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DEVELOPMENT METHODS OF LARGE-EQUIPMENT INSTALLATION IN DESIGN POSITION USING ELECTRONIC TOTAL STATIONS

Today in Ukraine there are dozens of turbogenerators (TG) in operation, a significant part of which have been in operation for over 35–50 years, which exceeds their service life in accordance with regulatory documents. The actual technical condition of the TG is determined by many geometrical parameters, among which the crucial ones are those that characterize it as a mechanical system (axis of the aggregate and the axis of the stator). Today, the control of the position of the axes must be performed with an accuracy of 0.5 mm, and is carried out in three ways (using a string, using an optical autoreflex system (PPS-11), using a test shaft). The purpose of these studies is to develop a method for monitoring the geometric parameters of the TG stator when replacing it with geodetic methods using high-precision electronic total stations and its testing on site. Based on previous research, we propose to solve the following problems by the spatial method of electronic total station using a high-precision total station Leica TCRP1201R300. We performed a priori estimation of accuracy and a number of experiments (research to determine refocusing error, determination of distance measurement error at short lengths using a spherical reflector, study of the effect of non-perpendicularity of the measuring laser to the reflector) to develop methods for improving measurement accuracy using electronic total station. This technique has been tested on site during the repair (replacement) of the generator stator. As a result of the work carried out, the spatial position of the axes of the aggregate and the stator was determined with an accuracy of 0.3 mm, which were fixed in the conditional coordinate system by four marks. The method provides for the selection of optimal conditions for electronic tacheometer measurements, which compensate for errors in the initial data, instrumental, external conditions, sighting, centering and fixing. Also, the method provides for the control of each stage of work on a standard deviation of up to 0.2 mm. The number of measurement methods is determined by achieving the accuracy of each stage of 0.2 mm.

Key words: calibration of large equipment, turbogenerator, spatial method of electronic total station, axis of generator and aggregate, increase of accuracy of measurements by electronic total stations.

Introduction

Reliable and economical operation of the power industry is determined by three interrelated components: the technical condition of the equipment, staff qualifications and efficient organization of production at all stages. All these issues are closely related to the widespread use of advanced modern technologies [Khomenko, 2020]. The technical condition of the equipment of hydro and nuclear power plants depends not only on proper operation, but also on timely and professional repairs. This is especially true due to the fact that the wear of the equipment is significant [Sukhodolya, et al., 2014].

Today in Ukraine there are 30 TGV-200 turbogenerators (TGs), 4 TGV-200D TGs, 11 TGV-200M units with a capacity of 200 MW and 41 TGV-300 TGs with a capacity of 300 MW, many of which are in operation for more than 35–50 years old, that

The complete replacement of so many generators that have exhausted their resources with new ones in a short period of time in the context of the global economic crisis and pandemic is too problematic. Therefore, it is important to control the actual situation. The actual technical condition of TG is determined by many parameters, among which crucial are those that characterize it as a mechanical system [Zaitsev, & Panchyk, 2021]. The situation in Europe and around the world is much better in terms of service life, repair and replacement of TG, but still much attention is paid to the safe operation of equipment, including geodetic methods [Lechner, 2012].

Previous research

Control over the preservation of geometrical parameters is especially important when repairing or replacing the main components of the TG, namely the rotor and stator, the turbine shafts. Currently, the calibration of the position of individual nodes of the TG should provide an accuracy of 0.5 mm, and is carried out in three ways:

- with the help of a string;
- with the help of optical autoreflective system (PPS-11);
- using a calibration shaft.

In the first method, a wire with a diameter of 0.6 mm, which is used in the production of piano strings, serves as a string. It is fixed at one end with a tripod and the other at the load unit. A rod with a special fork is moved along the string to fix the position of the equipment being controlled. Recently, laser emitters have been used instead of a string to set the axis.

Optical system PPS - 11 allows you to measure the non-creativity of individual components of the generator or turbine by self-reflection at three control points. This system consists of a telescope (theodolite telescope, autocollimation tube can be used) and a centering sight mark, which is first installed at checkpoints (boring) and then at the base. Special centrifuge detectors (NIITMASH, KNUBA autocenter detector) are used to establish the sighting mark [Baran, 2012]. Of course, to ensure the accuracy of the alignment of the PPS-11 system is quite difficult and time consuming, especially when restoring the center of the two-meter diameter of the stator with an insulating winding.

The calibration shaft is a separate part with support surfaces that mimic the rotor necks with high accuracy (standard tolerance of the part diameter is 0.03 mm, and the ovality of the direct rotor bore is 0.01 mm).

All these methods are mechanical or optical - mechanical and require significant time, human resources, and most importantly do not allow to automate the process of controlling the physical parameters of TG during repair or replacement.

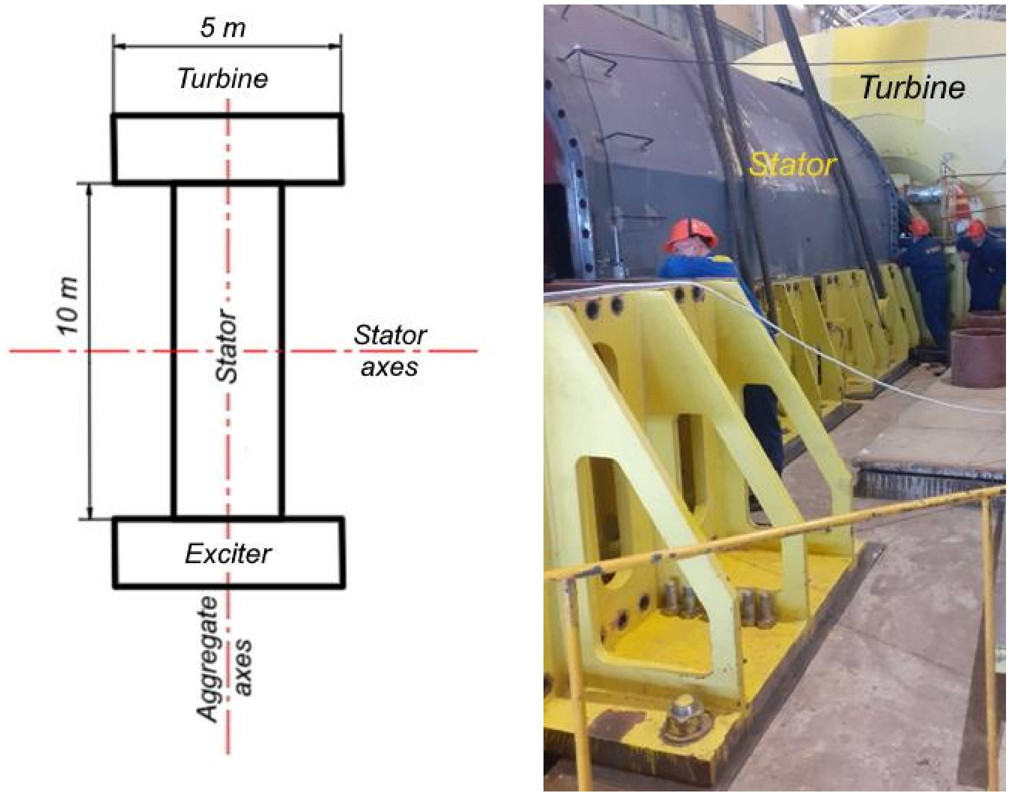
In world practice, such problems are solved by the hand coordinate machines [Petrakov, & Shuplietsov, 2018]. These machines can determine the center by the required number of points with a measurement accuracy of a few microns. But the question of fixing a certain center for its further reproduction remains. In [Zobrist, et al., 2009] high accuracy of a few hundreds of a millimeter was obtained in determining the surface of a spherical mirror using laser trackers and special spherical reflectors. The laser tracker is a slightly improved electronic total station with more accurate distance measurement and more stable mounting on a tripod. According to [Leica TS30 White Paper], the angles of the laser tracker and the electronic total station are proportional in accuracy. In [Burak, 2011], the accuracy of electronic total stations for executive surveys was investigated. The possibility of increasing the accuracy of short – distance measurements is shown. In [Litynsky, et al., 2014] the method of linear-angular measurements to increase the accuracy of determining small segments is proposed, and also the method of optimal planning of the accuracy of segment determination is proposed. In [Litynsky, 2015] the method [Litynsky, et al., 2014] was tested on the reference basis of the second category. The possibility of three-fold increase in the accuracy of determining ten-meter segments by electronic total stations has been investigated. In [Vivat, et al., 2018] the possibility of using electronic total stations with spherical reflectors to determine the geometric parameters of engineering structures was investigated. Also in this work the use of sighting targets on a light-reflecting basis for increase of accuracy of sighting is offered. All these studies can be the basis for the development of methods for controlling the geometric parameters of the stator TG.

Aim

The purpose of these studies is to develop a method for controlling the geometric parameters of the stator TG when replacing it with geodetic methods using high-precision electronic total stations and its testing at a specific site.

Research results

According to the technological map for the installation of the stator of the TVV-1000 generator, the average square error of centering the inner part of the winding is 0.5 mm. Also in this document there is a geometric diagram of the generator on which the main axes and components of the generator are marked (Fig. 1).



a *b*

Fig. 1. The stator of the TVV-1000 generator (b) and its main axes (a)

The task of geodetic support for the replacement of the generator stator consisted of two stages:

- restoration of the aggregat axes and fixing its spatial position. The stator that is being dismantled "old stator".
- installing the "new stator" in the same position as the "old stator".

Based on previous research, we propose to solve such problems by the spatial method of electronic tacheometry using a high-precision tacheometer. Based on our experience in performing high-precision engineering and geodetic works, a high-precision electronic total station of the Swiss company Leica-Geosystems was used for this task. Before starting work, we performed an a priori assessment of accuracy. We also performed research to develop a methodology for improving the accuracy of measurement using a total station Leica TCRP1201R300. For a priori estimate the accuracy, we use the formulas for the relationship between measured quantities and spatial coordinates.

$$
\begin{aligned}
X_p &= X_0 + S \times \cos_a \times \cos_v \\
Y_p &= Y_0 + S \times \sin_a \times \cos_v \\
Z_p &= Z_0 + S \times \sin_v
\end{aligned}
\qquad (1)
$$

where: S, v, a – measured distance, vertical and horizontal angles. By differentiating formulas (1), we calculated the root mean square errors (RMS) to determine the spatial position of points located at different distances (S), at different values of the vertical angle (v) and azimuth (a). (Table 1). For calculations, the RMS of distance and angle measurements are taken from the technical characteristics of the device, which are equal to 1 mm and 1", respectively.

Table 1

A priori mean square errors determine the spatial position of points

S, m	v, °	a, °	mx, mm	my, mm	mz, mm	M, mm
10	0	0	1.0	0.0	0.0	1.0
50	0	0	1.0	0.0	0.2	1.0
100	0	0	1.0	0.0	0.5	1.1
10	30	0	0.9	0.0	0.5	1.0
50	30	30	0.8	0.4	0.5	1.0
100	30	60	0.4	0.8	0.7	1.1

Analysing the data in Table 1, we can conclude that the error in determining the spatial position will depend on the change of angle, distance and position of the total station. It should also be noted that the total error M will be affected by instrumental error, external conditions, network geometry and sighting errors. All these errors in the end can further distort the results by 1–2 mm. Therefore, we have investigated which are aimed at improving the accuracy of measurements by electronic total stations at short distances and compensating for additional errors.

Investigation of refocusing error on the change of the sighting axis in the electronic total station in the range of lengths from 2 to 100 m.
According to the values of collimation error (C) and zero point (ZP) at different distances, we determined the oscillations of the sighting axis in the vertical and horizontal planes and their standard deviation (STD) (see Figs. 2, 3).

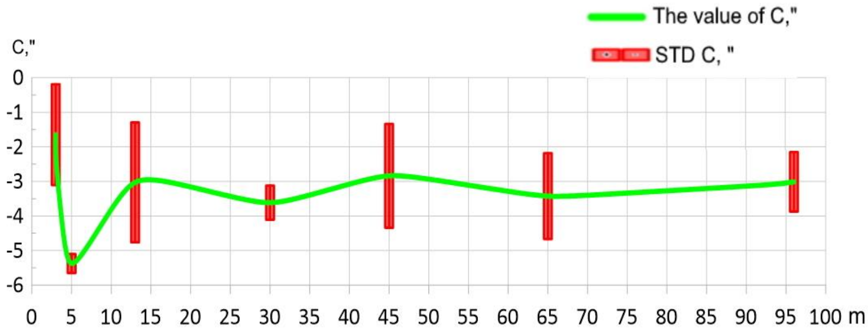


Fig. 2. Oscillations of the sighting axis of the electronic total station in the horizontal plane

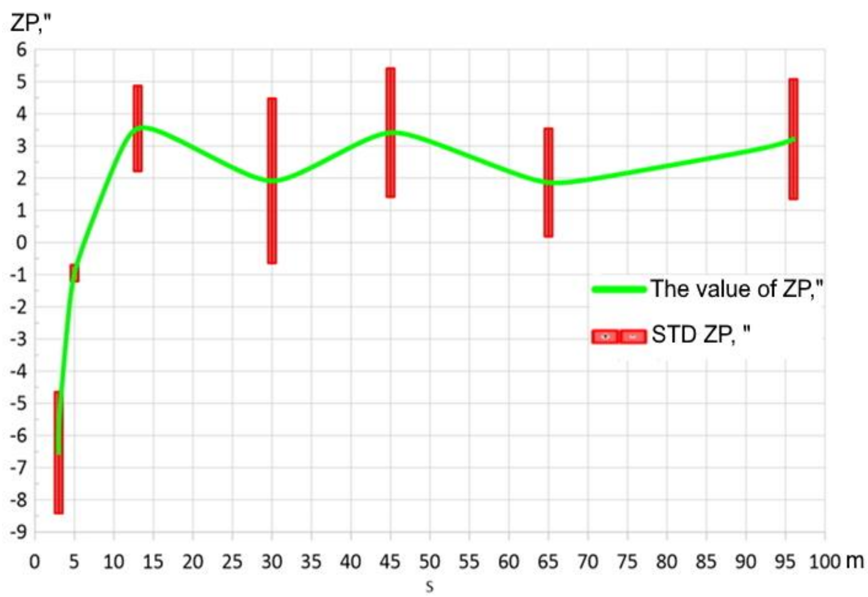


Fig. 3. Oscillations of the sighting axis of the electronic total station in the vertical plane

Fig. 2 and 3 show a significant effect of refocusing on the C and ZP change of the electronic total station at a distance of up to 10 m. The graphs show residual errors in sighting and external conditions, which are random variables. Table 2 summarizes the standard deviations of the oscillations of the sighting axis, determined from three complete receptions, as well as the standard deviation of the distance for the range of lengths from 10 to 100 m.

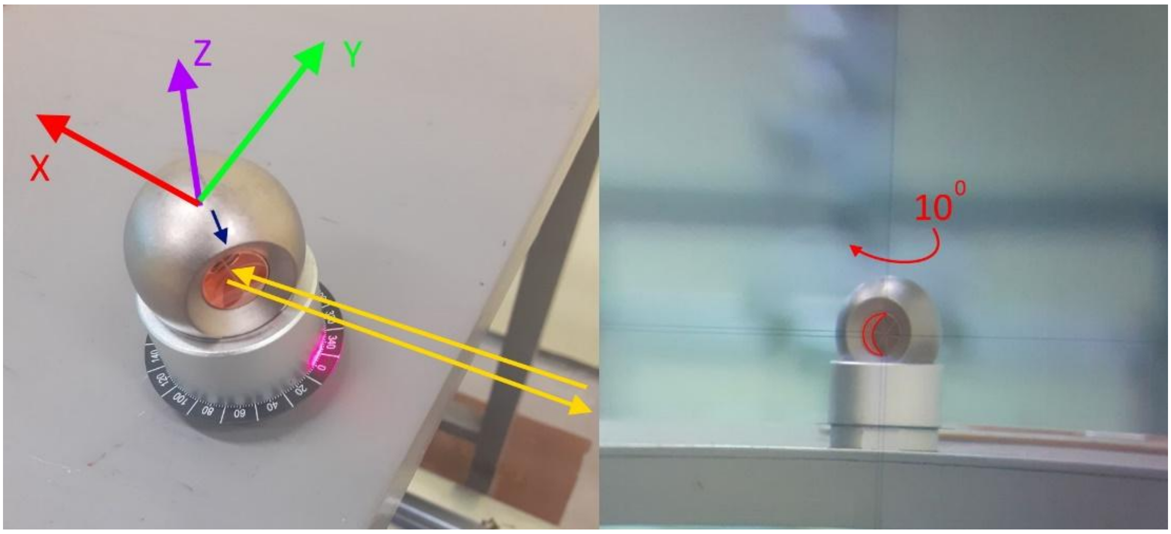
Measurements were performed on the reflective brands developed by us [Vivat, 2018]. The fall angle of the measuring laser on the mark was equal to 90°.

Further research was to determine the distance measurement error at short lengths using a spherical reflector (Fig. 4). The use of such a reflector during measurements should eliminate the error of fixing, centering and leveling of the sighting target. Control measurements of lengths in the range of 6–16 meters were carried out. A laser displacement interferometer was used as a reference. During the measurements, the fall angle of the laser on the reflector was 90°. Table 3 shows a sample of statistical data of the differences of the deviations (total station – interferometer) minimum – MIN, maximum – MAX value and standard deviation – σ in the forward and reverse directions.

Table 2

Standard deviations of C, ZP and distance, defined at different lengths from 2 to 100 m

STD	C, "	ZP, "	d, mm
σ_{MIN}	0.3	0.3	0.1
σ_{MAX}	1.7	2.6	0.2
σ_{MEAN}	0.5	0.5	0.1



a b

Fig. 4. Explanation to the study of the distance measurement error on a spherical reflector

Table 3

Characteristics of the accuracy determination of a short distance by electronic total station

Differences	$\delta_{fwd.}$, mm	$\delta_{rvs.}$, mm
MIN	-0.28	-0.23
MAX	0.16	0.22
σ	0.17	0.16

Fig. 5 shows the values of the differences for forward and reverse for the range of distances from 6 to 16 m. From the obtained results it can be concluded that the STD of short distances in the range of lengths of 6-16 m when using a spherical reflector is 0.17 mm. In addition, we conducted a study of the effect of nonperpendicularity of the measuring laser to the reflector. To do this, we attached a radial scale to the reflector stand (Fig. 4a). For research, the reflector was rotated from -40° to +40° with a resolution of 10°. In (Fig. 4b.) the field of view of the total station is shown on the reflector rotated by 10° in the horizontal plane.

Fig. 5. The differences between the distances of the total station and the interferometer

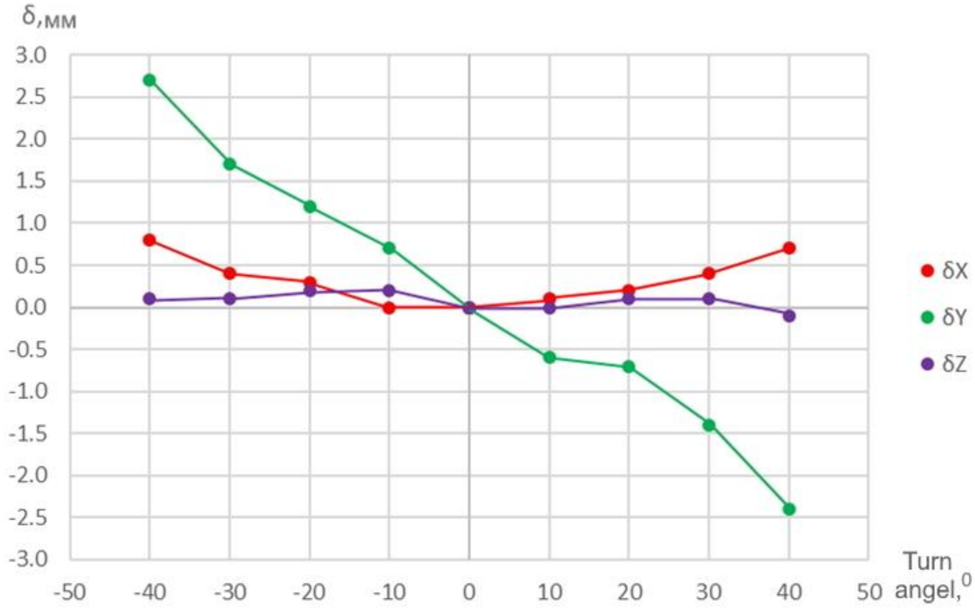
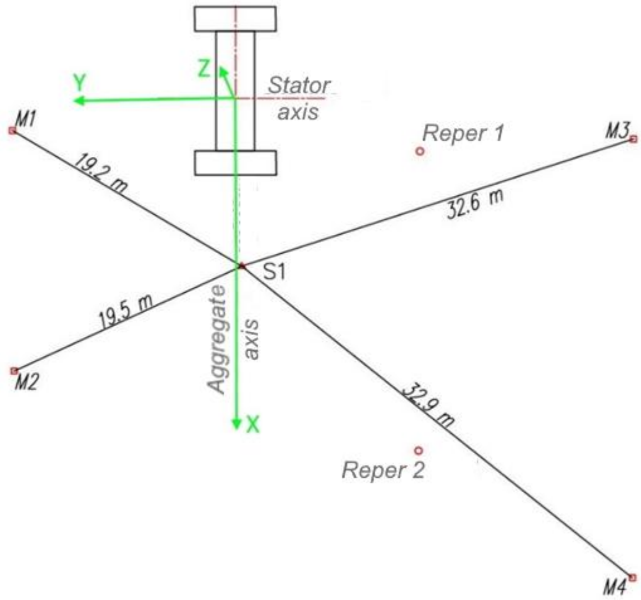


Fig. 6. Influence of nonperpendicularity of the measuring laser on the determined coordinates of a point

Analyzing the graph in Fig. 6, we can conclude that the use of the reflector with a triple prism with a diameter of 12.5 mm requires perpendicularity up to 5°. Such a non-perpendicular error will not distort the spatial coordinates of the point to be determined.

To minimize the impact of changes in external conditions (temperature, pressure, humidity), and hence horizontal and vertical refraction, we recorded through the eyepiece of the total station potential places of the original geodetic basis on a special scale [Litinsky, 2005]. Also, to eliminate the error of centering, we proposed to use the method of free station and determine the coordinates of linear-angular measurements. Using the method [Vivat, Nazarchuk, 2019] we calculated the horizontal and vertical angles of fixing 3D-marks to ensure the perpendicularity of the measuring laser. According to research [Fys, 2021], the position of the base marks was planned so that the device installation station was closest to the middle of the bases (Fig. 7a). Also, all three stages of work were performed from one installation station of the device to eliminate the error of the geometry of the geodetic network.



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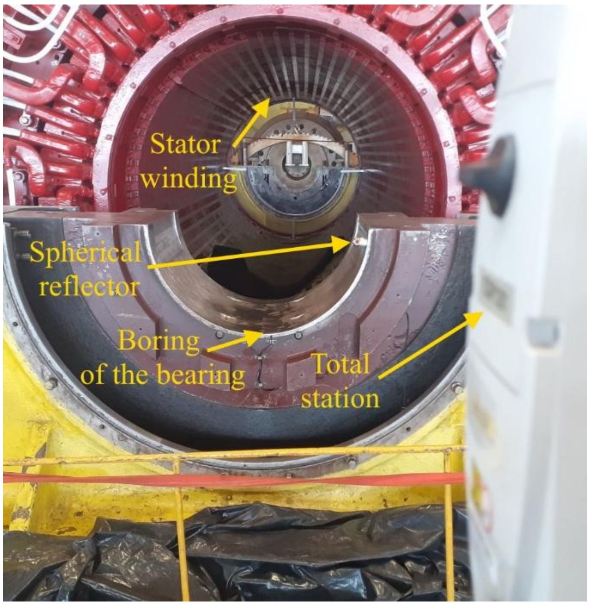

б

Fig. 7. Scheme of the geodetic network (a) and the device at the station S1 (b)

Having installed the electronic total station on the tripod at point S1, we performed measurements on two rotor bearings on the exciter and turbine side (five points for each full reception), and on the stator windings on the exciter side (ten points on each full reception). (Fig. 7b). As a result, we determined the aggregate axis with STD of 0.3 mm. The axis of the stator was determined by subtracting half the design size from the beginning of the winding. The coordinates of two analytically calculated points (the origin of the coordinate system and the direction of the X-axis) are entered into the memory of the electronic total station. To ensure the unambiguity of the spatial coordinates of the aggregate, the values of the beginning of the conditional coordinate system are set different (X = 1000 m, Y = 500 m, Z = 100 m). Determination of the spatial coordinates of the main point of the total station (the intersection of the vertical, horizontal and sighting axes) in the coordinate system of the aggregate is performed analytically using the application program “baseline”. Next, this coordinate system (Fig. 7a) was recorded by us measuring by fixing four 3D reflective marks. Measurements of spatial distance, vertical and horizontal angles were performed in three repetitions of measurements for each mark. Verification of the accuracy of fixing the geodetic base was performed by the method of invers linear-angular intersection in three repetitions of measurements. The standard deviation of determining the spatial position of the main point of the total station was within 0.2 mm. Each time during the measurements we installed the device and determined the coordinates of the main point of the total station by the method of invers linear-angular intersection from the marks of the geodetic basis. The standard deviation of the defined coordinates did not exceed 0.2 mm. The standard deviation of the defined coordinates of the point S1 was the criterion of accuracy in the first and second stages of work. In addition, to control the height position, we have set two benchmarks, and performed leveling according to the program of class I on the characteristic points of the stator.

The result of the first stage of work was the executive survey of the spatial position of the characteristic points of the stator that was dismantled. The result of the second stage of work was the restoration of the new 300-ton stator according to the defined axes in the first stage.

Scientific novelty and practical significance

As a result of our work, we have developed a method of restoring the spatial position of the stator of the generator relative to the axis of the TG during its repair (replacement). We performed a priori estimation of accuracy and a number of experiments (research to determine refocusing error, determination of distance measurement error at short lengths using a spherical reflector, study of the effect of non-perpendicularity of the measuring laser to the reflector) to develop methods for improving measurement accuracy using electronic total station Leica TC1201R300. This technique was tested on site during the repair of the stator of the generator and ensured the accuracy of the mutual installation of its individual components 0.5 mm.

Conclusions

The method of control of geometrical parameters of the generator stator at its replacement by geodetic methods with the use of electronic total station manufactured by the Swiss company Leica-Geosystems TCRP1201R300 is developed and tested in the work.

Analyzing the results of research, the following conclusions can be drawn:

· the method provides for the selection of optimal conditions for electronic tacheometer measurements, which compensate for errors in the initial data, instrumental, external conditions, sighting, centering and fixing,

· A study of the effect of refocusing on the change of the sighting axis showed that at short distances up to 10 meters this error changes the position of the sighting axis up to 5 “(see Figs. 1–2). At distances from 10 to 100 m, the standard deviation of the change in collimation and zero point is in accordance with the technical characteristics of the device and is equal to 1”. The method recommends the use of distances from 10 to 100 m,

· Studies of the accuracy of measuring short distances in the range 6–16 m have shown the possibility to achieving a standard deviation of measuring distances 0.17 mm,

· the use of a spherical reflector with a triple prism with a diameter of 12.5 mm requires ensuring perpendicularity to the measuring laser up to 5°, which will not distort the spatial positioning,

· development of a special method of measurement and research allowed to increase the accuracy of determining the geometric parameters of the stator to 0.5 mm,

· additional measurements of the control points height difference of the stator legs by geometric leveling confirmed the results with an electronic total station.

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РОЗРОБКА МЕТОДИКИ ВСТАНОВЛЕННЯ ВИЛИКОГАБАРИТНОГО ОБЛАДНАННЯ У ПРОЕКТНЕ ПОЛОЖЕННЯ З ВИКОРИСТАННЯМ ЕЛЕКТРОННИХ ТАХЕОМЕТРІВ

На сьогодні в Україні знаходяться в експлуатації десятки турбогенераторів (ТГ), значна частина яких в експлуатації понад 35÷50 років, що перевищує термін їх служби у відповідності до нормативної документації. Фактичний технічний стан ТГ визначається багатьма геометричними параметрами, серед яких вирішального значення є ті, що характеризують його як механічну систему (вісь агрегату та вісь статора). На даний час контроль положення осей повинна виконуватись з точністю 0,5 мм, та здійснюється в основному трьома способами (за допомогою струни, за допомогою оптичної авторефлексної системи (ППС-11), з використанням повірочного валу). Метою даних досліджень є розробка методики контролю геометричних параметрів статора ТГ при його заміні геодезичними методами з використанням високоточних електронних тахеометрів та її апробація на об’єкті. На основі попередніх досліджень, нами запропоновано вирішувати такі задачі просторовим методом електронної тахеометрії з використанням високоточного тахеометра Leica TCRP1201R300. Ми провели апріорну оцінку точності та ряд експериментів (дослідження з визначення похибки перефокусування, визначення похибки виміру віддалі на коротких довжинах з використанням сферичного відбивача, дослідження впливу неперпендикулярності вимірювального лазера до відбивача) з метою розробки методики підвищення точності вимірювання при умові використання електронного тахеометра. Ця методика апробована на об’єкті під час ремонту (заміни) статора генератора. В результаті проведених робіт визначено просторове положення осей агрегату та статора з точністю 0,3 мм, які були зафіксовані в умовній системі координат чотирма марками. Методикою передбачено вибір оптимальних умов вимірювань електронним тахеометром, за яких компенсуються похибки вихідних даних, інструментальні, зовнішніх умов, візування, центрування та фіксування. Також методикою передбачено контроль кожного етапу робіт за стандартним відхиленням до 0,2 мм. Кількість прийомів вимірювань визначається досягненням точності кожного етапу 0,2 мм.

Ключові слова: вивірка великогабаритного обладнання, турбогенератор, просторовий методом електронної тахеометрії, вісь генератора та агрегату, підвищення точності вимірювань електронними тахеометрами.

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