Запропоновано метод обчислення електричного навантаження об'єктів цивільного призначення. Новизна його, на відміну від визначення за чинними нормативами, полягає в підвищенні точності обчислення. Сутність його полягає в розробленні моделей графіків навантаження електроприймачів, їх синтезу на вводах цивільних об'єктів. Первинна інформація до моделювання базується на попередньо отриманій вимірюванням параметрів графіків навантаження і режимів роботи аналогічних функціонуючих систем електропостачання

Ключові слова: графоаналітичний метод, житлово-комунальне господарство, електричне навантаження, моделювання графіків, похибка обчислення

Предложен метод вычисления электрической нагрузки объектов гражданского назначения. Новизна его, в отличие от определения по действующим нормативам, заключается в повышении точности вычисления. Сущность его, в разрабатывании моделей графиков нагрузки электроприемников, их синтеза на вводах гражданских объектов. Первичная информация для моделирования базируется на предварительно полученной измерением параметров графиков нагрузки аналогичных функционирующих систем электроснабжения

Ключевые слова: графоаналитический метод, жилищно-коммунальное хозяйство, электрическая нагрузка, моделирование графиков, погрешность вычисления

UDC 621.316.11
DOI: 10.15587/1729-4061.2017.103032

DEVELOPMENT OF THE GRAPHICAL-ANALYTICAL METHOD FOR CALCULATING ELECTRIC LOAD AT CIVILIAN OBJECTS

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1. Introduction

The task of accurate calculation of electric load on the civilian objects requires advanced methods of its computation taking into account characteristics of modern household appliances, and the application of innovative technologies. The use of acting normative documents leads to exceeding the real load by 1.5 to 3.5 times as evidenced by the numerous recent studies. This greatly affects the magnitude of capital expenditures on the construction and operation of electricity supply systems.

The housing and communal services of Ukraine consume about 44 % of energy resources that makes up about 30 % of the total fuel consumption in the country. The housing fund of the state and social sphere consume about 85 % of energy resources of the total consumption in the sector, which is about 10 billion kW·h, with the alternative and renewable forms of energy not exceeding 1 million tonne of conditional fuel.

The recent years have witnessed a growth in the rates of design and construction of civilian objects, as well as in the level of electrical energy consumption, which reaches the level of its consumption by industrial enterprises. Given this, the exact determining of the estimated loading on civilian objects acquires a fundamental importance for the selection and protection of the elements of electrical supply system of the country as a whole.

The relevance of the chosen topic of research is in the development of a new approach to solve the problem of accurate determining of the electric load at civilian objects.

2. Literature review and problem statement

An analysis of the scientific publications testifies to the fact that the first results regarding the study and substantiation of electrical loads and their prediction appeared in the beginning of the 20th century. However, in terms of determining the loading of civilian objects, detailed coverage of its features has been carried out only in the last decades. Thus, the simulation is examined of daily schedules in power consumption by residential and municipal facilities in order to respond to its demand and to lower the load by using smart networks [1]. The modes of electrical consumption by residential areas with a 15-minute interval have been modeled [2]. Systems architectures are being developed to control the load on intelligent buildings by smart networks that are capable of integrating various sources of energy [3]. The algorithms are constructed for the regulation of electric energy of residential, municipal facilities based on statistical data regarding the forecast for demand in load considering self-adjusting electric receivers [4].

Mathematical models are presented of residential energy centers schedules with renewable power sources, which are included in the automated technological processes of decision making in intelligent networks [5]. The models are proposed to plan energy, as well as algorithms for the optimization of consumption by civilian objects with the dynamics of parameters of wind, solar energy, environment, and pricing [6, 7].

The dynamics of electric load is the result of summation of a large quantity of random processes, which can be subjected to general mathematical procedures when solving the tasks on statistical analysis and prediction of electricity consumption modes. However, no comparison of theoretical calculations and forecasts with actual values of electrical loads of dwellings, houses, civilian facilities exists in practice. In addition, the above-mentioned and other papers in related fields did not report any conducted research into dynamics of electric loads of electrical receivers with a discreteness at the level of ms and the synthesis of their charts at different levels of power supply systems, which greatly improves the accuracy of calculation of the estimated load.

3. The aim and objectives of the study

The goal of present research is to devise a graphic-analytical method, which would improve the accuracy in the calculation of electric load, the application of which would help decrease capital costs for the construction and operation of electricity supply systems of civilian objects.

To accomplish the set goal, the following tasks have been solved:

– we studied experimentally the features of technical specifications of baisc modern electrical receivers at civilian objects using contemporary information technologies, measuring instruments;

– we developed models of loading charts of electrical appliances and their synthesis at the inputs of civilian objects based on the information previously obtained by measuring the parameters of similar objects;

– a comparison was conducted of errors in the calculation of estimated loads obtained from the acting normative documents and by applying the graphic-analytical method, with actual data on the load of functioning civilian objects.

4. Materials and methods to examine parameters, synthesis of the load charts of electrical receivers at civilian objects

4. 1. Experimental research base

The study was carried out using the electric power quality analyzer Elspec G4500 manufactured by the company Elspec Technologies (Israel), from which we derived electric load charts of electrical appliances in a house, a building, and in a supply cable (Fig. 1).

The software PQSCADA Investigator from the company Elspec Technologies (Israel) effectively processes a large number of parameters that are instantly displayed on a PC monitor. The information that arrives from one or several measurement points is represented along one synchronized temporal axis. This allows the researcher to observe clear and instantenous graphical interpretation of the complex processes that occur in the network in a given moment [8].

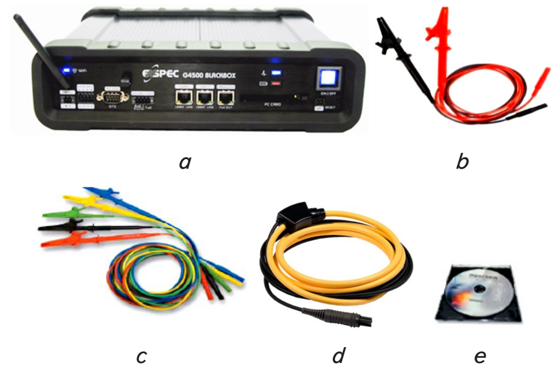

Fig. 1. Set-up for measuring the parameters of electric load charts: *a* — portable device G4500 BLACKBOX Portable; *b* — electric wires for direct current; *c* — electric wires for alternating current; *d*— flexible ticks for alternating current; *e* — the PQSCADA software

Complete continuous registration of data on the electrical signals from a set of measurement points takes place simultaneously.

4. 2. The essence of a graphic-analytical method for the calculation of electric load at civilian objects

According to the acting regulations, an estimated electric load for different levels of the power supply system is calculated at the stage of designing in the following way.

Electric loads of apartments, multi-flat buildings are random and differ from each other because they depend on capacity, quantity, operation mode of household appliances, electrical receivers. They vary significantly over 24 hours, day of the week, month, season of the year, and are calculated according to known formula [9]

$$P_{h.e} = p_{s.h.e} N, \tag{1}$$

where $p_{\mathrm{s.h.e}}$ is the specific estimated electric load of housing that depends on the level of electrification and the number of flats, connected to the given network link, kW/housing; N is the number of dwellings (apartments), connected to the input line.

In the case of connecting objects of various purpose (residential, public) to the building's input line, the resulting active estimated load is determined as [10]

$$P_{e\Sigma} = P_{\mathrm{e.max}} + K_1 P_{\mathrm{e1}} + \ldots + K_n P_{\mathrm{e}.n}, \tag{2}$$

where $P_{\mathrm{e.max}}$ is the estimated largest load from all objects connected to a general point of the network; $K_{1,}\, K_{2,...,} K_n$ are the coefficients of mismatch between the maxima of load of the n-th object and the maximal by load.

Estimated load of power supply and distribution lines and inputs for hotels, organizations is determined by the coefficient of demand.

By using the methods of probability theory and mathematical statistics, it was proved that the formation of load of electrical receivers abides the binomial distribution law. The probability of that out of their total number n, m is switched off at the same time is determined by known formula [9]

$$\overline{p}_{r(m,n)\Sigma}=\sum_{0}^{m}\frac{n!}{m!(n-m)!}K_{n}^{m}(1-K_{n})^{n-m}, \quad (3)$$

where $K_{п}$ is the averaged demand coefficient, that is, the averaged probability of switching off an EA independently from one another over a given period of time.

In the case of a large quantity of electrical receivers, formula (3) will take the form

$$\overline{p}_{r(m,n)}=\frac{1}{\sqrt{2\pi n\bar{K}_{n}(1-\bar{K}_{n})}}\int_{0}^{m}e^{-(m-n\bar{K}_{n})^{2}/2n\bar{K}_{n}(1-\bar{K}_{n})}dm. \quad (4)$$

However, applying these formulae does not reflect clearly the complexity and adequacy of the processes that occur in the electrical network, as their graphic mapping. Determining the estimated load by charts with the appropriate discreteness of dynamics ensures a minimal error in the result of its calculation.

For example, the estimated active capacity of the refrigerator ARC 4020 manufactured by the American concern Whirlpool using a graphical method, that is, by the parameters of chart, obtained experimentally using the software PQSCADA Investigator (Fig. 2), is calculated as [9]:

$$p_{\text{p.x}}=\frac{1}{30}\int_{0}^{30}p_{\text{x}}(t)dt=153 \text{ W}.$$

As an example, we determine the magnitude of the estimated and average active electric load of each EA and the resultant in an apartment with a gas stove based on the chart parameters of these 12 EA, which were experimentally obtained and are stored in the PQSCADA Investigator database, and employing the original data in Table 1.

Calculated by the graphical method, that is, by means of the synthesis of charts of maximal averaged load of each EA over a period of 30 min., it will provide a more accurate determining of the estimated load compared with that calculated in line with acting standards.

Fig. 3 (time 0 is accepted conditionally as 5.20 pm) shows the actual chart of electric load in an apartment for 3 h 45 min. in the evening of a weekday, with EA from Table 1, whose operation modes are given in Table 2.

The resulting estimated load of all EA that was connected to the input of a flat is given in Table 1.

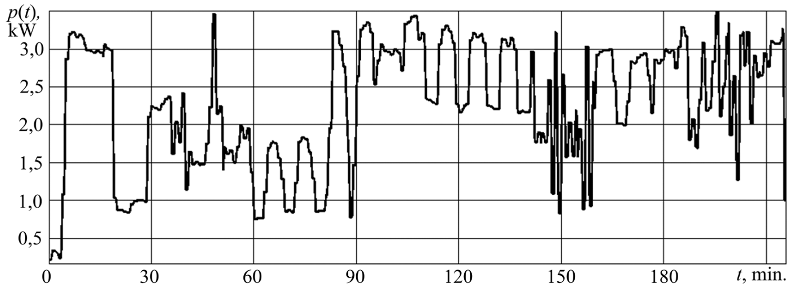

Fig. 3. Dynamics of active electrical load at the input of apartment with a gas stove

The estimated active electrical load of EA in the apartment, determined by the graphical method, that is, by the parameters from the chart obtained experimentally (Fig. 3) [9], is

$$p_{\text{p}}=\frac{1}{30}\int_{90}^{150}p(t)dt=2{,}7 \text{ kW}.$$

Table 1

Original and estimated data on the electrical appliances of an apartment

Original data			Estimated data	
Name	Type, brand	$p_{\text{established}}$, W	$p_{\text{estimated}}$, W	p_{average}, W
Refrigerator	Whirpool	144	153	68
Boiler	Thermex	1500	1470	1470
TV set	SAMSUNG	70	57	57
Washing machine	Elektrolux	2200	828	420
Iron set	BRAUN	1900	633	435
Lighting	CLL	5×20	93.5	93.5
Lighting	IL	6×60	294	294
Computer	Desktop	75	60	60
Air conditioner	Sensei	880	630	610
Electric kettle (3 min.)	TEFAL	2000	89	89
Microwave oven (7 min.)	Samsung	850	99.2	99.2
Total		10079	4406.7	3695.7

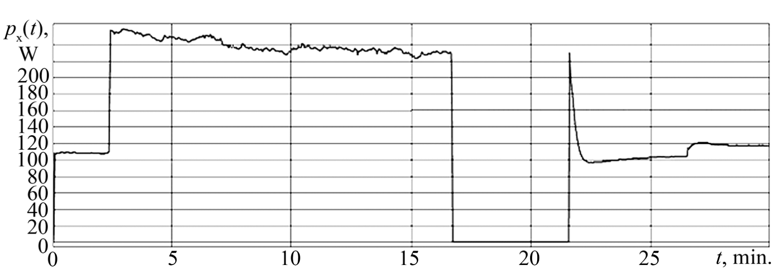

Fig. 2. Dynamics of maximal half-hour electric load of the refrigerator ARC 4020 made by Whirlpool

According to the standards, specific electric load is 5 kW/flat, which is almost 2 times larger than that calculated by the graphical method.

Operation modes of household electrical appliances in an apartment are given in Table 2.

Using the developed applied PC software in the MathCAD programming environment, employing the spline approximation, we constructed chart models for a daily load of 12 apartments with gas stoves over one week (Fig. 4) [9–11], which take the form

$$\text{n=25} \quad \text{TO:} = (0\,1\,2 \ldots\; 22\,23\,24)$$
$$P10 := (1{,}47\;0{,}66\;0{,}13 \ldots\; 1{,}28\;1{,}41\;1{,}68)$$
$$P20 := (0{,}56\;0{,}46\;0{,}35 \ldots 0{,}42\;0{,}23\;0{,}26)$$
$$\ldots$$
$$P110 := (0{,}10\;0{,}09\;0{,}05\; \ldots\; 0{,}28\;0{,}14\;0{,}05)$$
$$P120 := (0{,}70\;0{,}84\;0{,}85\; \ldots\; 0{,}75\;1{,}23\;0{,}37)$$
$$T := T0^T\; P1 := P10^T\;\; P2 := P20^T \ldots P11 := P110^T\; P12 := P120^T$$
$$s11 := cspline(T, P1)\;\; p1(t) := \mathrm{int}erp(s11, T, P1, t)$$
$$s12 := cspline(T, P2)\;\; p2(t) := \mathrm{int}erp(s12, T, P2, t)$$
$$\ldots$$
$$s111 := cspline(T, P11)\;\; p11(t) := \mathrm{int}erp(s111, T, P11, t)$$
$$s112 := cspline(T, P12)\;\; p12(t) := \mathrm{int}erp(s112, T, P12, t)$$
$$t := \min(T) - 0.1 - 0.01, \min(T) - 0.1 .. \max(T) + 0.1\; i := 0..n.$$

Original data for the apartments were obtained from the automated system of commercial account of electricity [9].

Table 2

Operation modes of household electrical appliances in an apartment

EA type	Switching on, hour, min.	Switching off, hour, min.
Lighting	17:20	–
Refrigerator	17:20	–
Freezer	17:20	–
Notebook PC	17:20	–
Desktop PC	17:23	–
Washing machine	17:23	18:30
Lighting	17:33	–
TV set	17:36	–
Air-conditioner	17:53	–
Electric kettle	18:06	18:09
Iron set	18:16	18:28
Microwave oven	18:51	18:56
Boiler	18:58	19:48
Washing machine	19:49	20:49
Electric kettle	20:35	20:39
Microwave oven	20:41	20:46
Iron set	20:47	21:10

The charts in Fig. 4 demonstrate a significant difference in the maxima of active electric load in apartments over time during 24 hours due to different daily activities of the residents in 12 flats.

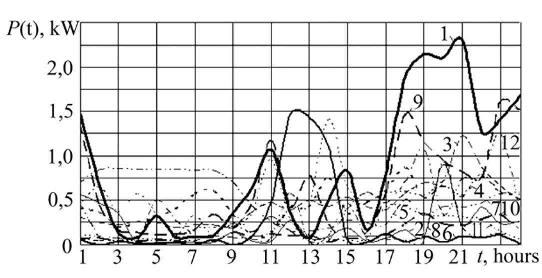

Fig. 4. Charts of daily electric load of 12 flats over Sunday: the number of chart in order corresponds to the number of the apartment

The resulting chart of daily load of 12 flats over Sunday (a day-off) is shown in Fig. 5.

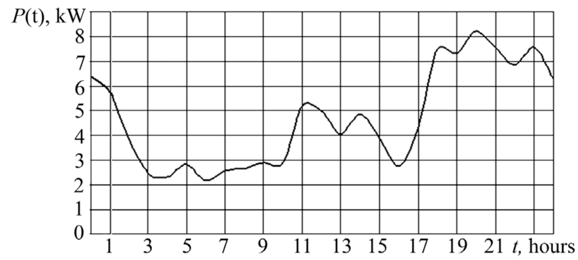

Fig. 5. Resulting chart of a daily load in 12 flats on Sunday

We determined analytically (at specific load on an apartment in line with DBN V. 2.5-23:2010) the estimated active electrical load of 12 apartments in a residential building from formula (1) [9]

$$P_{\text{h.e12}} = 2{,}36 \cdot 12 = 28{,}32 \;\text{ kW.}$$

We determine the resulting estimated active electric load of 12 apartments in a residential building by the parameters of chart in Fig. 5

$$P_p = \frac{\int_{19{,}75}^{20{,}25} P(t)\mathrm{d}t}{0{,}5} = 8{,}2 \;\text{ kW.}$$

Thus, the estimated electric load of 12 apartments in a residential building on Sunday, according to data from automated system for commercial accounting of electricity, and that calculated by the graphical method, is less than the load, which was received by the standards (by DBN) by 3.45 times.

As an example, we determine the estimated electric load in line with standards at the input of a 144-apartment residential building with gas stoves. The result is compared with the experimentally derived actual charts given in Fig. 6.

We determine specific load of one flat of a 144-apartment building by interpolating the standard values

$$P_{s.h.e} = 1{,}0 - \left(\frac{1 - 0{,}87}{200 - 100}\right) \cdot 44 = 0{,}943 \text{ kW/flat.}$$

We determine analytically (in line with the standards) estimated active electrical load of a 144-apartment residential building from formula (1)

$$P_{h.e} = 0{,}943 \cdot 144 = 135{,}8 \;\text{ kW.}$$

We determine active electric load of a 144-apartment residential building using the graphical method based on Fig. 6 as the resulting actual load by phases A, B and C, respectively,

$$P_{\text{h.e}} = 15.98 + 24.98 + 21.18 = 71.14 \text{ kW.}$$

Thus, the actual estimated active electrical load of a 144-apartment building, over the period of its measurement by automated system for commercial accounting of electricity is 1.9 times less than the load, which was obtained from the normative documents.

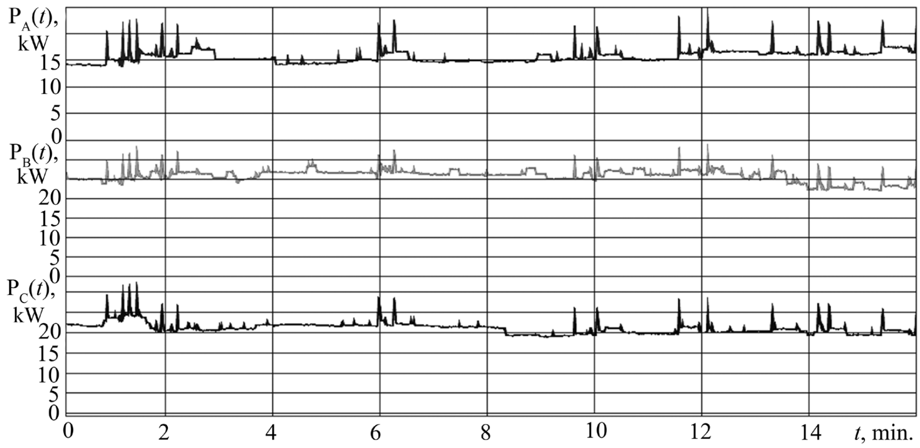

Fig. 6. Charts of actual evening electric load in winter by the input phases of a 144-apartment residential building

The expected daily electricity consumption of residential buildings can be determined graphically by the daily load charts based on automated system for commercial accounting of electricity information on the built-in objects, which are powered from a common input-distribution point (Fig. 7) [9–11].

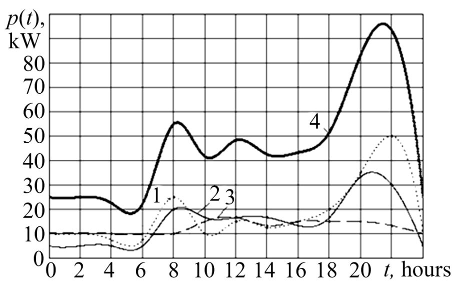

Fig. 7. Daily load charts: 1 – residential building with electric stoves; 2 – rented premises in the building; 3 – a built-in supermarket; 4 – resulting

The estimated active electric load of a residential building with built-in facilities will equal

$$P_{\text{д}.4} = \frac{\int_{21,25}^{21,75} P_4(t)\mathrm{d}t}{0,5} = 94 \text{ kW}.$$

By using Fig. 7, it is possible to determine by the graphical method from the following formulae:

– the amount of electricity consumed per 24 hours

$$W_{24hours.4} = \int_0^{24} P_4(t)\mathrm{d}t; \tag{5}$$

– averaged active electric load per 24 hours

$$P_{filling\ in\ the\ chart\,4} = \frac{\int_0^{24} P_4(t)dt}{24}; \tag{6}$$

– a chart filling coefficient

$$P_{filling\ in\ the\ chart\,4} = \frac{\int_0^{24} P_4(t)\mathrm{d}t}{24 P_{\text{e}.4}}, \tag{7}$$

electricity consumption for any period of the day, and other indicators of electrical load charts that take into account a mismatch in maxima, features of the dynamics of each of them, etc.

5. Results of study into error dynamics in the different methods of calculating the estimated electrical load

Calculation results of the estimated load of civilian objects in line with standards (1) and using the graphical method (2) can be represented in the form of approximating power functions given in Fig. 8, in particular:

1) $P_{e1}(n)$=5.1447$n^{-0,6532}$, kW, with reliability factor $R_1^2 = 0,9981$;

2) $P_{e2}(n)$=1,007$n^{0,8371}$, kW, with reliability factor $R_1^2 = 0,9998$.

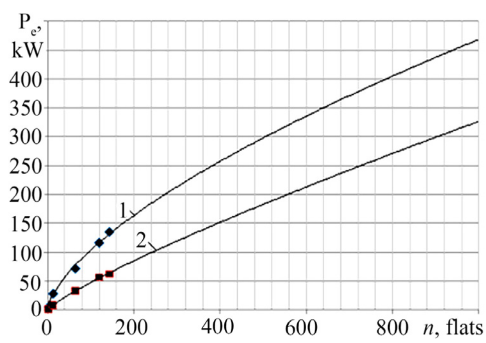

Fig. 8. Dynamics of the estimated load depending on the number of flats, received: 1 – in line with the standards; 2 – using the graphical method

Dynamics of the specific load per apartment in line with the standards (1) up to 1000 flats and using the graphical method (2) can be represented in the form of power functions, which are given in Fig. 9.

Therefore, according to the results of load samples approximation calculated by different methods, one may observe their significant differences. Especially pronounced is a considerable increase in the calculation error, as follows from its dynamics in Fig. 8, 9, with a decrease in the number of electrical receivers, dwellings, houses, objects in general.

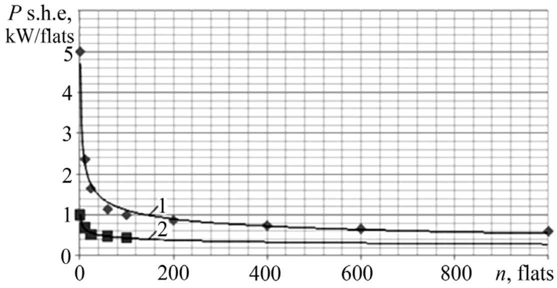

Fig. 9. Dynamics of the specific load per apartment depending on the number of flats, received: 1 — in line with the standards; 2 — using the graphical method

6. Discussion of results of the study on the accuracy of methods for calculating the estimated electrical load

The proposed graphic-analytical method, as evidenced by the study, significantly minimizes calculation error of the estimated electric load at civilian objects.

It is obvious that there is no sufficient information as yet to reconsider the standards in design in line with this method. For its effective use, it is necessary to compile a database of relevant chart models for characteristic EA, houses, buildings, and other objects. It is obvious that this requires the mobilization of significant organizational and technical measures, specialized information technologies. However, the ultimate goal will justify the costs of accumulating such information not only at civilian objects, but also at industrial enterprises, as well as in other sectors.

Taking the above into consideration, further research might be associated with the accumulation of information about chart models of load with a bigger number of objects specific to cities and metropolises (Fig. 10).

Extrapolating by power functions p_1=4.7015$n^{-0,313}$, p_2= =1.0063$n^{-0,186}$ testifies to the high reliability of approximation by the samples, since $R_1^2 = 0.9848$, $R_2^2 = 0.9719$ respectively.

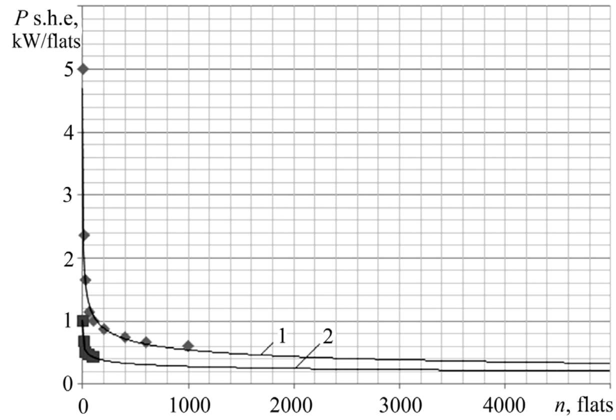

Fig. 10. Prediction dynamics of the specific load per apartment depending on their quantity, obtained: 1 — in line with the standards; 2 — using the graphical method

7. Conclusions

1. We established the need to set up a database on technical characteristics, chart models of electric load at the different levels of power supply systems at civilian objects using modern information technologies, measuring instruments.

2. The developed chart models of electrical appliances load and their synthesis at the inputs of civilian objects make it possible to determine, when compared with calculations in line with the standards, with a higher accuracy not only the estimated electric load, but also the starting, peak currents, averaged values of current, power, amount of power consumed over a certain period of time, etc.

3. According to the results of comparing calculation errors of the estimated loads at civilian objects in line with the acting standards and by using the graphic-analytical method with actual data on the load, we revealed a significant difference between them in a range from 1.5 to 3.5 times.

References

1. Lee, S. Joint Energy Management System of Electric Supply and Demand in Houses and Buildings [Text] / S. Lee, B. Kwon, S. Lee // IEEE Transactions on Power Systems. – 2014. – Vol. 29, Issue 6. – P. 2804–2812. doi: 10.1109/tpwrs.2014.2311827
2. Capasso, A. A bottom-up approach to residential load modeling [Text] / A. Capasso, W. Grattieri, R. Lamedica, A. Prudenzi // IEEE Transactions on Power Systems. – 1994. – Vol. 9, Issue 2. – P. 957–964. doi: 10.1109/59.317650
3. Costanzo, G. T. A System Architecture for Autonomous Demand Side Load Management in Smart Buildings [Text] / G. T. Costanzo, G. Zhu, M. F. Anjos, G. Savard // IEEE Transactions on Smart Grid. – 2012. – Vol. 3, Issue 4. – P. 2157–2165. doi: 10.1109/tsg.2012.2217358
4. Samadi, P. Tackling the Load Uncertainty Challenges for Energy Consumption Scheduling in Smart Grid [Text] / P. Samadi, H. Mohsenian-Rad, V. W. S. Wong, R. Schober // IEEE Transactions on Smart Grid. – 2013. – Vol. 4, Issue 2. – P. 1007–1016. doi: 10.1109/tsg.2012.2234769
5. Bozchalui, M. C. Optimal Operation of Residential Energy Hubs in Smart Grids [Text] / M. C. Bozchalui, S. A. Hashmi, H. Hassen, C. A. Canizares, K. Bhattacharya // IEEE Transactions on Smart Grid. – 2012. – Vol. 3, Issue 4. – P. 1755–1766. doi: 10.1109/tsg.2012.2212032
6. Hubert, T. Modeling for Residential Electricity Optimization in Dynamic Pricing Environments [Text] / T. Hubert, S. Grijalva // IEEE Transactions on Smart Grid. – 2012. – Vol. 3, Issue 4. – P. 2224–2231. doi: 10.1109/tsg.2012.2220385
7. Guo, Y. Optimal Power Management of Residential Customers in the Smart Grid [Text] / Y. Guo, M. Pan, Y. Fang // IEEE Transactions on Parallel and Distributed Systems. – 2012. – Vol. 23, Issue 9. – P. 1593–1606. doi: 10.1109/tpds.2012.25
8. Rozen, V. P. Enerhetychnyi audyt obiektiv zhytlovo-komunalnoho hospodarstva [Text] / V. P. Rozen, O. I. Solovei, S. V. Brzhestovskyi. – Kyiv: Delta Foks, 2007. – 224 p.
9. Bondarchuk, A. S. Vnutrishnobudynkove elektropostachannia: kursove proektuvannia [Text] / A. S. Bondarchuk. – Kyiv: Osvita Ukrainy, 2015. – 480 p.
10. Bondarchuk, A. S. Vnutrishnokvartalne elektropostachannia: kursove proektuvannia [Text] / A. S. Bondarchuk, V. H. Rudnytskyi. – Sumy: Universytetska knyha, 2012. – 371 p.
11. Bondarchuk, A. S. Zistavlennia teoretychnoho i realnoho rozrakhunkovoho pytomoho elektrychnoho navantazhennia zhytel v umovakh mista Odesy [Text] / A. S. Bondarchuk, D. P. Nyzova // Pratsi Odeskoho politekhnichnoho universytetu. – 2011. – Vol. 1, Issue 35. – P. 78–81.