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DEVELOPMENT OF AN EXTENSIVE NETWORK OF POWER-GENERATING MANEUVERING CAPACITIES BASED ON THE EXISTING INFRASTRUCTURE OF UKRAINE'S GAS TRANSMISSION SYSTEM

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The study shows that the high concentration of energy facilities within Ukraine's territorial-industrial regions on relatively small plots of land has made them highly vulnerable during military operations. Thus, since the start of the large-scale invasion, the energy sector has lost up to 30% of its installed capacity, which has a severely negative impact on the stability of the power system and hinders the ability to meet the needs of industrial and residential electricity consumers. The aim of this study is to analyze the possibility of creating additional power generation capacity based on Ukraine's gas transmission system energy technology equipment through the reconstruction and modernization of gas turbine units (GTUs) and the creation of an extensive network of small- and medium-capacity power plants based on them. A comprehensive systematic analysis of the structure and operating conditions of the energy-technological equipment fleet of gas pumping stations was carried out with the aim of improving the efficiency of existing power-generating systems and identifying promising directions for their modernization. It has been determined that increasing the inlet pressure by 10–12 kPa boosts the power output of the GT-35-770 power plant by 21–22%, which corresponds to 6.9–7.0 MW of additional electricity. Particular attention was devoted to the integration of gas turbine and steam turbine technologies into a unified combined-cycle system. A process flow diagram that utilizes excess natural gas pressure in the turboexpander to generate energy, which can be used to increase the initial air pressure at the gas turbine inlet using high-pressure fans, has been developed. It has been demonstrated that it is possible to extensively modernize gas turbine units by implementing combined cycle technologies and modifying the design of gas combustion systems. The research confirmed the feasibility of deep modernization of existing gas turbine units through the implementation of combined-cycle technologies, the integration of waste heat recovery systems, and the improvement of gas combustion chamber designs. In particular, the utilization of the thermal potential of GTU exhaust gases in the steam turbine section of the combined cycle makes it possible to limit the compressor pressure ratio to $\pi_k \leq 15$. This contributes to a simplification of compressor design, a reduction in mechanical loads on system components, and a decrease in the amount of additionally compressed gas circulating within the GTU cycle. According to the obtained technical and economic assessments, the implementation of the proposed modernization solutions may increase the installed capacity of the Ukrainian power system by approximately 4.0-5.0 GW. This can be achieved under conditions of relatively moderate capital investments estimated at $250-270/kW of installed capacity. In addition, the projected payback period does not exceed 2-2.5 years, which confirms the high economic attractiveness and practical feasibility of introducing advanced combined-cycle and turboexpander technologies into the national energy sector.

***Keywords**: electricity, gas transmission system, energy capacity, fan, air, pressure.*

Introduction

The energy complex of Ukraine was created in the 1960s and 1970s [1]. The implementation of a strategy that aimed to maximize the concentration of energy capacities within territorial and industrial regions on relatively small land areas resulted in their high vulnerability during military operations. Thus, since the beginning of the large-scale invasion, the energy sector has lost up to 30% of its installed capacities, which has an extremely negative impact on the stability of the energy system and prevents the satisfaction of the electricity needs of industrial and municipal consumers. Due to the significant impact of military operations on the energy infrastructure, an increase in electricity shortages should be expected, especially during peak loads at energy facilities. Therefore, the urgent problem is not only the restoration of damaged capacities, but also the creation of a more reliable and less vulnerable infrastructure by branching out the network of energy generating enterprises and increasing their autonomy.

In conditions of financial resources shortage and limited possibilities of new energy equipment production, it is urgent to involve energy technological equipment from related sectors of the fuel and energy complex, in particular, the Ukraine’s gas transportation system (GTS), in energy generation.

The gas transportation system consists of:

– gas pipelines of various types (main, distribution, jumpers);
– underground gas storage facilities;
– gas distribution stations;
– gas control points;
– compressor stations;
– supply and branch sections.

The total storage capacity is over 32 billion cubic meters of gas with a maximum possible injection of 250 million cubic meters per day.

In terms of the total active gas volume and productivity, the gas transportation system of Ukraine ranks third in the world. This is almost 9% of the world's gas storage capacity. One of the largest global gas transportation operators – the Ukrainian GTS – is able to function even in very difficult wartime conditions.

The aim of the paper is to analyze the possibility of creating additional energy capacities on the basis of the energy technological equipment of the GTS of Ukraine by reconstructing and modernizing of gas turbine units (GTUs) and creating an extensive system of small and medium-power power plants on their basis.

Research object

The gas transportation system of Ukraine is one of the largest gas transportation systems in the world, the scheme and technical characteristics of which as of 2019 are given in Fig. 1 and in Table 1 [2, 3]. The GTS performs two main functions: providing domestic consumers with natural gas, as well as transiting natural gas through the territory of Ukraine to the countries of Western and Central Europe.

Fig. 1. Gas transportation system of Ukraine

Thus, the gas pumping unit fleet consists of more than 700 units, including 448 with gas turbine drive, 158 with electric drive, and 96 gas motor compressors, with a total capacity of 5,440 MW. They are located at 73 compressor stations, which include 111 compressor shops, and represent a powerful material and technical base suitable for transformation into an energy-generating component of the Ukrainian power system [2].

Traditional measures are being taken to create and maintain in an operational state the regulating and shunting capacities designed to ensure peak and semi-peak loads in the Ukrainian power system. However, during the war, a new challenge arose that was practically unpredictable in terms of time and scale - damage to power-generating and power-transmitting equipment as a result of missile attacks on infrastructure. This requires new approaches to creating additional, more diversified capacities capable of generating additional electricity to support the operation of the power system in a sustainable mode. To solve this problem, it is advisable to reconstruct and modernize existing thermal power plants along with the restoration.

Table 1. Characteristics of the gas transportation system of Ukraine as of 2019 [2, 3]

GTS parameters	Unit of measurement	Quantity
Total length of gas pipelines		37600.177
including:		
main gas pipelines	km	22007.472
main gas pipelines-branches		13123.527
distribution gas pipelines		2469.178
Compressor stations, taking into account the ownership of JSC GASTRANSIT	pcs.	73
Compressor shops, taking into account the property of JSC GASTRANSIT	pcs.	111
Gas pumping units, taking into account the property of JSC GASTRANSIT	pcs.	705
Compressor station capacity	MW	5496
Gas distribution stations	pcs.	1473

Considering the structure of installed power capacities on the GTS, in the event of their reconstruction, it is quite possible to create 70–80 additional small power plants based on existing equipment, placing them at a distance of 100 km from each other, which increases the survivability of the power generating system in conditions of missile attacks. In addition, if 60–70% of the existing equipment is used to create additional capacities, the generation of 3–4 GW of electricity will be ensured. This will significantly reduce the existing deficit, which is 8–9 GW. The involvement of combined heat and power technologies in the reconstruction process will further add 20–25% to the installed capacity without additional fuel gas consumption. Analysis of the technological scheme of a typical gas pumping station (GPS) (Fig. 2) shows that it includes the main components necessary to create a power GTU by supplementing it with an electric generator to produce electrical energy [4, 5].

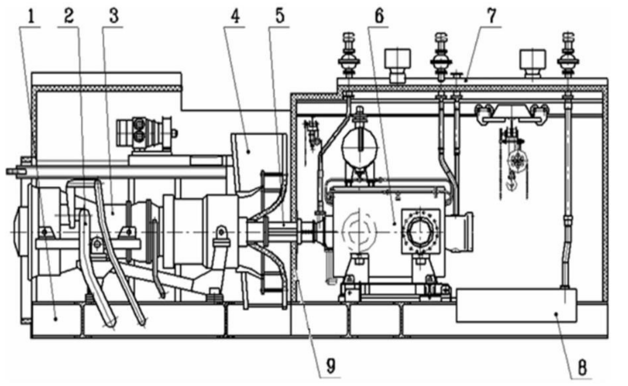

Fig. 2. Turboblock of the bench-mounted block-complete unit of container design GPA-C-6.3V/56-1.45:
1 – frame; 2 – gas pipeline; 3 – engine D-336-2/1; 4 – volute; 5 – torsion shaft; 6 – compressor NTsV-6.3/56-1.45; 7 – turboblock container; 8 – oil tank; 9 – hermetic partition between the magnetic motor and centrifugal compressor compartments

Research methodology

The location of the proposed gas turbine in close proximity to the high-pressure gas main (6–7 MPa) allows, by using excess pressure in the turboexpander unit, to obtain additional power, which is calculated by the formula

$$N^{\mathrm{E}} = \frac{m \cdot R \cdot T_2^{\mathrm{GTU}} \cdot K_{\mathrm{p}}}{(k-1)\cdot(1-\pi_{\mathrm{E}}^{(k-1)/k})},$$

where T_2^{GTU} – is the temperature of the GTU gas outlet; m – is the fuel gas flow rate, kg/s; K_{p} is the recovery coefficient; $k=c_p/c_v$ is the adiabatic index; π_{E} is the pressure drop in the turboexpander.

To perform more detailed calculations of work processes taking into account the dependence of the thermophysical properties of the working fluid on temperature and pressure and to determine the current values of the process parameters, it is necessary to use reference tabular data or universal software complexes. Data on the value of the adiabatic index for methane in the range of parameters corresponding to the considered option of the GTU technological scheme are given in Table 2.

At the stage of development and optimization of the design of a turboexpander with high thermo- and gasdynamic characteristics of the flow part, it is advisable to apply methodological approaches to the calculation and design of the main elements of the turbomachine, which are set out in [6].

Table 2. Thermophysical properties of methane in the temperature range 300–700 K

No.	Temperature, K	Pressure, MPa	Density, kg/m^3	Enthalpy, kJ/kg	Entropy, kJ/(kh·K)	c_v, kJ/(kg·K)	c_p, kJ/(kg·K)	c_{p0}, kJ/(kg·K)	c_p/c_v
1	300	3.5	23.882	880.57	4.7701	1.7467	2.4560	2.2301	1.4061
2	350	3.5	19.887	1004.30	5.1515	1.8693	2.5094	2.3663	1.3424
3	400	3.5	17.131	1132.60	5.4940	2.0272	2.6307	2.5312	1.2977
4	450	3.5	15,088	1267.90	5.8126	2.2036	2.7851	2.7118	1.2639
5	500	3.5	13.502	1411.40	6.1147	2.3881	2.9551	2.8989	1.2374
6	550	3.5	12.230	1563.50	6.4046	2.5741	3.1312	3.0868	1.2164
7	600	3.5	11.184	1724.50	6.6846	2.7581	3.3080	3.2720	1.1994
8	650	3.5	10.307	1894.30	6.9563	2.9379	3.4824	3.4527	1.1854
9	700	3.5	9.5611	2072.70	7.2207	3.1122	3.6527	3.6278	1.1737

As a result of the calculation, the power of the turboexpander according to the parameters of the GT-35–770 is 1.5–1.7 MW, which is quite sufficient for driving the fan. If it is necessary to increase the power of the turboexpander, it is advisable to increase the inlet temperature by burning a small amount of gas with high efficiency of using the energy of additional fuel.

The technological scheme of a GTU with an expander-fan system for increasing the initial air pressure is shown in Fig. 3.

The balance of material and energy flows according to the energy-technological scheme of the combined GTU with turboexpander supercharging, built on the basis of GT-35-770, has the following characteristics:

– electric power 32 MW;
– efficiency 23.8%;
– initial temperature 770 °C;
– compression ratio 6.5;
– air flow rate 215 kg/s;
– fuel gas flow rate 2.9 kg/s;
– gas temperature at the turbine outlet 430 °C;
– specific fuel consumption 0.3 kg/(kWh).

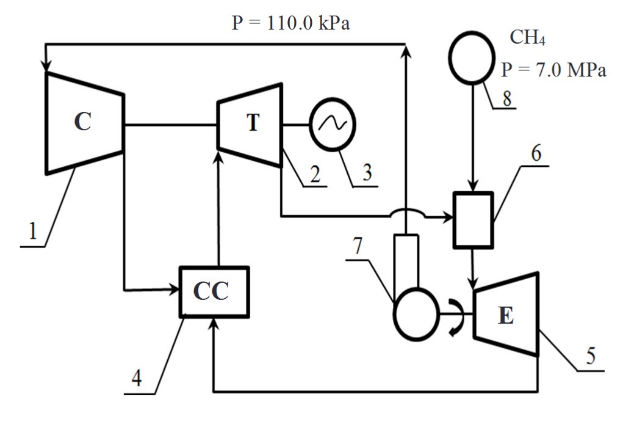

Fig. 3. Scheme of a GTU with an expander-fan system:
1 – compressor; 2 – turbine; 3 – electric generator; 4 – combustion chamber; 5 – turboexpander; 6 – heat recuperator; 7 – high-pressure fan; 8 – main pipeline

The paper [7] provides data on the VDN-25×2M unit, which indicate that under conditions of increasing air pressure to 110 kPa, the energy consumption for the fan drive to supply 215 kg/s of air does not exceed 1.5–1.7 MW. This power must be generated by the turboexpander. To determine the power of the turboexpander, we will use the equation for the adiabatic process of expansion of the working fluid [8].

We will correct it according to the developed scheme (Fig. 3) by introducing the heat recovery coefficient, which takes into account the influence of external thermodynamic irreversibility caused by the final temperature difference in the recuperative heat exchanger in the process of transferring heat from the exhaust gases of the gas turbine to the fuel gas, which is the working fluid in the turboexpander. For this, we will provide an estimate of the external irreversibility using the heat recovery efficiency coefficient, which, in relation to the option under consideration, has the form

$$K_p = \frac{T_2^{\mathrm{GTU}} - T_1^{\mathrm{E}}}{T^{\mathrm{GTU}}},$$

where T_1^{E} is the fuel gas temperature at the inlet to the turboexpander.

Fig. 4 shows, in accordance with the passport data, the dependence of the main indicators of the GT-35-770 GTU manufactured by JSC "Ukrainian Energy Machines" (until recently JSC "Turboatom" and JSC "Electrotyazhmash") on the temperature and pressure of the outside air [9–14].

The increase in the initial air pressure significantly affects the power of the GTU. Thus, an increase in the air pressure from 96 kPa to 100 kPa (by 4%) provides an increase in the power of the GTU from 32.1 MW to 34.2 MW (i.e. by 9% relative). The linear nature of the dependence of power on the initial pressure of combustion air allows us to extrapolate data on the change in power under conditions of an increase in pressure by 10 kPa. Such air pressure is provided by high-pressure fans of the VDN-25×2M type.

The power that must be used for the electric drive of the high-pressure fan can be obtained in a turboexpander unit by operating the fuel gas pressure with the regeneration of the heat of the exhaust gases. In the case of an increase in the initial pressure to 110 kPa, the GTU power will increase by 22%, which in absolute terms corresponds to 7.7 MW. Such an increase in capacity justifies the use of more complex technological schemes of gas turbine plants. Further improvement of the GTU efficiency during the reconstruction of GTS can be ensured by implementing steam-gas technologies for energy generation using the developed technological scheme of a GTU with turboexpander air supercharging as a component of a gas turbine plant [13]. The feasibility of practical application of such an approach should be substantiated by detailed studies of the reconstruction project of a specific GPS in order to convert it into a power plant with high efficiency, which is important for the energy-efficient use of natural gas in conditions of reducing its own production to a critically low level.

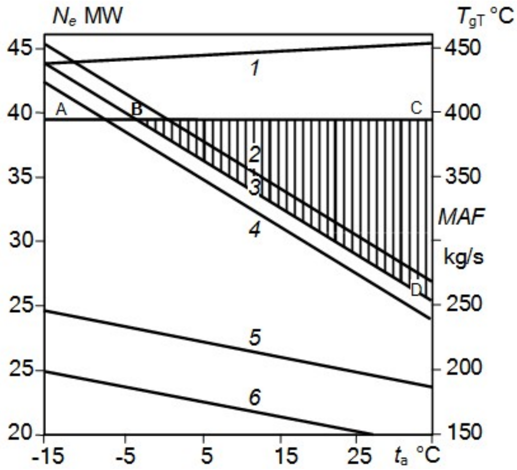

Fig. 4. Dependence of the main indicators of the GT-35-770 GTU of JSC "Ukrainian Energy Machines" on the temperature and pressure of the outside air:
1 – exhaust gas temperature; 2 – plant capacity at an air pressure at the compressor inlet of 100 kPa; 3 – plant capacity at an air pressure at the compressor inlet of 98 kPa; 4 – plant capacity at an air pressure at the compressor inlet of 96 kPa; 5 – compressor performance; 6 – GTU efficiency

Analysis of results and prospects for their application

It is known that the integration of the gas turbine (GTU) and steam turbine (STU) cycles leads to a significant increase in the efficiency of the combined-cycle gas plant (CCGP), which, in turn, depends on the efficiency of the steam and gas cycles and the ratio of the amounts of heat used in each of these units. When implementing a gas superstructure to existing power plants, there are limitations associated with the need to ensure the consumption and temperature parameters of the operation of the existing equipment, in particular, the STU steam generator for generating steam with parameters that meet the requirements for the working fluid of the steam turbine. Since part of the fuel energy in the case of the superstructure is used in the GTU for operation, it is necessary to introduce additional energy to maintain the volumes of its supply to the steam turbine cycle. From a thermodynamic point of view, the most effective way is to supply an additional volume of gas to the GTU combustion chamber. However, in this option, the temperature of the exhaust gases usually does not exceed 500 °C, which is lower than the temperature required for the operation of the steam generator. Therefore, it is necessary to heat them up to the nominal temperature.

It is possible to eliminate additional heat input into the steam generator by implementing a process that is close to isothermal into the gas turbine. In practice, this can be implemented using a specially designed gas turbine design with sequential heat input during gas expansion. The development of modern technologies and the use of new structural heat-resistant materials based on the so-called viscous ceramics and nickel-manganese steels or chromium alloys allow for an increase in the operating temperature of turbine blades by 200–500 °C and, as a result, an increase in cycle efficiency. New technical and technological capabilities make it possible to abandon traditional designs for stepwise heat input with remote combustion chambers and open up prospects for using the inter-disk space of the turbine as intermediate annular combustion chambers. In this case, through the cooling system of the blade apparatus, it is possible to introduce fuel in a circle into the inter-disk space, turning it into a combustion chamber with a high degree of turbulization. As a result of effective mixing, a uniform flame front is formed, which is supported by high-temperature surfaces of the flow part. To stabilize combustion, these elements must have a metal-ceramic coating that has catalytic properties, thanks to which the fuel oxidation process is intensified. Such heat supply brings the expansion process closer to isothermal, in which all the additionally supplied heat is converted into work. In this case, the temperature of the gases at the turbine outlet will be higher, which largely meets the needs of the steam generator. Using the thermal potential of the gas turbine exhaust gases in the steam turbine part of the combined cycle allows to limit ourselves to a compression ratio of $\pi_к \leq 15$, which simplifies the compressor design and minimizes the volume of additionally compressed gas in the GTU.

To increase the GTU efficiency by reducing the amount of combustion air and, consequently, the work spent on its compression, it is advisable to inject superheated water or wet steam with a low degree of dryness $x>0.6$ to bring the gas temperature to a technically acceptable level. The use of water in the liquid phase will significantly reduce its consumption compared to steam cooling. However, this requires the development of a special design of the gas cooler to prevent droplet moisture from entering the flow part of the gas turbine. Technically, this can be implemented by installing a ceramic nozzle with low hydraulic resistance at the outlet of the combustion chamber. When the gas turbine operates in an open circuit, regardless of whether water is used in the liquid or vapor phase, it needs to be replenished. In known designs, to compensate for water losses at the outlet of the steam generator, a contact gas-liquid heat exchanger is installed (by analogy with the "Vodolii" system) to capture water vapor from the combustion products. The high content of water vapor in the combustion products allows, even with its partial condensation (at the level of 70–80%), to obtain the necessary volume of water that is utilized for the operation of the gas cooling system.

At the stage of processing technical proposals for the project of modernization of the thermal power plant, data that allow determining the choice of the technological scheme and the influence of the operating parameters of the main elements on the integral energy characteristics are required[15, 16]. The dependence of the efficiency of the CCGP on the efficiency of the GTU and the STU, taking into account the additionally supplied heat, can be established using the equation [19]

$$\eta_{CCGP} = \frac{(1+\eta_{GTU}) \cdot \eta_{CCGP} - \eta_{STU}}{1+\eta_{GTU}+\eta_{GTU}^2},$$

where η_{CCGP} is the efficiency of a combined cycle plant; η_{GTU} is the efficiency of a gas turbine plant; η_{STU} is the efficiency of a steam turbine plant.

The calculations set the range of changes in the efficiency of the steam and gas parts, mastered by the energy industry [15–18]. Fig. 5 shows the efficiency of a combined cycle plant for generating electricity with different combinations of integrated cycles.

The analysis of the obtained results shows that even with moderate indicators of thermodynamic efficiency of the elements integrated into the combined scheme of the CCGP, a level of efficiency that is unattainable by other megawatt power plants known today is ensured. The small specific volume of the pre-connected gas turbine part (0.6–0.7 m^3/kW)allows them to be placed during modernization in the premises occupied by steam turbine power units. Due to this, it is possible to use the production areas of existing gas turbine power plants to accommodate additional equipment, which reduces financial costs during the reconstruction of energy facilities. During cogeneration modernization of existing energy equipment through the use of the existing construction and technical base, the cost of a unit of additional installed electric generating capacity does not exceed $ 250–270 per 1 kW. Such projects have a relatively short commissioning period and are characterized by lower specific capital costs compared to new plants, while simultaneously reducing the payback period of the invested investments to 2–2.5 years.

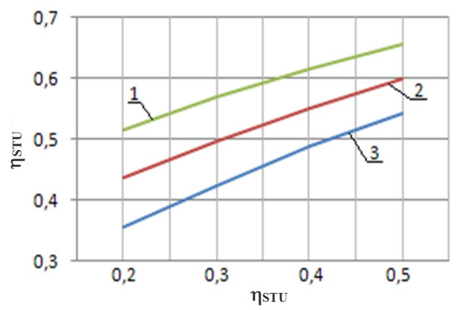

Fig. 5. Dependence of the integral efficiency of a CCGP on the efficiency values of GTU and STU: 1 – 0.4; 2 – 0.3; 3 – 0.2

Conclusions

1. A systematic analysis of the structure of the technological fleet of energy technology equipment of the gas turbine power plant was carried out and it was found that 60–70% of their equipment can be used to create gas turbine power plants for the development of an extensive network of autonomous gas turbine power plants with a capacity of 10–30 MW using the technical base of the gas turbine power plant, which will ensure higher survivability of the electricity generation system in conditions of permanent missile and drone attacks.

2. The effect of increasing the initial air pressure on the power of the GT-35-770 power plant was studied and it was found that increasing the initial pressure by 10 kPa increases its power by 22%, which corresponds to 7.7 MW of additional electricity.

3. A technological scheme was developed using excess pressure of natural gas in a turboexpander to obtain energy, which can be used to increase the initial air pressure at the inlet to the gas turbine power plant using high-pressure fans that use the energy obtained from the turboexpander.

4. Considering the ratio of energy consumed to increase the initial air pressure to that obtained by increasing the GTU capacity as 1:5, in the absence of excess fuel gas pressure, it is advisable to use an electric drive of a high-pressure fan. This will expand the range of GTUs that can be involved in modernization in the proposed way.

5. The possibility of deep modernization of GTUs is shown not only by implementing steam-gas technologies and making changes to the design of gas combustion systems, but also by using excess pressure in the turboexpander system of the fan drive. According to the results of the modernization, the capacity of installed power equipment in the power system of Ukraine will be increased by 4.0–5.0 GW under conditions of moderate capital investments at the level of $ 250–270/kW with a payback period not exceeding 2–2.5 years.

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Розбудова розгалуженої мережі енергогенеруючих маневрових потужностей на базі наявної інфраструктури ГТС України

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У роботі показано, що максимальна концентрація енергетичних потужностей в межах територіально-промислових регіонів України на відносно невеликих земельних ділянках зумовила їх велику вразливість під час військових дій. Так, із початку великомасштабного вторгнення енергетична галузь втратила до 30% встановлених потужностей, що вкрай негативно впливає на сталість роботи енергосистеми і перешкоджає задоволенню потреб в електроенергії промислових і комунально-побутових споживачів. Метою роботи є аналіз можливості створення додаткових енергетичних потужностей на базі енерготехнологічного обладнання газотранспортної системи України шляхом реконструкції та модернізації газотурбінних установок (ГТУ) і створення на їх базі розгалуженої системи електростанцій малої і середньої потужності. Проведено системний аналіз структури технопарку енерготехнологічного обладнання газоперекачувальних станцій. Встановлено, що підвищення початкового тиску на 10–12 кПа збільшує потужність енергоустановки ГТ-35-770 на 21–22%, що відповідає 6,9–7,0 МВт додаткової електроенергії. Інтеграція циклів газо- та паротурбінних установок приводить до суттєвого підвищення ККД парогазової установки, який залежить від ККД парового і газового циклів і співвідношення обсягів теплоти, що використовуються в кожній з цих установок. Розроблено технологічну схему із застосуванням надлишкового тиску природного газу в турбодетандері для отримання енергії, яку можна використати для підвищення початкового тиску повітря на вході в ГТУ за допомогою високонапірних вентиляторів. Доведено, що існує можливість глибокої модернізації ГТУ за рахунок втілення парогазових технологій та внесення змін до конструкції систем спалювання газу. Використання термічного потенціалу відпрацьованих газів ГТУ в паротурбінній частині комбінованого циклу дозволяє обмежитися ступенем стиснення $\pi_к \le 15$, що спрощує конструкцію компресора і зводить до мінімуму обсяги додатково стисненого газу в циклі ГТУ. За результатами модернізації буде збільшено потужність встановленого енергообладнання в енергосистемі України на 4,0–5,0 ГВт за умов помірних капіталовкладень на рівні 250–270 $/кВт із строком окупності, що не перевищує 2–2,5 роки.

***Ключові слова**: електроенергія, газотранспортна система, енергетичні потужності, вентилятор, повітря, тиск.*

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