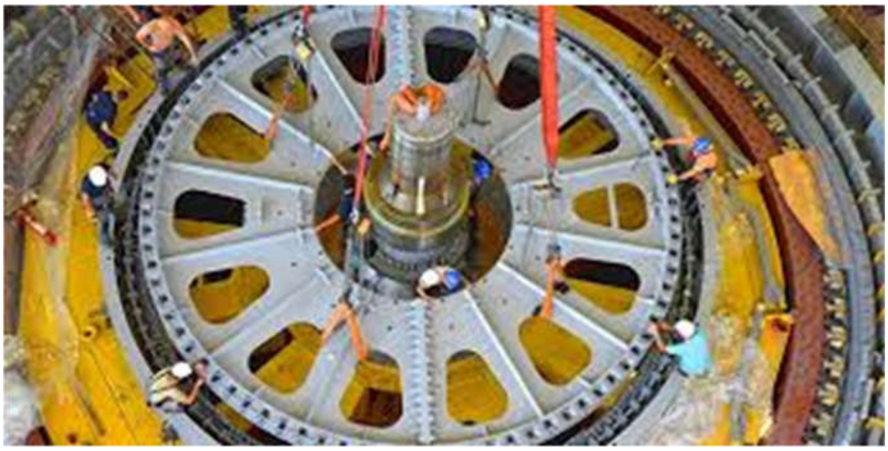
Performance testing after upgrade of HPP Iron Gate 1

The Iron Gate 1 hydropower plant is a power station built on the 943rd kilometre of the Danube from its confluence with the Black Sea. The dam is symmetrical, with an overflow dam in the middle, machine buildings with 6 hydro units and ship locks on the Romanian and Serbian sides.

HPP Iron gate 1

The first synchronization of aggregates to the network was carried out in 1970.

In the period from 2009 until today, works are being carried out on the revitalization and modernization of the Serbian part of the power plant, which includes the replacement of parts of aggregates and block transformers, as well as auxiliary systems such as the excitation system, the turbine regulation system, control, protection and monitoring systems, and the HPP's auxiliary power supply system.



Assembling of new generator

The new generators have the following characteristics:

- generator	type vertical with the thrust bearing below the rotor and the guide bearing above the rotor (according to IEC 60034-7 type 8310)
- manufacturer	Elektrosila - Russia
- rated apparent power	211.1 MVA
- rated speed	71.43 rpm
- frequency	50 Hz
- maximum constant load	216 MVA
- maximum voltage on units' outlet	15.75 kV ± 5%
- rated current	7739 A
- nominal power factor	0.9

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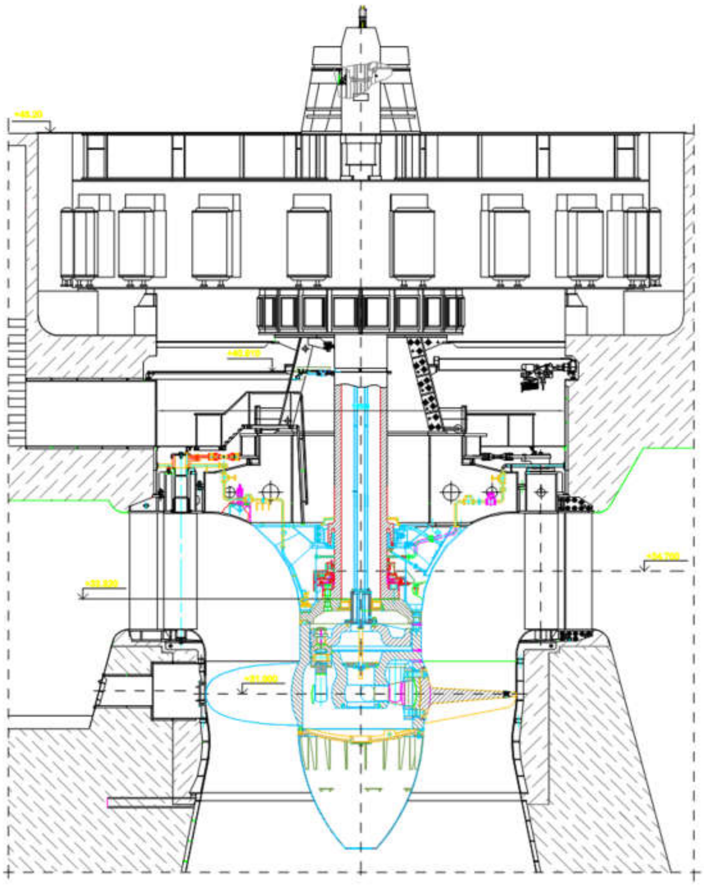


Cross section trough the Unit

Equipment installed on the generators used for continuous measurement and monitoring of:

- Temperatures,
- Partial discharges,
- Vibration and air gap and
- Magnetic flux.

Temperature monitoring

Monitoring, i.e. continuous measurement of generator temperatures, is performed using platinum resistance thermometers of 100Ω at 0 °C (Pt100 temperature transmitters) and modules for analogue temperature inputs in the Unit master station. Temperature measurement of the following generator elements is provided:

- In the stator windings and core of the main generator,
- On the end packages of the stator core sheets of the main generator,
- In the stator windings and core of the auxiliary generator,
- In the segments of the guide and thrust bearings,
- In the zones of hot and cold air,
- At the inlet and outlet of the water from the air coolers of the generator,
- At the inlet and outlet of the water from the thrust bearing oil coolers,
- At the water outlet from the oil coolers of the guide bearing,
- On the inlet collector of water for cooling system of the generator,
- On the outlet collector of water for cooling system the generator.

In addition, for the thermal control of the generator, capillary pressure gauges were installed, for the purpose of signalling the exceeding of the limit values for temperatures at the following points:

- in the thrust bearing segments,
- in the guide bearing segments,
- in the hot air zone,
- on the inlet and outlet collector of cooling water.

Monitoring of partial discharges

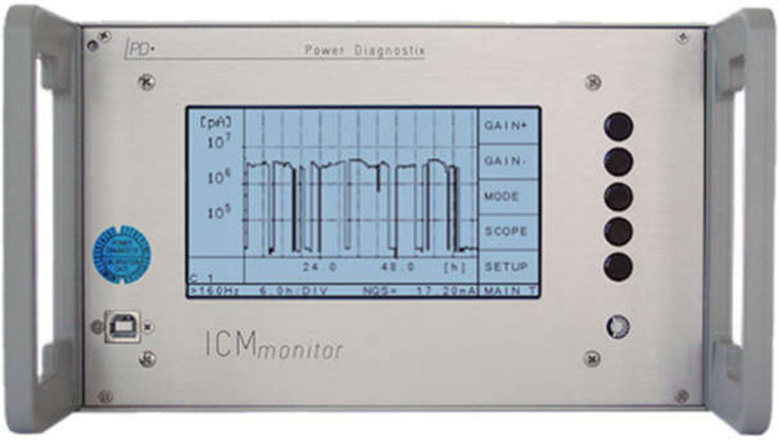
The system for measuring and monitoring partial discharges is intended for continuous monitoring of important parameters of the state of the insulation of the generator stator windings, as well as monitoring their dependence on the dynamics and changes in conditions during the operation of the generator.

This achieves the following goals:

- increasing the operational safety of the hydrogenerator based on control of the level and the dynamics of the development of the discharge process in the insulation of the stator windings,
- assessment of the current, pre-overhaul and post-overhaul condition of the insulation.
- The method of automatic continuous monitoring, measurement and analysis of the insulation condition of the hydrogenerator (on-line monitoring) is complementary to the methods applied in the case of the machine being turned off (off-line). Its advantage is that it can provide data on the condition of the isolation system of the hydrogenerator in real operating conditions, which are difficult to achieve during off-line tests. This method will fulfil the following requirements:
- inspection of the state of insulation during the operation of the generator under operating conditions, when electric, magnetic, thermal and mechanical stresses are present in the generator;
- tests that do not require a change in the operating mode of the generator;
- permanently installed partial discharge measurement sensors as safe passive components, selected so that they do not endanger or interfere with the operation of the generator.

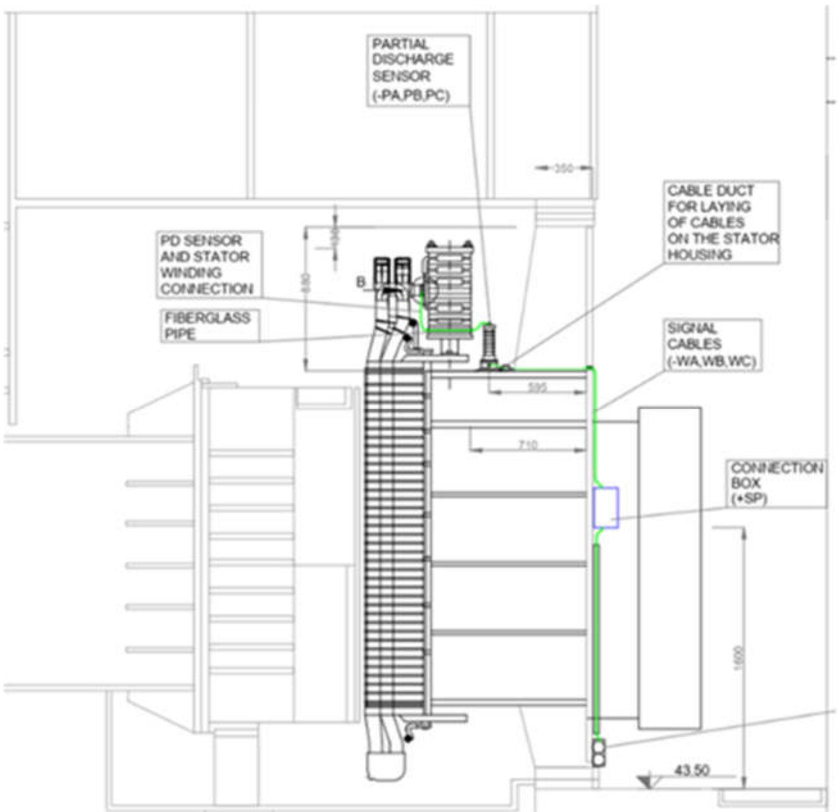
- The system for measuring partial discharges on the unit consists of the following elements:
- partial discharge signal transmitters, type CC20B (145 pF, 21kV)
- a cubicle with a data acquisition system (signal conditioning, multiplexer, preamplifiers and I/O modules, partial discharge analyser, data storage, etc.)

The equipment is manufactured by Power Diagnostix.



PD analyser – Power Diagnostic

The generator windings are three-phase, with three parallel branches per phase. Measurement and monitoring of partial discharges is performed on each parallel branch. The sensors are located around the perimeter of the stator, on the upper shelf of the stator housing, in the axis as well as the output (high-voltage) ends of the parallel branches of each phase.



Location of PD sensors

Monitoring of Vibration, shape of the rotor and stator and air gap

The monitoring system should control the following parameters during operation of the hydro aggregate in operational and transition modes.

Position	Measuring parameter	Number of probes pre unit
Generator guide bearing	Bearing vibrations along the XY axis	2
	Shaft run-out along the XY axes	2
Generator thrust bearing	Vibration of the thrust bearing in the axial direction	1
Stator core	Vibration of stator core	6

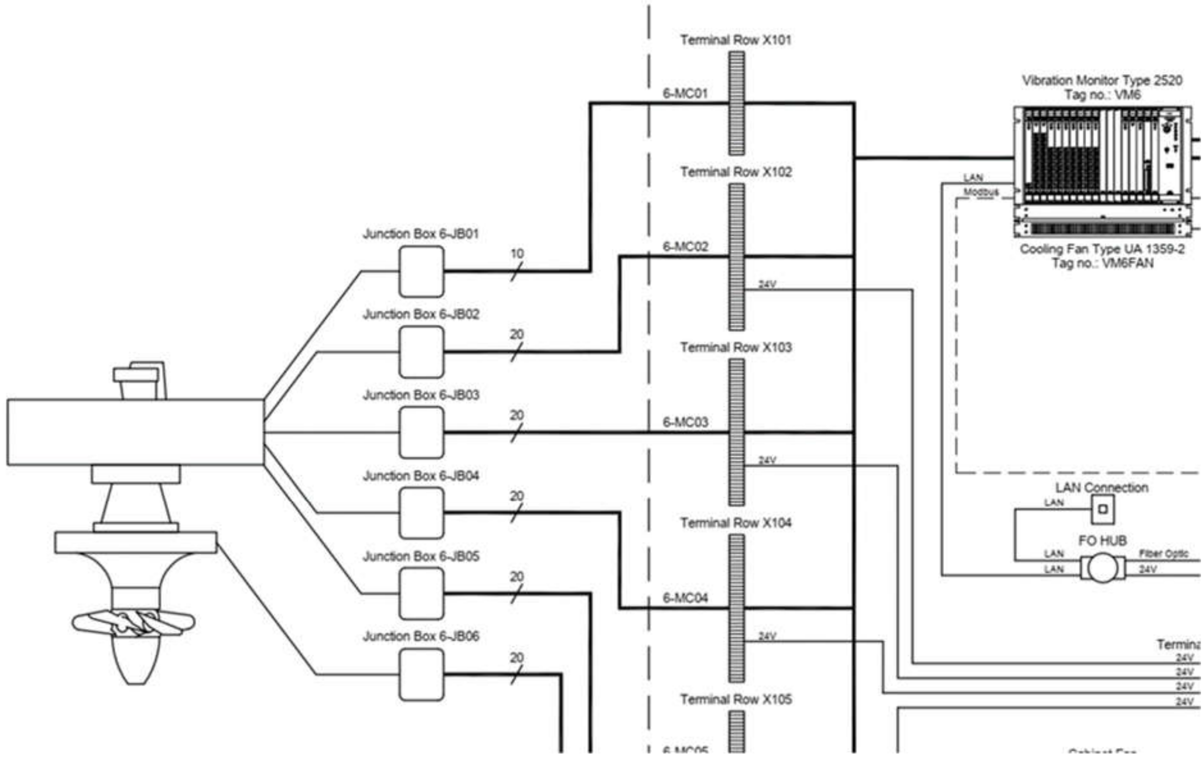
The Unit level monitoring system, type 3540 COMPASS manufactured by Brüel & Kjaer Vibro Gmbh, consists of:

- transmitters, signal amplifiers and corresponding elements for their assembly on the unit;
- connecting cables, connection boxes with signal amplifiers;
- a cubicle with a device for collecting and processing data (vibromonitors VM 2520), equipment for communication connections, equipment for powering installations (rectifiers, protective circuit breakers), terminal strips, a fan, a service socket and internal lighting.

Each hydraulic unit is equipped with 14 absolute vibration sensors - accelerometers (type 8315), with four (4) relative vibration sensors (type IN-081), one (1) speed/phase measurement sensor (type IN-081) and with 16 air gap sensor/rotor and stator shape (type EQ 2431).

The collection and processing of measured information is performed by the VM 2520 vibromonitor, within system and measurement modules are implemented.

The vibration monitoring system at the power plant level includes equipment for connecting individual equipment on aggregates into one centralized system.



Monitoring system of vibrations, shape of the rotor and stator and air gap – simplified scheme

Magnetic flux monitoring

The system for monitoring the magnetic flux of the rotor enables continuous monitoring of the total magnetic flux of the rotor in order to detect the development of the state of the inter-turn insulation of the rotor poles windings, without interrupting the operation of the aggregate.

This achieves the following goals:

- inspection of the state of the inter-turn insulation of the windings of the rotor poles during the operation of the generator under operating conditions, when electric, magnetic, thermal and mechanical stresses are present in the generator;
- tests that do not require a change in the operating mode of the generator;
- permanently installed magnetic flux measurement transmitters as safe passive components, selected so that they do not endanger or interfere with the operation of the generator.

The system for measuring the magnetic flux of the rotor consists of the following elements:

- magnetic flux measurement transmitters (one per unit),
- measurement synchronization transmitters (one per unit),
- junction boxes (one per unit) i
- data acquisition equipment (FluxTracII-S device made by Iris Power) located in the factory assembled cubicle.

Signals from the magnetic flux measurements and synchronization transmitter (sensor) from each of generators are introduced to the corresponding channels of a unique data acquisition device.

At the same time, the one device is used for the acquisition of data from sensors for monitoring the magnetic flux of the rotors of three aggregates.

Flux monitoring is based on measurements of the local magnetic field from each pole of the rotor.

FluxTracII-S device by Iris Power

Checking the Unit parameters after completing the assembly of the new generator

After the installation of the new generator was completed, commissioning tests of the turbine and generator were performed, which included measurements of mechanical and electrical parameters in several stages:

- before filling the flow tract with water,
- after filling the flow tract,
- starting the unit by manual control of the turbine governor,
- no-load tests without and with excitation,
- automatic Unit start-up and synchronization,
- on-load operation testing,
- load rejection tests.

The following tests were performed:

- measuring the insulation resistance of the stator windings,
- measurement of the leakage current with High Direct Voltage,
- High voltage withstand test of the stator windings,
- tests of the inter-turn insulation of the rotor poles,
- measurement of the dielectric loss factor and the capacitance of the stator phase windings,
- measuring the ohmic resistance of the stator winding and the rotor winding,
- measuring the impedance of the rotor winding while supplied with 380V AC,
- determination of the generator no-load characteristic,
- determination of the generator short-circuit characteristic,
- voltage and current symmetry check and phase sequence control,
- determination of the Direct-axis synchronous reactance of the generator (xd) and the short-circuit ratio Kc,
- determination of the regulation characteristic,
- temperature rise tests of generator parts when heating the generator,
- measurement of mechanical and electrical values during power rejection,
- recording of the electrical braking process of the unit.

Generator testing procedures are fully in accordance with the requirements of the technical standard for testing rotating machines GOST 10169-77 and the international standard IEC 60034-4.

Based on the analysis of the results, it was concluded that the characteristics of the insulation system of the generator meet the requirements of technical standards.

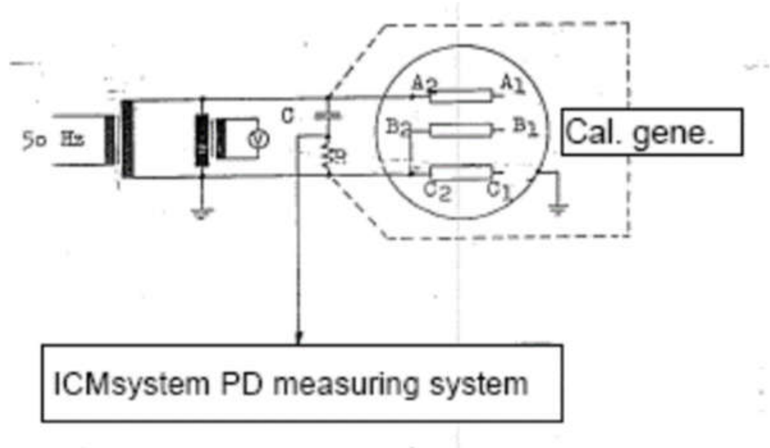
In addition to above mentioned tests, in accordance with relevant standards and recommendations, measurements of generator partial discharges and generator vibrations were processed as part of the test.

Measurements of partial discharges

The measurement is based on the collection-acquisition of PD pulses and intensity measurement, as well as determination of other parameters - place of occurrence depending on the phase of the test voltage, polarity, number, etc., based on which it is possible to more accurately determine the location and possible cause of PD.

During the calibration the voltage is supplied from the neutral side, while the coupling capacitor is placed on the outlet terminal connections. The calibration of the measurement scheme is performed by connecting the calibration generator to the terminal of the tested winding. The value of the calibration signal is chosen so that it is as close as possible to the real value of the actual measurement signal at the reference voltage value of 0.6Un.

The intensity of partial discharges is measured with the same power supply schemes as for measuring the dielectric loss factor and capacitance, i.e. voltage is applied to the winding under test, while the other two phase windings are grounded.



Principle connection diagram during testing

Reference documents

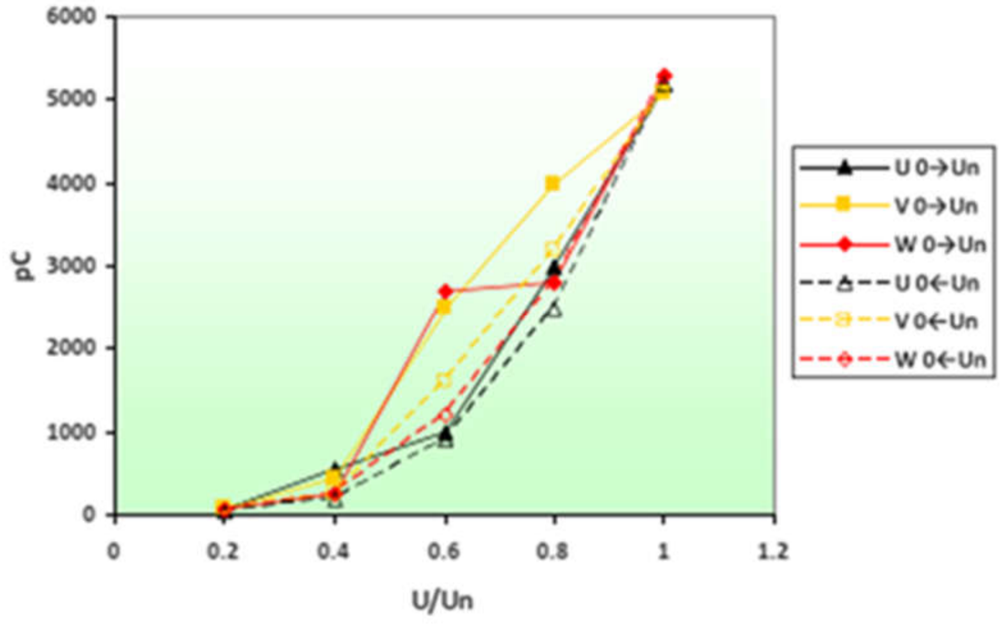
When measuring the intensity of partial discharges, the following reference documents are taken into account:

- IEEE 1434: 2000 Trial-Use Guide to the Measurement of Partial Discharge in Rotating Machinery,
- IEC 60034-27/2006 Rotating electrical machines -Part 27, Off-line partial discharge measurements on the stator winding insulation of rotating electrical machines.

Measurement results

The intensity of the partial discharges of the individual windings is satisfactory and uniform across phases.

	Phase	U_{isp}/U_n	0,2	0,4	0,6	0,8	1,0
		U_{isp} [kV]	3,15	6,30	9,45	12,60	15,75
PD (pC)	U	0→U_n	60	550	1000	3000	5200
		0←U_n	50	200	900	2500	5200
	V	0→U_n	70	450	2500	4000	5100
		0←U_n	80	250	1600	3200	5100
	W	0→U_n	60	250	2700	2800	5300
		0←U_n	60	250	1200	2800	5300



Measured PD intensity in all three phases, in relation to applied voltage is presented within the table and on the graph above

Vibration measurement

The methodological approach applied in this tests consists in the simultaneous recording of all measured values and their processing in the time and frequency domain using the so-called "on-line" and "off-line" processing procedures.

In order to perceive the spatial displacement of the shaft axis, it is necessary to simultaneously register the relative vibrations of the shaft in the zones of the generator and turbine guide bearing. The range of linearity of the converters is within 2.5 mm, which practically means that there is no chance for the shaft to be outside these limits in the most unfavorable modes of unstable operation.

For measurements in unstable operating modes, in addition to the registration of the measured values, parallel registration of the opening of the blades of the wicket gate - the stroke of the servo motor and the speed of the unit is performed.

The tests were carried out in different modes of stable operation of the unloaded and loaded aggregate:

- No-load unexcited, n = $1.0*_{nnom}$ (PHN)
- No-load excited, Ug = $1.0*U_{nom}$ (PHP)
- Aggregate on the grid, P_A = 80 MW
- Aggregate on the grid, P_A = 90 MW
- Aggregate on the grid, P_A = 100 MW
- Aggregate on the grid, P_A = 130 MW
- Aggregate on the grid, P_A = 150 MW
- Aggregate on the grid, P_A = 165 MW
- Aggregate on the grid, P_A = 180 MW
- Aggregate on the grid, P_A = 190 MW
- Aggregate on the grid, P_A = 205 MW

Tests were also performed in different modes of unstable operation:

- Starting the aggregate
- Stopping the aggregate with mechanical braking of the generator
- Stopping the aggregate with electrical braking of the generator
- Continuous power increase 0-190 MW
- Increasing the number of revolutions - runaway: mechanical and electrical
- Power rejection_100 MW
- Power rejection _148 MW
- Power rejection _204 MW
- Power rejection _98 MW with emergency shut-down
- Power rejection _194 MW with emergency shut-down
- Quick shut-down_190 MW

Reference documents

While measuring Unit vibrations, the following reference documents are taken into account:

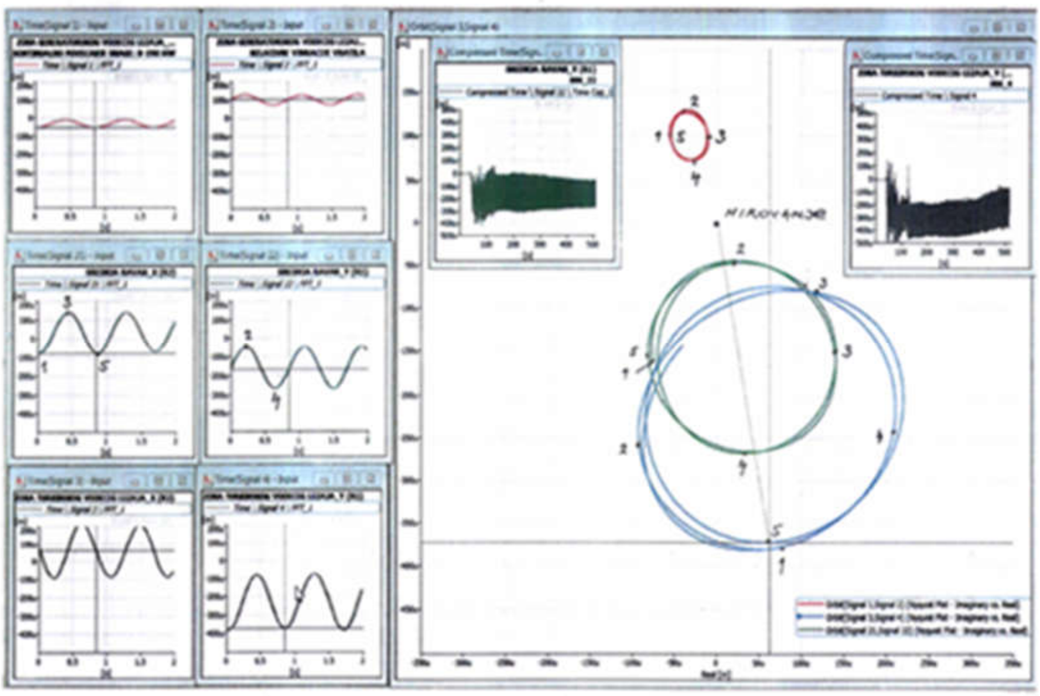
- ISO 7919-5 Mechanical vibration–Evaluation of machine vibration by measurements on rotating shafts_Machine sets in hydraulic generating and pumping plants;
- ISO 20816-5 Mechanical vibration — Measurement and evaluation of machine vibration — Part 5: Machine sets in hydraulic power generating and pump-storage plants;

- IEC 60034-33 Rotating electrical machines - Part 33: Synchronous hydrogenerators including motor-generators - Specific requirements;
- GOST 5616-89. Water-wheel type generators and motor-generators. General specifications;
- Contract Conditions – Particular Employer Requirements for Generators.

Measurement results

The highest values of relative vibration amplitudes were registered in no-load modes. In the recorded vibration spectra, the dominant components correspond to the basic frequency by the number of revolutions (1.19Hz) and its third harmonic (3.6Hz). The most probable cause is the resonant frequency of the rotating parts of the aggregate, which is close to the frequency of the third harmonic.

The figure below shows the orbital trajectory of the path of the shaft axis in the area of the turbine guide bearing (blue colour), in the area of the top of the turbine shaft (green colour) and in the area of the generator guide bearing (red colour), at the nominal load of the aggregate 190MW. It can be seen that the trajectory in the turbine guide bearing zone several times higher than the trajectory in the top of the turbine shaft zone, and several times higher than the one in the generator guide bearing zone. This indicates the fact that there is a certain breakage of the axis of the shaft and that the shaft rotates at a certain inclination, facing the Y direction.



Orbital trajectory of the path of the shaft axis in the area of the turbine guide bearing

By recording the characteristics at lower aggregate loads (from 80MW to nominal power 190MW), it was observed that with increasing power, the trajectory in the top zone of the turbine shaft decreases, while that in the turbine guide bearing zone increases, which confirms the conclusion of shaft axis breakage.

The aggregate state assessment was carried out according to the relevant standards and by the contract defined limit values of relative and absolute vibrations in stable regimes.

	Measured values	Limits defined by standards or Contract
Relative vibrations:		
Shaft run-out (amplitude - $A_{o\text{-}peak(\Sigma)}$)	68 µm	≤ 170 µm as per A/B* boundary zone in accordance with ISO 20816-5
Absolute vibrations:		
Bearings (housing) (double vibration amplitude - $2A_{o\text{-}peak(\Sigma)}$)	34 µm	≤ 180 µm as per A/B* boundary zone in accordance with ISO 20816-5
Magnetic stator core, component of 100 Hz (double vibration amplitude - $2A_{o\text{-}peak(100\ Hz)}$)	2.5 µm	≤ 30 µm as per IEC 60034-33
Stator frame and magnetic stator core, component of 1.19 Hz / 4.545 Hz (double vibration amplitude - $2A_{o\text{-}peak(2.083\ Hz\ /\ 4.545\ Hz)}$)	10.4 µm	≤ 30 µm as per Contract
Lateral connections of stator winding (end-winding) with jumpers and ring connections, component of 100 Hz (double vibration amplitude - $2A_{o\text{-}peak(100\ Hz)}$)	32 µm	≤ 100 µm as per GOST 5616-89
Upper generator bracket, component of 1.19 Hz / 3.6 Hz (double vibration amplitude - $2A_{o\text{-}peak(1.19\ Hz\ /\ 3.6\ Hz)}$)	16 µm	≤ 180 µm as per Contract

* Zones defined in Standard ISO 20816-5 are:

- A – Zone defined for new units commissioning
- B – Zone that refers to the normal operation of machines without any restrictions on their operation
- C – Zone that refers to machines with a limited exploitation period
- D – Zone that refers to the condition of the machine whose subsequent operation may lead to their serious damage

In order to compare the measurement results, the measured values on the aggregate before its replacement are shown below.

number	Mode of operation	Generator guide bearing		Turbine guide bearing	
		X	Y	X	Y
1	No load of operation speed 80% (n)	-	-	-	-
2	No load of operation speed 100% (n)	-	-	-	-
3	Unit load 90 (MW)	-	-	-	-
4	No load of operation speed 130 (MW)	80	100	100	100
5	No load of operation speed 180 (MW)	150	130	120	140
6	Head water level (m)	68,44			
7	Gross head (m)	27,77			

Shaft run-out measurement (presented values are in µm)

As it can be seen from the measurements of the shaft displacement on the old unit, the unit could be in operation without any restrictions in operation (Zone B).

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