Innovative Turbine Expanders with Asynchronous Generators for the Use of Throttled Gas Energy

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Innovative Turbine Expanders with Asynchronous Generators for the Use of Throttled Gas Energy

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Abstract. The spending energy for gas transportation reaches 10% of the produced gas. After the reaching of the consumer, this pressure must be reduced to a certain. The created energy of the gas in gas pipelines in compressor shop can be extracted in the mechanical energy form and delivered to the turbo-expander shaft. Using of new turbo expanders with asynchronous generators for the use of throttle gas energy will save energy costs for gas transportation in main gas pipelines. For reliable operation of the asynchronous generator systems and devices are needed to stabilize the voltage. The principle of the new device for adjusting and stabilizing the voltage of an autonomous asynchronous generator is based on the selective inclusion of capacitors with three-phase electronic keys as a function of the feedback signal from the output voltage.

1. Introduction

The need for natural gas is growing all over the world. In most cases, the natural gas field locates far away from consumers. Therefore, connections of gas pipelines for worldwide gas transportation includes hundreds of kilometers of gas pipelines and thousands of stations to increase and reduce the pressure [1].

This problem is especially relevant for Russia. According to data [2,3] general length of the gas transportation system «Gazprom» in Russia is 170,7 thousand kilometers. In gas transportation, 276 compressor stations (CS) or more than 730 compressor shops with the total installed capacity of gas pumping aggregates 46,1 thousand MW are using. Compressor shops use the drives to create the necessary pressure (5.5-8.0 MPa): gas turbine - 86.9%, electric - 12.6% and piston - 0.5%.

The spending energy for gas transportation reaches 10% of the produced gas. After the reaching of the consumer, this pressure must be reduced to a certain. This achieves by the reduction valves. A huge amount of energy is lost to the atmosphere. The created energy of the gas in gas pipelines in compressor shop can be extracted in the mechanical energy form and delivered to the turbo-expander shaft. This process in turbo-expander is almost isentropic. The using of turbo-expander has an old history in different industries. Initially, expanders were mainly used in cryogenic technology for cooling gases and obtaining low temperatures [4,5]. Later, expanders began to be used to obtain mechanical energy, which is converted into electrical energy in the generator.

The choice of the expander construction is determined by its purpose and operating conditions. In all advanced countries, expanders are currently being used for a large capacities from 0.5 to 20 mW (Belgium, the Netherlands, Germany, Great Britain, Russia, etc.).

2. The Problem Statement

One of the main problem in low power expander generator aggregates (EGA) is the difficulty in frequency stabilization of rotor rotating of turbo-expander with alternating gas consumption. The second problem: complexity of turbine shaft seals from gas leaks. To implement the technology in the simplest form is possible by including in parallel the gas distributing station (GDS) or gas regulation point (GRP) the expander of generator aggregate (EGA), which is working on a differential pressure of gas (fig. 1).

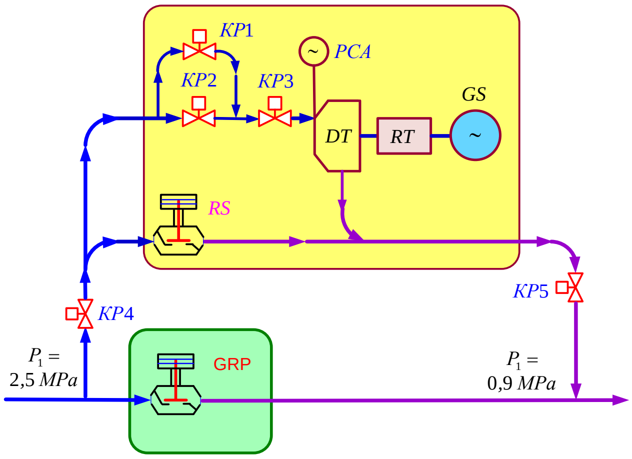

Figure 1. Simple diagram of inclusion EGA in parallel with GRP or GDS.

On the picture: *DT* – expander turbine; *RT* – mechanical reducer; *GS* – asynchronous generator; *PCA* – electric drive of regulated nozzle apparatuses; *KP1*, *KP2* – control valves; *KP3* – stopper (protective) valve; *KP4*, *KP5* – shut-off valve for disconnection of EGA; *RS* – throttle device; P_1, P_2 – input and output gas pressure.

It can be seen from the figure that the gas under the high pressure arrives into the system by two ways. First way is through the regulated valve *RS* (throttle device). Another way includes the turbo-expander *DT* and some additional equipment. In normal mode, the *DT* turbo-expander way is open for gas transportation. Regulated valve *RS* can be open every time, when it becomes necessary. In some systems, the temperature of gas is significantly reduced when it passes through the turbo-expander. A low temperature on output can damage the turbine.

The energy potential of the energy carrier of excess pressure is determined by the work of the isentropic expansion *l* [5]. For the case of an adiabatic expansion of 1 kg of gas, the specific work will be:

$$q = \frac{k}{k-1} \cdot p_1 \cdot v_1 \cdot \left[1 - \left(\frac{p_2}{p_1} \right)^{\frac{k-1}{k}} \right] \tag{1}$$

or $$q = Z_{cp.} \cdot \frac{k}{k-1} \cdot R \cdot T_1 \cdot \left[1 - \left(\frac{p_2}{p_1} \right)^{\frac{k-1}{k}} \right] \tag{2}$$

where *k* – adiabatic index; p_1, T_1, v_1 – pressure, Pa; temperature, *K*; specific volume, m^3/kg, gas according to the condition ***1*** – on input; p_2 – gas pressure in condition ***2*** – on output, Pa; Z_{cp} – coefficient of compressibility; *R* – gas constant J/(kg·K) [5].

The specific total yield of excess pressure in the case of its useful use for obtaining electric energy in expansion turbines is determined by the power of N, W, i.e. the amount of work which took from the generator shaft per unit time [5]:

$$N = G \cdot q \cdot \eta_{0i} \cdot \eta_{0i}, \tag{3}$$

where *G* – gas consumption, kg/s; *p* – specific work of gas expansion in turbine, kJ/kg; η_{0i} – internal relative energy conversion efficiency of expander; η_{0i} – electromechanical energy conversion efficiency of generator [5]. Based on the received value of the power, an estimation of the total output volume and, accordingly, its potential – received energy kW/h are made

$$E = N \cdot t \tag{4}$$

where N – power, kW; t – period of the time. If the pressure on input in GDS or GRP is higher than the pressure on output in 4,5 times, the step pressure release schemes are used [5].

In the well-known literature, the results of research and simulation of turbo-expanders with different construction are presented [7-12]. They based on the implementation of operative models and static modes in very small scales [7]. In some research, turbo-expander is not modeled, but only observes just in working condition by creating the necessary operational facility [8]. Using the turbo-expanders for creation the electric power with the help of generator with permanent magnets is shown in the work [9]. In other works, the efficiency, torque and useful power on the shaft were investigated. The change of mass flow rate of gas, its temperature and the pressure on input of expanders has a significant effect on the power and the parameters of output voltage, causing it to change [10-12].

Using the accumulated experience in the research of expanders, in our projects we adopted the following concept of creating turbo-expanders with asynchronous generators [13-16]. Their peculiarity is that the turbine and the asynchronous generator (AG) are in the hermetic chamber, and the AG control is carried out through the bushing insulators. In the device [13], an asynchronous machine is used as a generator in generator mode with energy recovery to the supply network.

An autonomous device for utilization of gas energy in main gas pipelines contains a turbine and a multi-pole asynchronous generator of increased frequency of current with excitation capacitors [14]. The turbine is connected to the speed sensor and the driving shaft of the electromagnetic clutch, which is connected to the generator rotor by an output shaft.

The turbine, the electromagnetic contactless coupling and the generator are placed in the hermetic chamber, so there is no need to seal them. Asynchronous generators based on standard asynchronous motors have a four-speed version, for example, with current frequency 50 Hz: 750/1000/1500/3000 min^{-1}, but on the current frequency 200 Hz: 24000/12000/8000/6000 min^{-1}. Thus, the technical solution can be realized on "slow-moving" and "high-speed" turbines. A multipolar AG generator can operate over a wide range of speeds, so the proposed device can be used in the gas pipelines with different pressure drops. At the same time, the issue of the output pressure regulation is simply solved by changing the load on the generator.

The work of AG with energy recovery in the supply network is shown in [15]. This invention makes it possible to improve the reliability and energy performance of the gas turbine generator.

The analysis of the operation of the expansion generator aggregates (EGA) showed that for their optimal operation it is necessary to heat the gas. This is since a significant decrease in the gas temperature occurs during operation. This leads to the appearance and loss of hydrates in the gas to be reduced, which is unacceptable. To prevent this, the temperature of the gas must be maintained at a certain level, depending on the pressure and humidity of the gas. The gas heating system is one of the main systems that determine the technical and economic performance of the EGA. Its thermal power is selected according to the conditions for ensuring the normal operation of the GDS at the most extreme parameters of the gas to be reduced.

The question of choosing a source of gas heating is one of the fundamental issues when deciding on the expediency of using these aggregates. In addition, the indicators of the gas heating system significantly affect the operating costs of the EGA and, therefore, the cost of electricity generated by EGA. Therefore, the selection and optimization of the gas heating scheme in the EGA is one of the priority tasks to be performed when designing them.

Modern EGA with gas heating [16] is explained by drawings (fig. 2,3,4). Figure 2 shows a construction with a partial cut; figure 3 shows the construction of the heating device phase with a partial cut and a cut along the line AA.

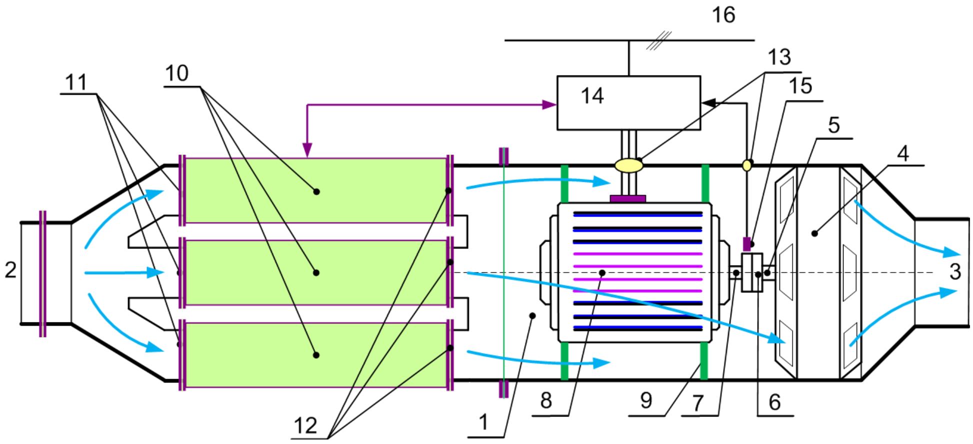

Figure 2. The construction of the expander of generator aggregate with a partial cut.

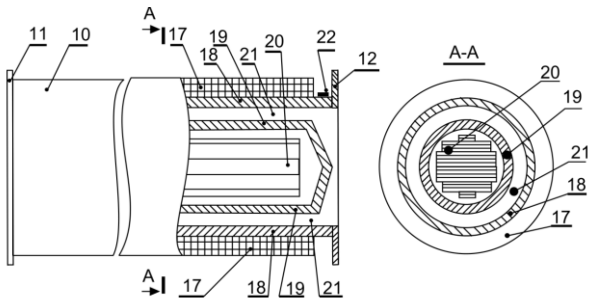

Figure 3. The construction of the heating device phase with a partial cut and the section of the device along the line AA.

The expander generator aggregate (figure 2) contains the hermetic chamber 1 with the input 2 and the output pipeline 3. The turbine 4 with the output shaft 5 via the clutch 6 is connected to the shaft 7 of the asynchronous generator 8, which is fixed to the corpus of the hermetic chamber 1 by pillars 9. The network gas enters the chamber 1 through a three-phase gas preheater 10 with flanges 11 and 12. The bushing insulators 13 are connected on one side to the control unit 14 and, on the other hand, to the windings of the asynchronous generator 8 and the turbine speed sensor 15. The control unit 14 connected with a power network 16.

Each phase of the three-phase gas preheater 10 (figure 3) consists of a winding 17 that is wound on a non-magnetic conductive tube 18, with flanges 11 and 12. Inside the non-magnetic tube 18, a ferromagnetic tube 19 is hermetically closed with a laminated magnetic core 20 of electrical steel inside. Between the tubes 18 and 19 there is a gap 21 for passing the heated gas in a thin layer. On the outside of the non-magnetic tube 18, the temperature sensor 22 is fixed.

The detailed description of the gas turbine generator is given in [16].

The main disadvantage of AG is that they do not generate the reactive power necessary to supply the motor load. Therefore, for reliable operation of the AG, systems and devices are needed to stabilize the voltage.

The new device for adjusting and stabilizing the voltage of an autonomous asynchronous generator has new functionality (figure 4). This device can be used for generators of any power [17].

The principle of the device is based on the selective inclusion of capacitors C4 - C12 with three-phase electronic keys DD1 - DD3 as a function of the feedback signal from the output voltage [17, 18].

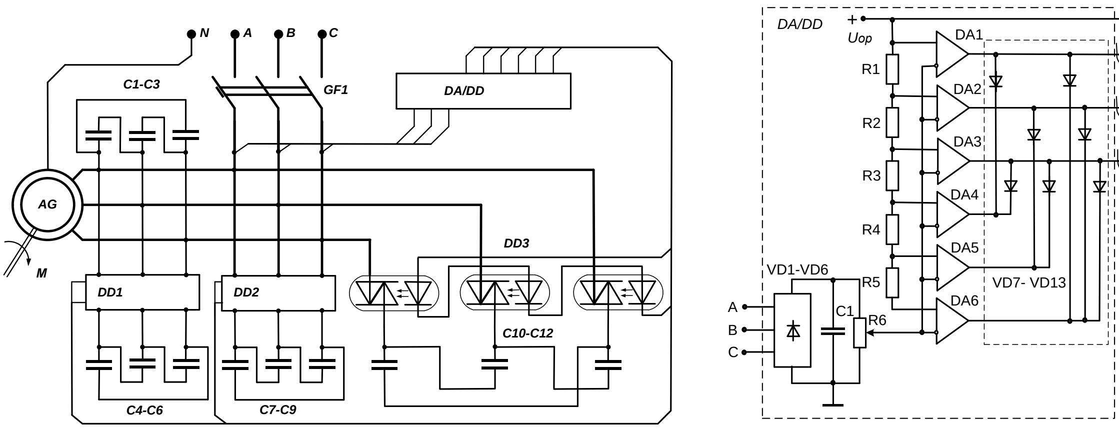

Figure 4. Power section of the device and the control unit for regulation and stabilization of the voltage of an autonomous asynchronous generator.

The device contains a self-contained AG *AG*, to the phases of which C1-C3 excitation capacitors, a control unit, three-phase electronic switches DD1 to DD3, a block of commutated capacitors C4-C6, C7-C9, C10-C12, a three-phase rectifier VD1 to VD6, a filter capacitor C1 , variable resistor R6, voltage comparators DA1 - DA6, voltage divider R1 - R5, decoder VD7 - VD13, optronic inputs VS1-VS3 three-phase electronic keys DD1-DD3.

Three-phase electronic keys DD1-DD3 are connected when switching the commuting voltage through zero, therefore there are no harmonic components of current and voltage, as well as switching overvoltage and interference. By changing the position of the slider of variable resistor R6, the switching time of the comparators DA1 to DA6 is changed, and thus the output voltage of the AG.

Let's consider the construction of the external characteristic AG on the basis of AD series with a power of 400 kW. The capacitance of capacitors providing self-excitation of AG at idle and compensation of reactive power of load is determined by the known formula

$$\tilde{N}_{\Sigma} = \frac{P_{\acute{i}}(tg\varphi_{\tilde{A}} + tg\varphi_{\acute{I}})}{2\pi f m U_c^2}\cdot 10^6, \mu\text{F}.$$

where $P_{и}$ – power given by the generator; U_c – capacitors voltage; f – current frequency; $\varphi_{Г} = 0{,}88$ and $\varphi_{H} = 0{,}8$ – angles of generator and load phase shift; *m* – number of phases; $\varphi_{H} = 37^0$.

For nominal load

$$\tilde{N}_{\Sigma} = \frac{400000(tg31{,}5^0 + tg41^0)}{2\cdot 3{,}14\cdot 50\cdot 3\cdot 380^2}\cdot 10^6 = \frac{516000}{136024800}\cdot 10^6 = 3796\ \mu\text{F}.$$

Capacity of capacitors providing the self-excitation of AG at idle:

$$C_{voz} = \frac{P_{и}\cdot tg\varphi_{Г}}{2\pi f m U_c^2}\cdot 10^6, \mu\text{F}.$$

$$C_{voz.} = \frac{400000\cdot 0{,}54}{2\cdot 3{,}14\cdot 50\cdot 3\cdot 380^2}\cdot 10^6 = \frac{216000}{136024800}\cdot 10^6 = 1588\ \mu\text{F}.$$

The additional control capacity is defined as the difference between the total capacity for operation at the nominal load and the excitation capacitance. $C_{dop.} = C_{\Sigma} - C_{vozb.}$, $C_{dop.} = 3796 - 1588 = 2208\ \mu\text{F}$.

In accordance with the AG power part scheme, the additional capacitance of the capacitor bank is divided into the three parts.

$$\tilde{N}_4 - \tilde{N}_6 = 368\ \mu\text{F},\ \tilde{N}_7 - \tilde{N}_9 = 736\ \mu\text{F},\ \tilde{N}_{10} - \tilde{N}_{12} = 1104\ \mu\text{F}.$$

When the control circuit is operating, the capacitance is switched according to algorithm:

$$368 \Rightarrow 736 \Rightarrow 1104 \Rightarrow 1472 \Rightarrow 1840 \Rightarrow 2208\ \mu\text{F}.$$

When determining the specific gravity of AG which is for working with an autonomous load, it is necessary to take into account the both actual mass of generator and capacitor unit. The capacitor's power is determined by the known formula

$$Q_c = \frac{mU_c^{\ 2}}{X_c} = 2\pi\, fmC \cdot 10^{-6} U_c^2 .$$

$C_4 - C_6 = 2 \cdot 3{,}14 \cdot 50 \cdot 3 \cdot 368 \cdot 10^{-6} \cdot 380^2 = 50057 \text{ var} = 50 \text{ kVAr}.$

$\tilde{N}_7 - \tilde{N}_9 = 2 \cdot 3{,}14 \cdot 50 \cdot 3 \cdot 736 \cdot 10^{-6} \cdot 380^2 = 100 \text{ kVAr}.$

$\tilde{N}_{10} - \tilde{N}_{12} = 2 \cdot 3{,}14 \cdot 50 \cdot 3 \cdot 1104 \cdot 10^{-6} \cdot 380^2 = 150 \text{ kVAr}.$

The external characteristics of the AAG are shown in figure 5.

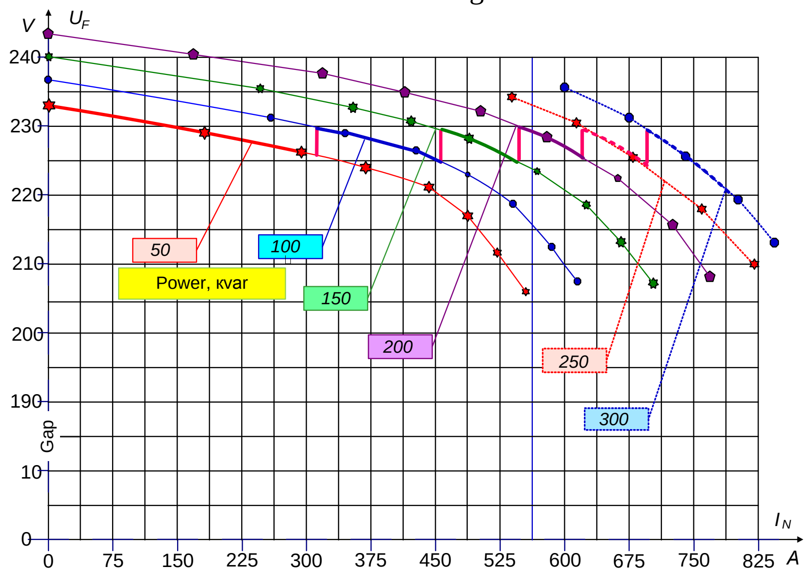

Figure 5. External characteristics of AAG with discrete voltage regulation.

3. Conclusions

1. Using of new turbo expanders with asynchronous generators for the use of throttle gas energy will save energy costs for gas transportation in main gas pipelines.
2. Facilities with asynchronous generators have great prospects, especially on the basis of energy efficient induction motors of the energy efficiency class: IE2 - high; IE3 - "Premium".
3. The developed device for voltage regulation and stabilization of an independent asynchronous generator can be used for the generators of different power. It gives the following positive properties:
- three-phase electronic switches DD1-DD3 are connected when switching over the commuting voltage through zero, so there are no harmonic components of current and voltage, as well as switching overvoltage and interference.
- by changing the position of the variable resistor R6 slider, the switching time of the comparators DA1-DA6 is changed, and thus the output voltage of the AG.

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