and the operator of the electric distribution network EVN Bulgaria.

Table 1 presents data on sold active and sold/bought reactive electrical energy for the month of April in the second year under review. The bought reactive electricity is necessary for the operation of the excitation of the electric generators, since they work in parallel with the power system, and not independently.

Table 2, Table 3 and Table 4 present calculated summarizing indicators of the produced active electricity during night, day and peak respectively for the two years under consideration.

Figure 4 presents the sold active electricity in kWh for a period of one year for the three reporting zones: I – night, II – day, III – peak.

Table 1: *Sold active and sold/bought reactive energy for the month of April of the second year.*

Zone	Inter-change	New reading	Old reading	Difference	Active electricity sold, kWh	Reactive electricity, kVArh
I - night	*sold*	12700	5400	7300	219000	
	bought	10	10	0		
II - day	*sold*	17300	7800	9500	285000	
	bought	20	20	0		
III - peak	*sold*	12800	6900	5900	177000	
	bought	0	0	0		
Total sold active electricity					**681000**	
I - night	*sold*	1700	1220	480		14400
	bought	650	120	530		15900
II - day	*sold*	2400	2000	400		12000
	bought	2000	600	1400		42000
Total sold reactive electricity						**26400**
Total bought reactive electricity						**57900**

Table 2: *Summarizing indicators of the active electricity produced in zone II - day by the HPP 'Enina' for the period of the two years under consideration.*

Indicators					
arithmetic mean	median	quadratic mean	geometric mean for year I	geometric mean for year II	harmonic mean
$\bar{x}$	M_e	S	$\bar{\sigma}_I$	$\bar{\sigma}_{II}$	Q_{mean}
85761,67	82500	73149,27	21513,91	102074,70	10172,7

Table 3: *Summarizing indicators of the active electricity produced in zone I - night by the HPP 'Enina' for the period of the two years under consideration.*

Indicators					
arithmetic mean	median	quadratic mean	geometric mean for year I	geometric mean for year II	harmonic mean
$\bar{x}$	M_e	S	$\bar{\sigma}_I$	$\bar{\sigma}_{II}$	Q_{mean}
64966,25	63600	56291,72	13634,91	75118,17	5325,91

***Table 4:** Summarizing indicators of the active electricity produced in zone III - peak from the HPP 'Enina' for the period of the two years under consideration.*

Indicators					
arithmetic mean	median	quadratic mean	geometric mean for year I	geometric mean for year II	harmonic mean
$\overline{X}$	M_e	S	$\overline{\sigma}_I$	$\overline{\sigma}_{II}$	Q_{mean}
60623,7	53550	43144,34	24697,77	70598,09	10253,42

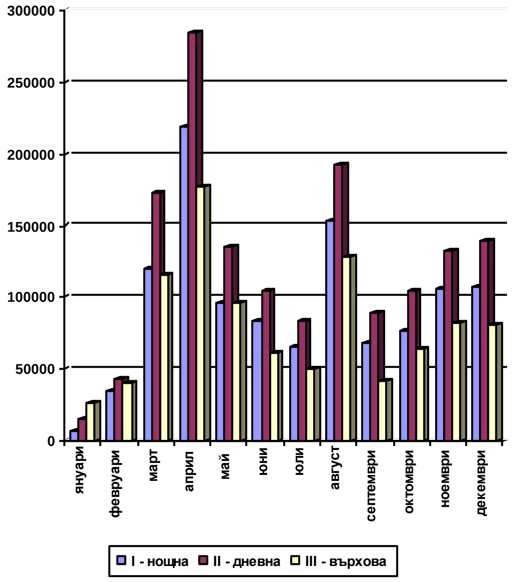

***Fig. 4** Graphic representation of the sold active electricity in kWh for zones I – night, II – day, III – peak for a period of one year.*

As an addition, it should be mentioned that the Bulgarian State Commission for Energy and Water Regulation, as of January 1, 2022, determined an estimated market price respectively for the electricity transmission operator (TSO), the electricity distribution operators and the producers of electricity from hydroelectric power plants with an installed capacity of no more of 10 MW in the amount of BGN 283.48/MWh excluding VAT [7]. Active electricity generated by the HPP 'Enina' is currently being purchased at this price.

From the graphical presentation of the sold active electricity in kWh for zones I - night, II - day, III - peak for one year in Fig. 4 it can be seen that the highest values are in the months of April and August, followed by March and December.

Generators can supply the grid with more power if the driving power on the hydropower side can be increased. The rotational frequency does not change, as it is determined by the mains frequency.

In February of the second monitored year, purchased amounts of electrical energy of 10 kWh at night and 20 kWh during the day were reported. It is likely that there was a failure in one of the turbines or in the transmission mechanisms shortly before 06:00 a.m. when the electricity meter switches between reading night and day energy. In principle, any rotating electrical machine is reversible and can be used as a generator or a motor. If the driving machine (turbine in this case) fails (shuts down), the generator continues to rotate as a synchronous motor, powered by the grid to which it is connected.

5. Conclusions

Statistics is a mathematical discipline that studies the extraction of information through the analysis and interpretation of empirical data using probability theory. Using statistics, the measures of dispersion were determined - arithmetic mean value, median, root mean square deviation, geometric mean value, harmonic mean value. The root mean square deviation is important because it is a more precise measure than the range (i.e., width of variation or the numerical difference between extreme values). The root mean square deviation acts as the most accurate and adequate measure of population dispersion and is therefore the most widely used.

After examining the HPP as a source of electricity and presenting the features of the activity of the HPP 'Enina', the main goal has been achieved, namely the summarizing indicators for the plant's activity have been derived based on registered data for a two-year period.

The advantages of RES are: inexhaustibility and ubiquity; the possibility of their energy being accumulated and then transformed (analogous to photosynthesis in botany); the possibility of building relatively small power plants that do not load the transmission network. Or more generally, the development of renewable and alternative energy sources has a positive effect in the following directions:

• diversification of energy sources;

• more rational utilization of local resources and reduction of imported ones, i.e. greater resource independence of our economy in general and especially in a period of energy crisis, when decentralized resources such as renewable energy provide essential help for the security of supply;

• increasing energy efficiency;

• improvement of the environmental indicators of the Bulgarian energy sector.

As with other sources of energy, the goal of RES is to generate energy at the least cost. However, adequate programs, investments and mechanisms are needed to encourage the further development of this production. The dynamic regulatory environment that has been observed in recent years and the introduction of retroactive measures have a significant negative effect on the financial situation of companies, worsen the competitiveness of hydroelectric power generation and prevent the implementation of new projects in the sector. In order to avoid the adverse consequences of this policy, which will most sensitively affect the price of energy for society, the creation of a predictable regulatory framework ensuring the sustainable development of the sector is an urgent priority.

6. Acknowledgments

The implementation of this paper is thanks to the support from:

- the University Project 2206S 'Applied mathematical investigations in electric power supply and electrical equipment focused on energy and economic efficiency', financed by the Ministry of Education and Science of the Republic of Bulgaria.
- the Project BG05M2OP001-1.002-0023 Competence Center 'Intelligent Mechatronic, Eco- and Energy-Saving Systems and Technologies' financed by the Operational Program 'Science and Education for Intelligent Growth' of the European Regional Development Fund.

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