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On Possibilities of Creating Systems for Autonomous Power Supply of Pipeline Cathodic Protection Stations.

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ABSTRACT

Results of development and approbation of a hydraulic unit based on a low-head axial-type propeller hydraulic turbine with a power up to 1500 W intended for operation in pipelines DN 250 are presented. Feasibility is experimentally confirmed of construction of a simple and inexpensive system for electric current generation, with an asynchronous generator and a serial frequency converter for autonomous power supply of remote stations for cathodic corrosion protection of pipelines.
Keywords: pipeline, electrochemical corrosion protection, cathodic protection station, flow potential, low-pressure microhydropower plant, built-in microhydroturbine.

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INTRODUCTION

At present, devices for electrochemical pipeline corrosion protection have become an inseparable part of process equipment of pipeline transport. Being an active method for protection from corrosion processes, they are widely used on trunk and local pipelines as they assure guaranteed long-term protection of critical surfaces from corrosion, as distinct from the passive method (application of insulating materials), where through corrosion processes are intensely manifested as soon as after 7 to 8 years of operation. Cathodic protection stations (CPS) used in pipeline transport are intended for electrochemical protection of pipelines from corrosion and are based on imposition on the pipeline surface of a so-called "protective anode" – a metal with a larger negative potential than that of the object to be protected. Therefore, the "pipeline – protective anode" system is, in essence, a galvanic couple placed into an electrolytic media, where the metal of the protective anode is the first to be destroyed. The CPS is a complex device generally comprising a power supply unit and a cathodic protection system, as such, which forms a specified potential at output electrodes of the station [1]. Serial multipurpose stations are generally able to provide direct current voltage at the output electrodes within the range from a few units (e.g., the minimum protective potential for heat supply networks is 1.1 V, and the maximum figure is 2.5 V) to 50 V (or 100 V) at the output power within 5 kW. External power supply of serial CPS is also generally provided from an AC power supply with a frequency 50-60 Hz and voltage 220 V. As the object to be protected is often operated in conditions variable with time, today, the most promising CPS are invertor stations (equipped with a thyristor transducer) ensuring continuous automatic voltage control and considerably advantageous over transformer stations, in terms of weight and energy parameters. CPS often have to be arranged at places situated kilometers away from existing power grids. Provision of cathodic protection in areas remote from centralized power supply networks always involves difficulties associated with the fact that its implementation requires construction of power transmission lines (PTL) along the pipeline route. Construction of a dedicated network for power-supplying cathodic protection stations is generally economically unfeasible (which is, among other factors, due to the variable nature of pricing on the market of components). In these conditions, the problem of autonomous power supply of CPS without arranging additional PTL is quite relevant. At present, this problem is mostly solved by providing CPS with autonomous electric power supplies based on diesel generators, which cannot be regarded as an efficient solution owing to high operating expenses.

At the same time, in pipelines serviced by cathodic protection stations, the flow of working medium often has some energy potential of its own in the form of hydraulic energy of excessive pressure that may be used for power-supplying CPS. In particular, Russian construction standards and regulations allow for pipelines with nominal diameter up to *DN* 1400 the range of excessive pressure from 1.2 MPa to 10 MPa. This energy potential may be converted into electric energy by means of built-in hydropower devices, particularly, today, as concepts of low-head compact modular hydraulic units are being actively developed. In this paper, it is proposed to consider such object of power supply by example of a microHPP with a hydraulic turbine that may be installed inside the pipeline. For this idea to be implemented, a hydraulic turbine is needed, which would provide the CPS with required energy, on condition of consumption of the lowest possible pressure in the pipeline. That is why the authors of the paper suggest considering a low-head hydraulic unit as an efficient source of electric energy that could be easily built into the trunk pipeline and would produce no serious impact on the efficiency of transportation of the working fluid.

Design of a hydraulic unit with an axial type propeller hydraulic turbine

It has to be noted that in development of a hydraulic turbine operating in low head conditions, the main emphasis was put on ensuring generation of designed power, with the device having low prime cost and high reliability. Besides, to this effect, one had to achieve reduction of hydraulic friction of the flow part of the hydraulic unit for raising its efficiency. Therefore, researchers of NRU "MPEI" developed an axial type hydraulic turbine, which is designed to have neither inlet guide vanes, nor swivel-vane mechanisms of impeller. Such design solution would adapt the hydraulic turbine to operation under low head with high energy efficiency [2 and 3], as it incurs no considerable hydraulic losses determined by the presence of guide vanes, and has a simpler design which is beneficial for reliability parameters of the power unit.

The hydraulic unit presented in fig. 1 comprises electric machine 1, which was constituted by a squirrel-cage asynchronous electric machine, housing 2 in the form of a hydraulic pipeline branch, hydraulic turbine impeller 4 and its impeller fairing 5 intended for improving conditions for entry of the flow into the vane system of the impeller and stabilization of the flow conditions. The electric machine is connected to the hydraulic machine with coaxial shafts by means of a jaw coupling ensuring transmission of torque. The turbine shaft has supports in the form of rolling-element bearings and is mounted thereon in a “non-locating” arrangement.

The hydraulic unit has the following design characteristics:

– rated capacity of generator ………………………………………… 2.2 kW;
– synchronous rotation speed of generator shaft ………………… 1000 RPM;
– outer diameter of impeller of hydraulic turbine …………………….. 0.25 m;
– full designed head of hydraulic turbine …………………………….. 1.33 m;
– designed output electric power ……………………………………. 1500 W.

Fig. 1. Photograph of hydraulic unit with a propeller turbine

Experimental approbation of hydraulic unit

The manufactured pilot model of the hydraulic unit was experimentally approbated on a special hydraulic bench of NRU “MPEI” intended for examination of energy characteristics of small and microhydroturbines. Its schematic diagram is presented in fig. 2:

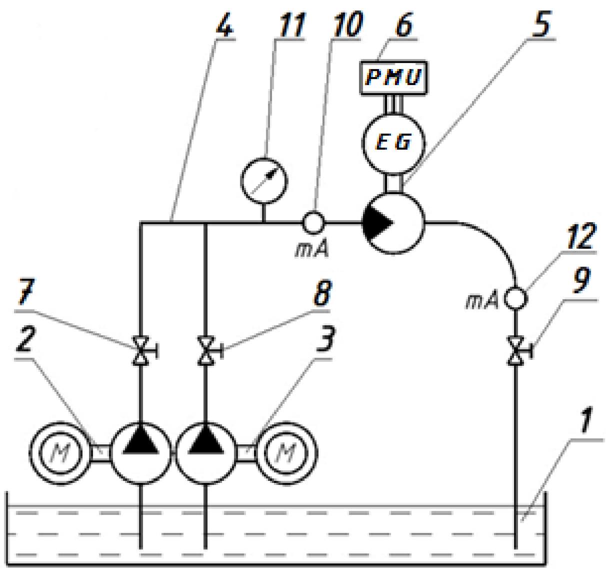

Fig. 2. Schematic diagram of hydraulic bench of NRU “MPEI”:

1 – tank with working fluid; 2,3 – pumping units; 4 – pressure pipeline;
5 – hydraulic unit under examination; 6 – electric supply parameter measurement unit,
7,8 – delivery gates; 9 – gate for regulation of flow rate through the hydroturbine;
10 – Pitot-Prandtl tubes; 11 – pressure vacuum gauge; 12 – Prandtl tube.

Operation of the bench proceeds as follows:

From tank 1 with the working fluid, console type centrifugal pumping sets 2,3 ensure transportation of the working fluid along delivery pipeline 4, which accommodates built-in hydraulic unit 5 with a turbine, which characteristics are examined. The hydraulic turbine drives the electric machine of the hydraulic unit ensuring generation of electric energy by converting hydraulic energy of the flow of the working medium being transported. The electric machine of the hydraulic unit is connected to the network via integrated power supply parameter measurement unit 6, which ensures acquisition of information on the monitored parameters (pressure in the flow part, rotation frequency of the hydraulic turbine shaft) in real time. The working fluid, having passed through the hydraulic turbine and having given some of its energy thereon, is discharged back into the tank thus forming a circulation arrangement of the bench simulating a section of a trunk pipeline. Delivery gates 7, 8 are intended for regulation of delivery of pumps, gate 9 – for regulation by throttling of the pipeline throughput (or the flow rate through the hydraulic turbine). Pressure-measuring instruments of the bench are located on the axis of the hydraulic machine at the same level and constitute Pitot-Prandtl tubes 10 with check pressure vacuum gauge 11, which are installed at the inlet into the hydraulic machine, as well as Prandtl tube 12 installed at the outlet of the hydraulic unit. The instruments are connected to the measurement unit with strain pressure gauges controlling dynamic and static pressure in the flow part of the pipeline. Their readings are recorded in real time with a MIC-200M measuring complex.

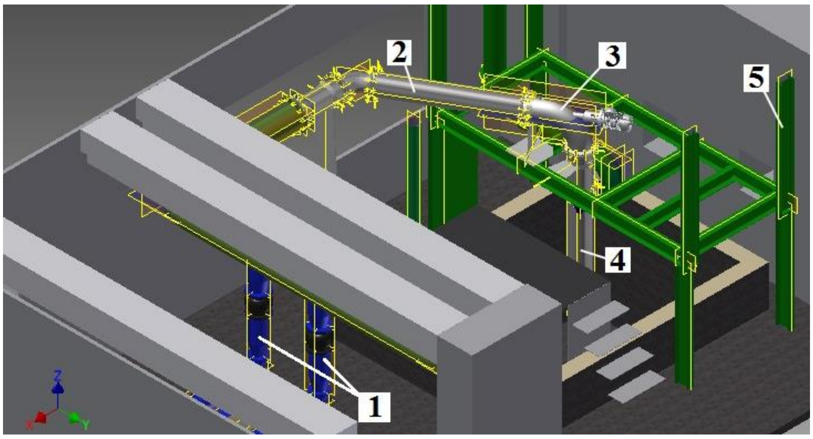

Fig. 3. Model of hydraulic bench of NRU "MPEI":

1 – step-up pumps, 2 – delivery pipeline, 3 – hydraulic unit,
4 – discharge pipeline of hydraulic unit, 5 – supporting platform.

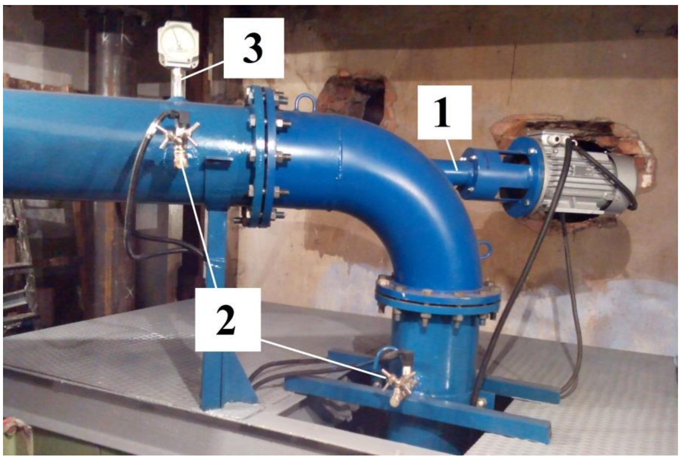

Fig. 4. Hydraulic bench of NRU "MPEI":

1 – hydraulic unit built into the flow part of the pipeline; 2 – pressure gauges at the inlet and outlet of the hydraulic turbine; 3 – check pressure vacuum gauge.

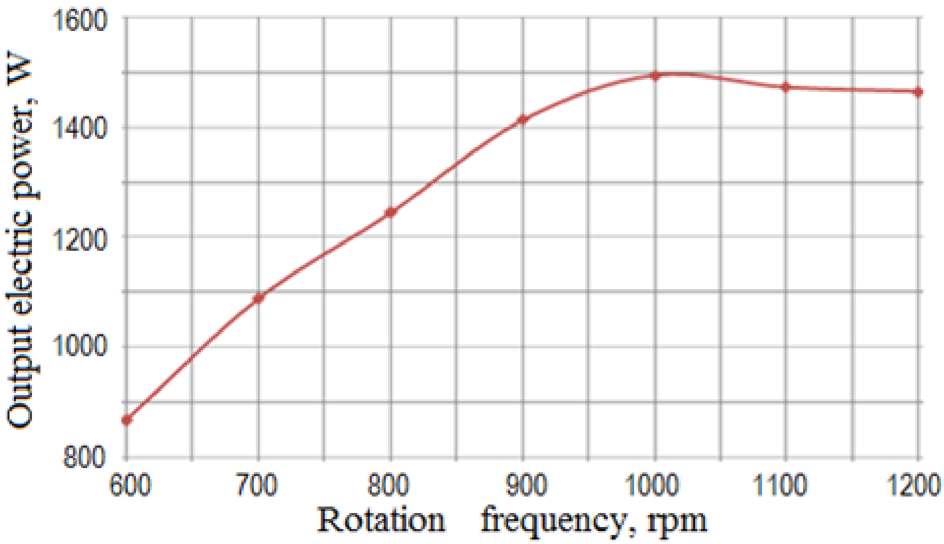

Fig. 5. Experimental dependence N=f(n) of the power of hydraulic unit on the shaft rotation frequency at the designed head on the turbine

The schematic diagram is further explicated by a virtual model of the bench represented in fig. 3 and its photograph (fig.4). In the course of experimental studies, dependence of power on rotation frequency N=f(n) is obtained (fig.5). This experimental characteristic shows that the maximum power is achieved at n=1000 RPM and is just above 1500 W. Therefore, the hydraulic unit approbation results presented in fig. 5 have shown virtually exact consistency between designed and experimental parameters of the turbine and the hydraulic unit, as a whole. The turbine's maximum efficiency (about 85%) was achieved close to the designed shaft rotation frequency at the flow speed values in the pipeline DN 250 at about 1.5 m/sec.

It has to be noted that experimental studies of energy characteristics of the hydraulic unit were conducted on tap water; therefore, in case of its operation in a different working fluid (in particular, oil), the results of experiments must be adjusted for the medium density and viscosity. The decreasing factor of adjustment for density is found as follows

$$k_{\rho} = \frac{\rho_{н}}{\rho_{в}},$$

where $\rho_{н}$ – oil density; $\rho_{в}$ – water density,

corresponds to the ratio of oil and water density values and may be estimated as equal to k_{ρ} = (0,833…0,862) for oil grades classified as middle ones. The decreasing factor of adjustment for viscosity k_{ν} is a priori much more complex as the scientific and technological literature provides no data on research on effect of viscous medium on characteristics of axial type propeller hydraulic machines. At the same time, most of researchers of blade hydraulic machines tend to believe that the defining effect of viscosity on characteristics of the hydraulic machine may be estimated in proportion to variation of the Reynolds number at transition between two working *fluids* (see, e.g., [4]). The Reynolds number in the presented experiments for water at the designed working conditions in the turbine may be estimated at *Re* = 500 000. This *Re* value corresponding to a developed turbulent flow, with kinematic viscosity growing 10-…20-fold, will also decrease 10…20 times at identical flow velocities; however, the flow regime will stay in the turbulent zone. Therefore, owing to an increase in the friction coefficient on surfaces of the turbine, its efficiency will fall by about 3…4 per cent. This is clear from analysis of Prandtl-Schliechting equation

$$C_{F\,м} = \frac{0{,}455}{(lgRe_{м})^{2{,}58}},$$

which describes in the most precise way the pattern of variation of friction resistance with the flow passing around a flat plate within the range of the Reynold numbers $250\,000 < Re < 500\,000\,000$. Based on the first a priori approximation, the factor of power reducing for density k_{ρ} and viscosity k_{ν} at designed conditions for oil grades classified as middle ones may be estimated at 0.8…0.82. This means that at the output of the presented hydraulic unit operating on oil, one can obtain electric power of about 1200 W. The power consumed by cathodic protection stations, depending on the scale of the trunk pipeline, is 0.5-5 kW. Given the possibility of accommodating a number of hydraulic units into pipelines under protection, this unambiguously indicates that such power is sufficient for supplying a typical CPS.

Seeking to develop a reliable yet inexpensive device, the authors of the offered design, for the sake of reducing the prime cost of the energy plant, used a serial squirrel-cage asynchronous generator operating in the generator mode as a generator. This solution has a number of advantages and disadvantages. This electric machine worked well in parallel with a powerful network. However, in an autonomous mode, an asynchronous generator requires additional excitation capacitors, as well as a complex system for control and stabilization of output electrical energy parameters. Still, using an electric machine of this type in the design of a hydraulic unit remains an attractive option owing to its reliability and low cost. The authors of the article further suggest a solution, which enables to eliminate the aforesaid considerable shortcomings.

Autonomous asynchronous generator with a frequency convertor

For the aforesaid shortcomings of the asynchronous generator to be eliminated, in the proposed hydraulic unit, an arrangement was proposed for operation of an autonomous asynchronous generator with a frequency convertor and an uninterrupted power supply (fig. 6).

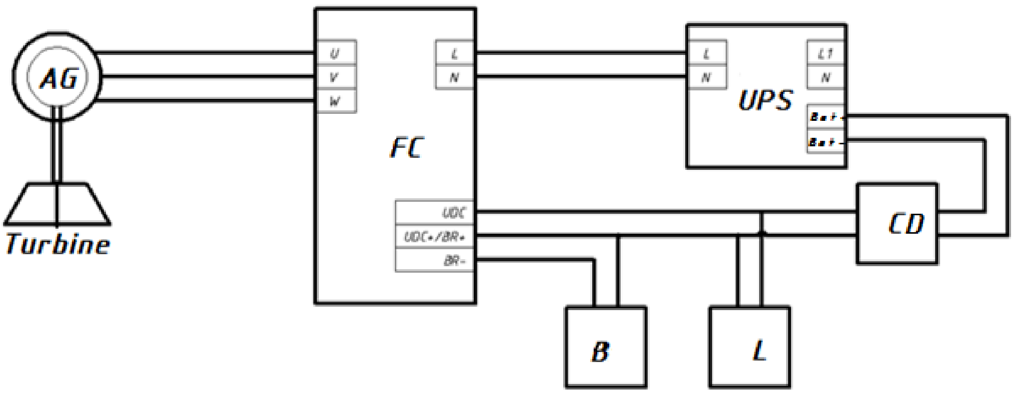

Fig. 6. Diagram of autonomous asynchronous generator with a frequency convertor and an uninterrupted power supply unit:

AG – asynchronous generator, FC – frequency convertor, UPS – uninterrupted power supply, B – ballast (braking resistor), L – useful load, CD – charging device.

The arrangement includes standard elements, which require no further elaboration: a serial asynchronous electric motor; a serial frequency convertor; a serial uninterrupted power supply and a standard charging device (power supply *DC/DC*). As a frequency convertor, we used a frequency convertor OVEN PChV103-2K2-A with single-phase power supply (terminals *L/N*), outputs from the direct current link (terminals *UDC/UDC+*) and a jack for connection of a braking resistor (terminals *BR+/BR-*).

The frequency convertor may in principle be regarded as a two- or three-phase rectifier and a thyristor- or transistor-controlled invertor, which have a common direct current link with a capacitor [5]. The generation system with such a convertor operates as follows. In the starting mode, the frequency convertor receives power from the UPS (under the arrangement implemented by the authors, U_p=220 V). Voltage on the direct current link (on terminals *UDC*) rises to the value of $\sqrt{2}U_{\rm p}$. Control signals are delivered to the invertor keys; the electric motor starts developing speed according to a pattern set on the frequency convertor. At this time, the hydraulic turbine operates in the pumping mode. As the turbine rotation frequency is increasing, the torque on its shaft reverses its sign, and it starts transmitting power to the electric machine. The electric machine switches to the generator mode; voltage on the direct current link of the frequency transducer (on terminals *UDC/UDC+*) starts growing above $\sqrt{2}U_{\rm p}$. On exceedance of a certain maximum value of voltage on the direct current link determined by the components applied and the convertor settings, the BR braking resistor key is opened. The key operates under the control from a pulse-width modulator with an on-off ratio ensuring maintaining the maximum value of voltage of the direct current link (for the implemented arrangement with an OVEN convertor, this voltage U_{DC}=380 V). If in this mode an external load with resistance R_L is connected to the terminals *UDC/UDC+* of the convertor, this load is given the power $P_L = U_{DC}^2 / R_L$, and the on-off ratio of the BR braking resistor key varies so that voltage U_{DC} on the direct current link would be maintained fixed. This ensures keeping the balance of power between the generator (P_{gen}) and the aggregate load (P_{cons}), i.e., the sum of: P_{cf} – power consumer by the convertor for its own needs; P_{UPS} – power consumed by the UPS for charging the storage battery; P_{BL} – power consumed by ballast load; P_{UL} – power of useful load. In the course of operation of the generator, there occurs partial accumulation of charge by the UPS storage battery through the charging device (CD) from the direct current link with voltage U_{DC}. The capacity of the storage battery must cover the own needs of the UPS and the frequency convertor at the time of starting of the power plant. Once the storage battery is charged in full, it is possible to disable the UPS. In this case, if $P_{gen} > P_{cons}$ (in particular, in case of a rise of the hydraulic turbine power, or on disconnection of consumers), the on-off ratio of the BR key would increase, and the excessive power would be dissipated on the ballast load heating the braking resistor. Here, it is quite natural that the rated power of the braking resistor must at its limit correspond to the maximum power of the generator. If $P_{gen} < P_{cons}$ (in particular, on reduction of the hydraulic turbine power, or in case of connection of additional consumers), the on-off ratio of the BR key would decrease up until its complete closure. It has to be noted that the described algorithm of operation of the *BR* key is already embedded by manufacturer into the electronic circuit of the serial frequency converter, which requires no further configuration of the convertor, apart from setting the parameters of the braking resistor (resistance to electric current of ballast load) and, if necessary, the time of the unit's reaching the rated rotation frequency.

DISCUSSION OF OBTAINED RESULTS

The suggested system of generation of electric current based on a hydraulic unit with a low-head turbine, as applied to cathodic protection stations of trunk pipelines, has a number of advantages.

– First, the system is totally autonomous. With no other network available, an uninterrupted power supply is used for launching. In the generator mode of the asynchronous machine, the UPS storage battery is being charged.

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- Second, the asynchronous generator requires no additional capacitor-based excitation units: the reactive power generated by the frequency convertor is sufficient. The source of reactive exciting power of asynchronous generator is the valve-type convertor FC [6].
- Third, the possibility to adjust the rotation frequency of the electric machine by means of controlling the FC enables to ensure operation of the hydraulic turbine at the maximum possible efficiency in case of variation of the working fluid flow conditions.
- Fourth, at the output of the hydraulic unit, the stable direct current voltage is generated U_{DC}=380 V, which ensures guaranteed continuous provision of power supply to the CPS.
- Fifth, the system is rather simple and can be easily automated. This, in its turn, determines high reliability and maintainability parameters of the power plant.
- Sixth, the prime cost of the hydraulic unit on completion of the process cycle of its manufacture is relatively low as standard serially produced electric equipment is used.

It has to be noted that this system also has a drawback of its own. A rise of load at the output of the direct current link with the BR key totally closed would result in a drop of voltage on the direct voltage link. On the other hand, a decrease of voltage below a minimum permissible value (for the convertor used by the authors, this value is U_{DCmin}=220 V) is perceived by the frequency convertor as an accident, and the control system forces its shutdown. Therefore, with this configuration of the hydraulic unit, overload conditions are unacceptable.

A specific feature of the proposed current generation system is that the current at the output of the hydraulic unit is direct. This should not be considered a drawback. On the contrary, in case of transfer of energy from the power plant to a consumer in conditions of remote areas, power-supplying with direct current enables to do it with no extra "branches", directly; reactive power losses are eliminated; a direct current network may be synchronized with an alternating current network of energy generated by renewable sources.

At present, a trend can be observed throughout the world towards development and implementation of direct voltage power transmission lines. Application of such lines is economically justified [7]. Moreover, this specific feature enables to use the above power plant based on a hydraulic unit without further elaboration for power-supplying modern invertor CPS.

Fig. 7 presents a functional diagram of power supply unit of standard invertor CPS with a power factor adjuster enabling to obtain the station's maximum efficiency.

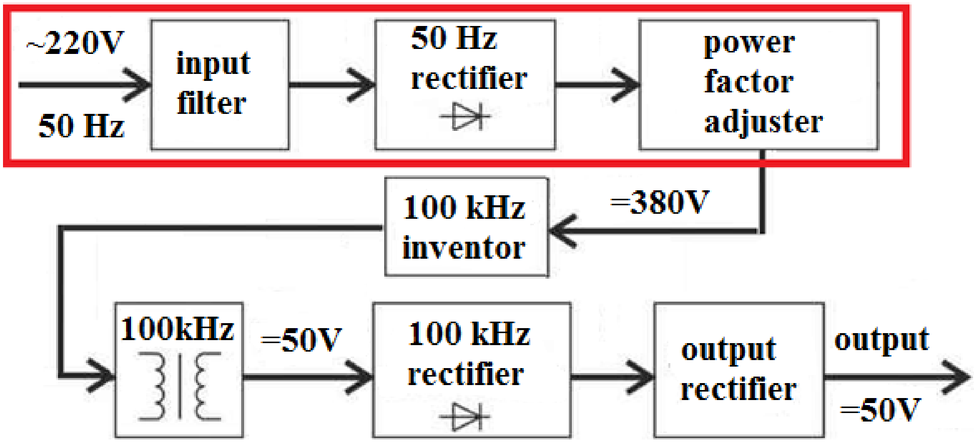

Fig. 7. Functional diagram of power supply unit of standard invertor CPS

In the power supply diagram, the high-frequency invertor is supplied with direct current of the voltage 380 V. The diagram of this power supply may be considerably simplified, with the first three of its elements removed (framed into a red rectangle in fig. 7), if the CPS is power-supplied by the h hydraulic unit presented in this article. This is actually possible as the current generation system of the hydraulic unit provides stabilized voltage U_{DC}=380 V at the outputs UDC/UDC+. Thus, the generalized structural diagram of the CPS with an autonomous power supply system based on a hydraulic turbine will be as presented in fig. 8.

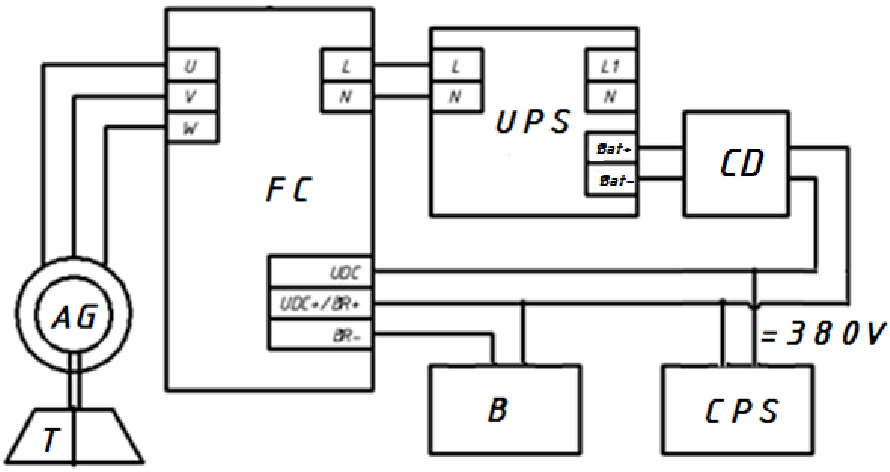

Fig.8. Generalized structural diagram of CPS with an autonomous power supply system based on a hydraulic turbine:

T – turbine, AG – asynchronous generator, FC – frequency convertor, UPS – uninterrupted power supply, CD – charging device,
CPS – cathodic protection station

CONCLUSIONS

1. The developed and approbated hydraulic turbine in a pipeline with DN 250, at flow velocity values about 1.5 m/sec, and at the full head 1.33 m, is able to provide power supply to cathodic protection stations with a power 1200…1500 W.
2. The developed system for generation of electric current based on a hydraulic unit with an asynchronous generator enables to make an efficient and inexpensive system for autonomous power supply of cathodic protection stations of trunk pipelines.
3. The developed principle for power supply of cathodic protection stations enables to simplify the station power supply unit and reduce its cost.
4. From the point of view of operation of a power plant based on the above-described hydraulic unit, electric energy is generated by a "clean" method. This indicates at environment-friendliness of the produced electric energy, compared to a diesel electric plant, which, given the current trends towards stricter environmental requirements, makes an undisputable advantage of the proposed device.
5. Power-supplying pipeline cathodic protection stations through conversion of hydraulic energy referred to a cheaper tariff segment does not only enable to cut capital expenses of the device, but also reduce operating costs considerably.

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