

# Combined electromachine generators for energy-efficient mini-power plants

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**Abstract.** The design, principle of operation and features of new combined electric machine – generator-transformer unit (GTU) are considered. The units are designed for generating units of mini thermal power plants with extreme parameters of moving media (steam-gas, gas-liquid, etc.) at high pressure and temperature. The possibility of reliable and efficient conversion of electric power by means of electric machines directly in sealed objects with extreme environmental conditions with help of new GTU is shown.

## 1 Introduction

At present, there is increasing need for autonomous power plants of low power for simultaneous heat and power supply of industrial and civil facilities not only in areas remote from existing thermal and electric power grids, but also near them. [1]. This is largely due to the economic feasibility of their use, since there is a constant increase in tariffs for network heat and electricity, and simultaneous reduction in the cost of same types of energy produced by autonomous energy sources.

Mini-TPP is increasingly widely used in autonomous power supply of housing and communal facilities: houses, entertainment and shopping centers, office centers, baths, swimming pools, hospitals, fast food, winter stadiums, etc. Promising objects for the use of cogeneration plants in Russia are small industrial enterprises, gas stations, floating drilling platforms, gas compressor stations, boilers, etc. Mini-TPP can be used as the main or backup sources of heat and electricity, operating both in stand - alone mode and in conjunction with existing heat and power networks [2].

Today in the Russian Federation there are several thousand mini-TPPs operating both in power systems and autonomously. The total annual generation of electricity from these power plants reaches 5% of the production of all power plants in the country [3]. The average capacity of such mini-thermal power plants is about 350 kW, which are mainly owned by consumers of both small industrial enterprises and civil facilities, fully or partially providing them with electricity and heat.

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## 2 Main part

As it is known, the produced generating devices for autonomous power supply systems are based on two main types of generators: synchronous and asynchronous. Asynchronous generators (AG) have well-known advantages: simplicity and high reliability, low weight and dimensions in comparison with other machines, low cost, low sensitivity to short circuit, etc. Because of this, AG are used as generating devices for renewable energy sources, to power on-board networks of mobile facilities, in small-sized gasoline power plants, etc. The current trend in the development of electricity suggests that in these areas for the supply of Autonomous power receivers with a capacity of up to 400 kW it is most advisable to use AG instead of synchronous generators.

However, AG have a number of known drawbacks that limit their wide distribution. These include:

- statistical nature of the excitation AG, which depends on random factors;

- AG excitation mainly at speeds equal to or greater than synchronous;

- the need to have an external source of reactive power (usually capacitor bank), which creates reactive currents, when magnetizing AG, as well as covering the needs for reactive power from load side, if the load is active-inductive;

- the need to stabilize the voltage and frequency of autonomously operating AG having a "soft" external characteristic.

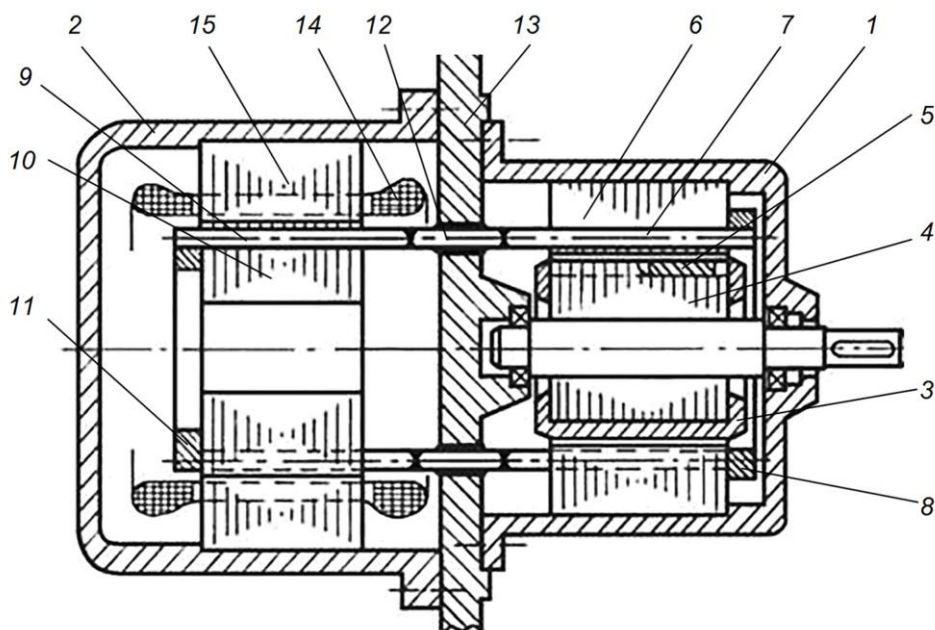
In this case, the power of capacitors in AG circuit with self-excitation should be large enough, approximately equal to active power of AG [4].

The main problems of existing power generation units with extreme conditions of moving gas, steam-gas and liquid media with high pressure and temperature are their insufficiently high reliability, low resource, complexity of operation and repair. This is largely due with need to use sealed seals between the rotating shaft connecting the turbine and the generator shaft and the hermetic body of the installation with extreme parameters of the moving medium. The asynchronous (or synchronous) generator itself in these installations is always located outside the sealed housing.

The main purpose of research was to theoretically substantiate and experimentally confirm possibility of reliable and efficient conversion of electric energy by electric machine means directly in sealed objects with extreme environmental conditions with help of new designs of electric machines, so-called machine-transformer aggregates (MTA). [6, 14].

The proposed construction of generator-transformer unit (GTU) [5] solves above problems in fundamentally new way, due to the fact that conversion of energy from mechanical to electrical occurs in oneself sealed object with extreme conditions of moving environment, since the generator part of unit is located directly in a sealed object.

Generator-transformer unit (Fig. 1), being a kind of machine-transformer units [6, 7], consists of two parts: generator part 1 in form of asynchronous generator with guaranteed self-excitation (AGGS) [8] and transformer part 2 in the form of transformer-voltage converter and number of phases with rotating magnetic field (TNF) [9].



**Fig. 1.** Generator-transformer unit (GTA): 1 – generator part (AGGS); 2 – transformer part (TNF); 3 – short-closed winding of rotor AGGS; 4 – rotor AGGS; 5 – permanent magnets; 6 – stator core, AGGS; 7 – Z-phase rod stator winding AGGS; 8 – short-closed ring of rotor winding; 9 – primary rod winding TNF; 10 – inner ring core TNF; 11 short- closed ring of rod winding TNF; 12 – electric seals; 13 – hermetic partition; 14 – secondary three-phase winding TNF; outer ring core TNF

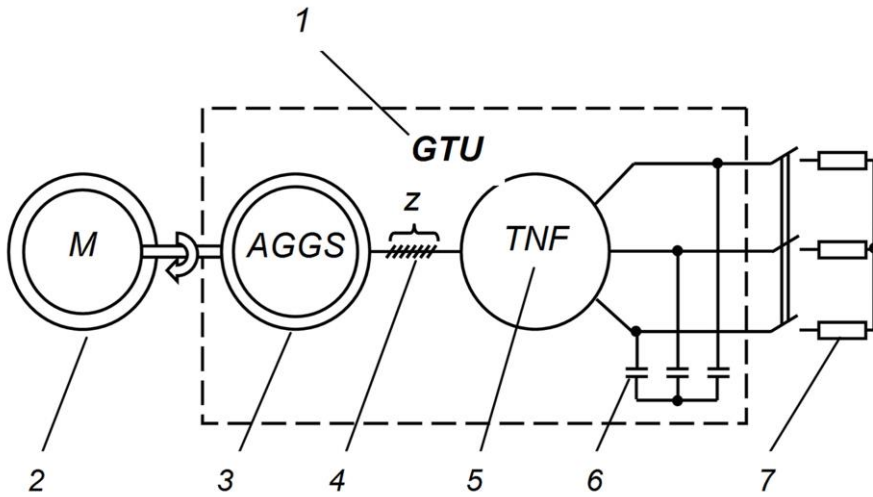
In turn, AGGS can be represented as a combined electric machine, which combines conventional AG with capacitor excitation and synchronous generator (SG) with permanent magnets.

Structurally, AGGS, that is, generator part 1 of unit is an asynchronous machine with a short-circuit winding 3 of rotor 4, in teeth of which are mounted small permanent magnets 5. Permanent magnets are placed evenly in teeth of rotor core level with its working surface, forming alternating poles, at that the number of rotor teeth is a multiple of the number of magnets. In the slots of stator core 6 located AGGS Z-phase rod winding 7 (where Z – number of stator teeth), closed at the end portion of short-closed ring 8, similar to short-closed rotor winding. This rod winding is electrically connected to primary Z-phase rod winding 9 of transformer part 2 GTU. The primary rod winding 9 is located in grooves of the inner ring core 10 TNF and in the end part is closed by short-closed ring 11. The other ends of the rods 9 are electrically connected via electric seals 12 to rods 7 of Z-phase stator winding AGGS. The electric seals 12 are evenly spaced along the circumference and pass through hermetic partition 13 separating generator part 1 and transformer part 2 GTU. The secondary three-phase winding 14 of transformer part GTU is located in Z grooves of outer ring core 15. The cylindrical surfaces of teeth of outer 15 and inner 10 cores, touching each other, are separated by a small (0.05 mm) technological gap.

The generator part 1 of the unit receives a combined excitation from permanent magnets 5 and capacitors. To reduce the capacitance of capacitors, they are connected according to the scheme "star" or "triangle" to the secondary three-phase winding TNF.

Generator-transformer unit works as follows. When the rotor 4 AGGS is rotated from drive motor, its permanent magnets 5, forming alternating poles with a number equal to number of poles of stator 6, induce z-phase EMF system in rods 7 of stator's Z-phase

winding. These EMF cause the phenomenon of symmetrical Z-phase currents that flow through the rod winding 7 and the primary Z-phase rod winding of 9 transformer part 2 connected to it. In this case, in magnetic circuit of the transformer part 2 GTU, a rotating magnetic field with the same number of poles as in the stator winding 6 of the AGGS is formed. This field induces symmetrical three-phase EMF system in the secondary three-phase winding 14 and causes the appearance of currents both in winding 14 and reactive capacitor currents connected to secondary winding TNF (Fig. 2). Reactive currents of capacitors serve as a source of additional reactive power, which, folding with reactive power from rotating magnetic field of permanent magnets, provides strengthening of magnetic field in AGGS. Thus self-excitation AGGS and return of active power to three-phase load connected to secondary three-phase winding of transformer part GTU is provided (Fig. 2).



**Fig. 2.** The scheme of inclusion GTU: 1 – Generator-transformer unit (GTU); 2 – Drive motor; 3 – Asynchronous generator with guaranteed self-excitation (AGGS); 4 – Z-phase connection AGGS and TNF; 5 – Transformer-voltage converter and number of phases with rotating magnetic field (TNF); 6 – Excitation capacitors; 7 – Three-phase load GTU

Unlike conventional asynchronous generators, AGGS self-excitation is provided in a wide range of rotation speeds. It is theoretically and practically established that at any rotor AGGS speed, its magnets induce EMF in the stator rod winding, which are transformed into TNF and cause the appearance of reactive capacitor currents with subsequent self-excitation GTU. In this case, the relative excitation power can range from a few percent of aggregate power to a value that is determined when designing GTU. Thus, AGGS as part GTU has one important property: it, unlike usual AG, generates tension at any, even very small speed of rotation. It should be noted that the frequency of voltage and current is set by rotor AGGS speed, as is the case for conventional synchronous generators.

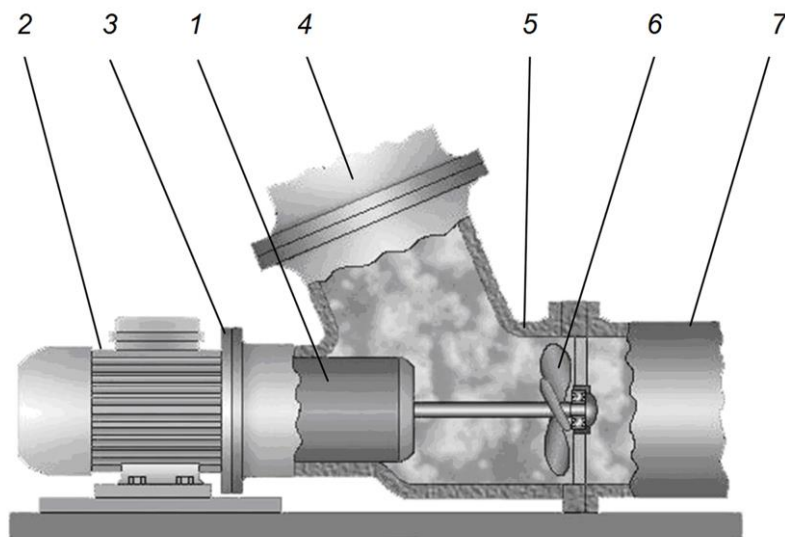
At the same time, the parameters AGC rotor-stator circuit and TNF circuit, that is, active-inductive parameters of their windings and of exciting capacitors, participate in the formation GPU voltage and frequency. In this respect, GTU differs from conventional AG, in which the voltage frequency depends on the ratio of total inductance of stator circuit and the value of excitation capacitors, as well as the load of generator. These circumstances are the subject of theoretical and experimental studies [10, 12].

An important property GTU is the possibility of compensating the part of reactive power by permanent magnets of AGGS and, thereby, reducing the capacitance of excitation capacitors. It is extremely interesting both in theoretical and in practical terms the property

is the subject of study which is related to problem of optimizing energy permanent magnets and generated by them the magnetic flux in AGGS [10, 12, 14]. In this case, the limit value of the energy of permanent magnets  $B \cdot H$  should be such that AGGS in GTU would remain AG, without turning in its properties into a synchronous generator (SG) with permanent magnets. Thus, the AGGS is an electric machine occupying an intermediate position between the AG and the SG with permanent magnets, which has their advantages, and is free from a number of disadvantages of both machines.

These features of AGGS in GTU are of fundamental importance, as it significantly expands the range of speeds of steam, gas or liquid moving media to generate electricity in the mini thermal power plant and significantly reduces the weight and cost of installation due to a significant reduction in the capacitance of capacitors.

Figure 3 shows one of the design options of proposed GTU as part of mini TPP. From Fig. 3 it can be seen that the actual generator part (AGGS) 1, which is part of the unit, receives rotation of rotor from the working wheel 6 of turbine under the action of the water flow passing through inlet 4 and outlet 7 of turbine of mini TPP. In this case, the generator part of the unit is located in the turbine housing 5 of the mini TPP, i.e. in the moving medium, and transformer part of unit 2, separated from generator part by a sealed flange-partition 3, is located in usual air environment. Thus, the hermetic partition can be a flange 3 of generator part of unit, hermetically closing the hatch in housing of hermetic object (Fig. 3), or – part of body of sealed object (partition 13 in Fig. 1).



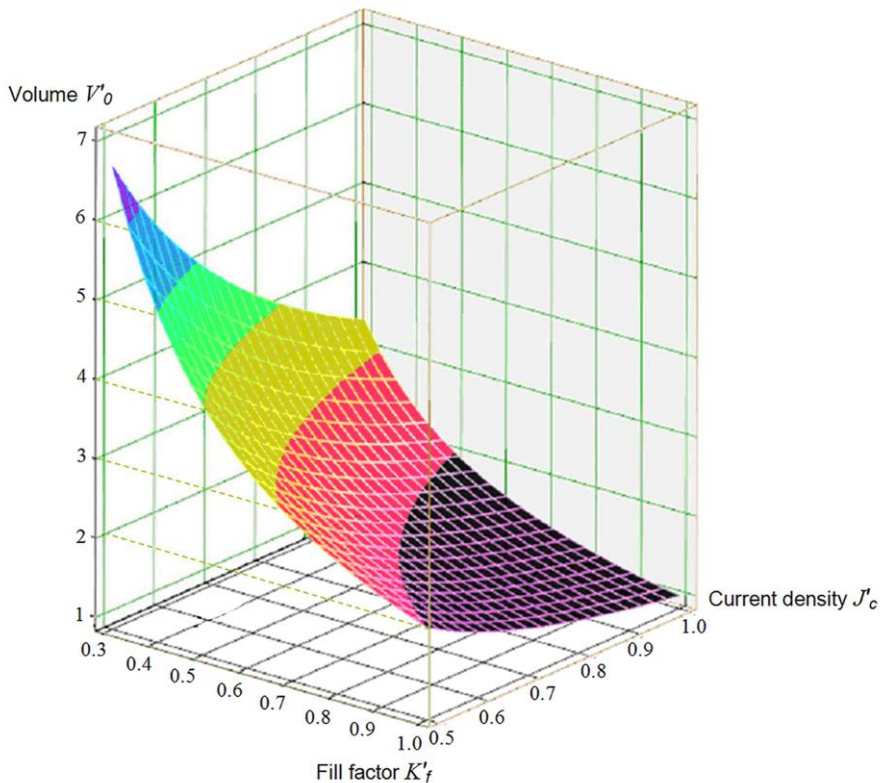
**Fig. 3.** Design GTU in mini TPP: 1 – generator part of unit (AGSS); 2 – transformer part (TNF); 3 – hermetic partition; 4 – inlet pipe of turbine; 5 – shell of mini hydroelectric power station; 6 – impeller of turbine; 7 – outlet pipe

As a result of the works carried out, the provision on more efficient and reliable conversion of magnetic field energy in the active volume of generator part GTU in comparison with existing electric machine generators is theoretically substantiated and experimentally verified [11-16]. This provision is based on the fact that magnitude of electromagnetic forces, torque and power generated in any electric machine (both in generator and in electric motor) is directly proportional to product of normal component of induction and tangential component of magnetic field strength in the working gap of this machine. The tangential field strength is determined by magnitude of the linear current load on stator boring, which, in turn, is directly proportional to the current density and the

volume of material of active conductors in the winding. In conventional electric machines, the linear load is limited by the permissible current density in conductors covered with insulation with a certain class of heat resistance and the filling factor of stator grooves with a conductor material, which has a value not exceeding  $0.3\div 0.5$  (depending on the power and rated voltage of windings).

In the generator part GTU, absence of conductor and slot insulation and the single filling factor of grooves with conductor material of Z-phase rod winding, create the prerequisites for a significant increase (2-5 times) of the linear current load along the stator boring in comparison with linear load of traditional electric machines with the same geometric dimensions of active zones [9, 14]. The frontal parts of stator rod winding performed in form short-closed ring, which are closed Z-phase generator rod winding of the with only one end. Therefore, the length of frontal parts of the stator rod winding GTU is several times less, than the length of frontal parts of the loose multi-turn stator windings for traditional asynchronous machines. These factors allow to increase in  $2\div 3$  times the value of specific power for generator part GTU, located in an autonomous object with extreme environmental conditions [14].

In figure 4 shows the 3D-graph dependence of relative volume  $V'_0$  of active parts of a conventional AG and the generator part GTU with rod stator winding, on relative filling factor  $K'_f$  of the stator slots by conductors and relative current density  $J'_c$ .



**Fig 4.** Dependence of relative volume  $V'_0$  of conventional asynchronous generator and generator part GTU from fill factor  $K'_f$  and relative current density  $J'_c$

The given dependences show that the volume of active materials of generator part GTU can in principle be less than the volume of a conventional asynchronous generator by 5-6 times at the same values of power, speed and induction in the working gap. This is due to

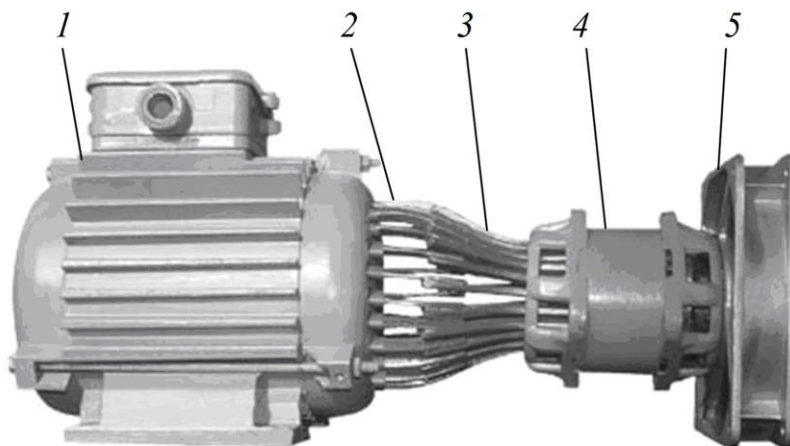
fact that the value of linear current load MTU, determined by the product of filling factor and current density of conductors can be higher in the same 5-6 times, compared with conventional AG with multi-turn stator windings [6].

Detailed computational studies show [6] that the real reduction in active volume of generator part GTU is slightly less. This is due to the fact that the above formulas for determining the relative volume do not take into account the non-constant value voltage of the generator part GTU, depending on operation mode.

The absence of conductor and slot insulation in generator part GTU, as one of the most vulnerable places of traditional electric machines, and low phase voltage (units of volts), significantly increase the reliability of electric machine energy conversion in such machine-transformer units. The design features GTU provide that often arise the necessity of placing in sealed objects with extreme environmental parameters highly reliable units at the lowest possible weight and size.

Another advantage GTU, which is part of cogeneration mini-TPP, is the direct utilization of thermal energy (due to inevitable electrical and magnetic losses in generator), removed from surface of generator part GTU, located directly in the micro-turbine unit and added to the main thermal energy of mini-TPP.

At a model sample GTU with AGGS<sup>†</sup> (Fig. 5) the results were obtained, qualitatively confirming the calculation and theoretical studies of the considered electric machines.



**Fig. 5.** Operating model of mini power plant with generator-transformer unit (GTU): 1 – transformer part (TNF); 2 – primary Z-phase rod winding TNF; 3 – Z-phase rod winding of stator AGGS; 4 – generator part (AGGS); 5 –impeller

### 3 Conclusions

The proposed development of generator-transformer unit solves the problem of improving reliability and maintainability of power generation plants with extreme conditions of moving gas, vapor-gas and liquid media in a fundamentally new way, due to the fact that generator part of the unit does not have traditional conductor and slot insulation of the windings, which is least reliable part of conventional electrical machines. This achieves the

<sup>†</sup> The operating model GTU received gold medals at the IV Moscow international Salon of innovation and investment (Moscow, all-Russian Exhibition Center, 25-28 February, 2004) and at the XVII Moscow international Salon of inventions and innovative technologies "Archimedes-2014" (Moscow, Expocentre Sokolniki, 1-4 April, 2014).

highest possible filling factor of stator grooves with a conductive material equal to 1. Thus, the specific power of generator part located in a sealed object can be two to three times more than conventional generators.

Transformer of voltage and number of phases TNF can be designed for three-phase output voltage 6/10 kV. In this case, there is no need to use an additional transformer in transmission of electricity by this voltage.

In this GTU, due to peculiarities of its design, provides maximum unification of parts and assembly units, as well as the ability to assemble GTU of removable and interchangeable machines and create such units on the basis of commercially available asynchronous motors. This will reduce the complexity of manufacture GTU to the level of serial machines and improve the maintainability of units, as well as use the production capacity of electric machine-building plants, which are engaged in production of such electric machines without significant capital investment in the preparation and maintenance of new production.

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