Paper ID – 10354 Session 2022
A1 ROTATING ELECTRICAL MACHINES
Developments of rotating electrical machines and operational experience

Features of Akkuyu NPP turbogenerators and factory test results

Evgeny KADI-OGLY, Alexander TSVETKOV
Turbine Technologies AAEM, Russia
Bouchra WAHDAME, Philippe MEYER, Pascal CHAY, Damian DE-ROZARIO
GE Power Portfolio, France
e.f.kadi-ogly@aaemturbines.com

SUMMARY

The goal of the article is to summarize the requirements of the Turkish grid operator, IEC standards, GOST, regional seismic requirements and Russian nuclear codes for the Akkuyu NPP project, describe how they have informed the design of the turbogenerators developed and manufactured for this power plant and give the results of testing the turbogenerator for the first unit. The article will also introduce readers to unique technical solutions and design features of this type of turbogenerators.

Presently, the Rosatom State Corporation's program of nuclear builds outside the Russian Federation (the VVER-1200 and VVER TOI projects) equipped with the Russian nuclear technologies is gaining big momentum. Turbine islands based on GE's ARABELLE (*) steam turbine and GIGATOP 4-pole turbogenerators of 1200 MWe class have been selected and contracted for plants such as Hanhikivi (VVER-1200), Paks (VVER-1200), El Dabaa (VVER-1200) and Akkuyu (VVER TOI). These projects are being executed in close cooperation between General Electric and Turbine Technology AAEM (a joint venture of General Electric and Atomenergomash, the Engineering Branch of Rosatom). All in all, 11 turbine-generator sets will be supplied for the above projects.

Special attention was given to the following design considerations:

– The grid operator's requirements
– The specific aspects of design review and acceptance in line with the requirements of the Russian codes and standards applicable to the use of nuclear power.
– The seismic properties of the construction site
– The requirements of the plant General Design
– Climatic design
– Service life.

Strength and seismic calculation analyses and the acceptance tests of separate generator parts and complete generator performed on the test bench at the manufacturer's factory (GE) have demonstrated the machine's design performances, as well as compliance with the applicable standards, project specific features and national grid operator's requirements..

KEYWORDS
Turbogenerator, Akkuyu NPP, Four-pole generator, turbogenerator test, turbogenerator running tests, Design, Development

(*) "Trademark of General Electric Company"

1. INTRODUCTION

The generator supplied for Akkuyu NPP are related to GIGATOP 4-pole type. The GIGATOP 4-pole turbogenerator is the GE half speed powerful electrical generator coupled to ARABELLE^{TM} steam turbines for Nuclear Power Plants.
Inside a GIGATOP 4-pole turbogenerator, hydrogen gas cooling is used for the stator core and end regions as well as the rotor field winding and water-cooling for the stator windings and all stator current-carrying parts [1]. These cooling systems ensure that the turbogenerator meet all the necessary standards (including GOST) and grid codes regarding e.g., power output capability, voltage-frequency variation, short-circuit ratio or even overload/overcurrent requirements. GIGATOP 4-pole is designed to comply with thermal class 130 (B) in terms of temperature rise, and with thermal class 155 (F) regarding insulation.
For Akkuyu, the main design parameters of the GIGATOP 4-pole type W100 (*) turbogenerators are as follows:

- Rated active power: 1251.9 MW,
- Rated voltage: 24 kV (+5/-10%),
- Rated frequency: 50 Hz (+1/-2%),
- Rated power factor: 0.9,
- Speed: 1500 rpm,
- Cooling water temperature: 27˚C.

2. REQUIREMENTS FOR EQUIPMENT AND EQUIPMENT ACCEPTANCE AND TESTING

2.1 Grid operator's requirements

Among the important requirements the turbogenerator and its equipment shall meet, are those defined by the grid operator managing the power system the turbogenerator is connected to. The requirements of the Turkish grid operator are provided in the *Grid Code*. In recent years, as a result of nuclear power industry developing to include installation and connection of large power units to the grid, these requirements were updated to include special requirements applicable to nuclear power plants. These, in particular, cover the planning of the NPP installation and electricity transmission system, system design requirements, requirements for power factor at turbogenerator terminals and reactive power variation range, and secondary control conditions.
As concerns the turbogenerator, those requirements which have a direct influence on the turbogenerator terminals characteristics shall be accounted for first of all.
The main special requirements of the Turkish grid operator are as follows:

- Power factor 0.9, operating conditions in reactive power consumption mode at a power factor of 0.95,
- Rated voltage change, at which the turbogenerator power shall be maintained,
- The frequency variation range, conditions and duration of operation at these frequencies under normal and abnormal conditions are listed in the table below:

Frequency range, Hz	50.5 – 51.5	49.0 – 50.5	48.5 – 49.0	48.0 – 48.5	47.5 – 48.0
Duration of a single case, max	60 min	No limit	60 min	20 min	10 min
Duration over the entire turbogenerator lifetime, max	4 h	60 y	100 h	100 h	4 h

Other characteristics determined by the grid and directly affecting the parameters of the turbogenerator meet the IEC standards.

2.2 Requirements of Russian codes and standards applicable to nuclear power use

The Russian codes and standards in the field of nuclear energy apply to Akkuyu NPP. In particular, the turbogenerator, brushless exciter and excitation system are assigned safety class 3 in accordance with NP-001 (equipment important for NPP safety) and quality assurance category QA3.

Therefore, the turbogenerator acceptance is subject to special conditions that include additional manufacturing supervision by NDK, a dedicated Turkish authority, and special arrangements for the acceptance procedure, in particular, for factory acceptance:

- Issue, review and approval of the Terms of Reference (design specifications) for turbogenerator, detail design documentation, preliminary quality plans as per the special form, program and methods of running test on the factory test bench, strength and seismic studies (in accordance with Russian nuclear power codes), obtaining permits,
- Review of the entire scope of above documentation by the entity authorized by the Owner to supervise the equipment manufacturing and acceptance (the Authorized Organization),
- Approval of Quality Plans,
- Obtaining NDK's permit to start manufacturing,
- Manufacturing readiness assessment at the manufacturer’s,
- Acceptance based on quality plans during the equipment manufacturing with all parties involved witnessing the tests of the main components, including the tests of wound stator at the assembly site and rotor tests at the balancing pit, and other intermediate tests,
- Thorough review of non-conformity reports,
- Intermediate tests of a partially assembled turbogenerator on the test bench that are witnessed by all interested parties,
- Running tests of the turbogenerator on the test bench that are witnessed by all involved parties.

2.3 Seismic conditions of construction site

Special requirements covering seismic exposure of equipment apply to Akkuyu NPP. They result from specific landscape and seismologists' observations in the NPP construction area.

In particular, the Akkuyu NPP turbogenerator and its associated auxiliaries shall remain capable of normal and safe operation following a design earthquake (DBE) of at least and including 8 points on the MSK-64 scale.

Turbogenerator's compliance with the seismic requirements shall be confirmed through calculations. The turbogenerator design shall meet these requirements considering the response spectra at the equipment elevation and foundation vibrodamping requirements. The seismic study shall comply with the Russian design codes covering seismic-resistant NPPs (NP-031) and consider the entire range of loads during the operation of the turbogenerator with the imposition of a given level of seismic exposure.

2.4 Specific requirements of general designer

There are a number of requirements for turbogenerators imposed by the general designer of the turbine island that have to be verified by and considered in the equipment design, including:

- Short-circuit ratio: not less than 0.5,
- Efficiency: not less than 98,9%,
- Excitation ceiling ratio and field forcing duration:2 p.u. for a period of 10 s,
- Voltage at stator winding terminals: 24 kV (+ 5/-10%, considering voltage drop at unit step-up transformer),

- Considering the rotor thermal capability in unbalanced conditions, the turbogenerator shall withstand continuous operation with negative sequence current I_2=0.08·In, and on a short-term basis, thermal effects according to criterion $(I_2)^2$·t=6 s,
- The sound pressure level at a distance of one meter from the external acoustic enclosure of the turbogenerator and at a height of 1.5 meters from the surface of service platforms shall not exceed 85 dB(A) in all normal generator operation conditions,
- Service life: 60 years,
- Climatic design: tropical.

3. TURBOGENERATOR DESIGN

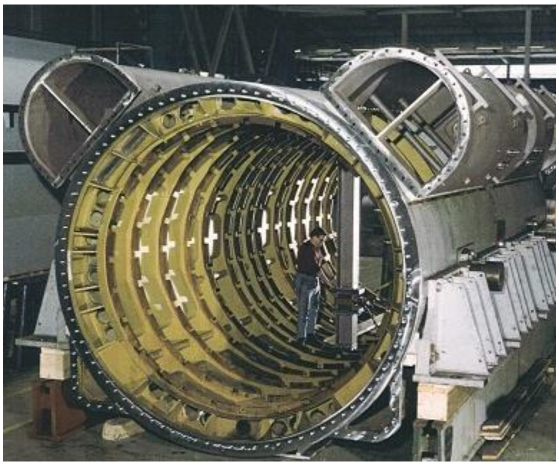

Fig.1. Central part of GIGATOP 4-pole stator farme.

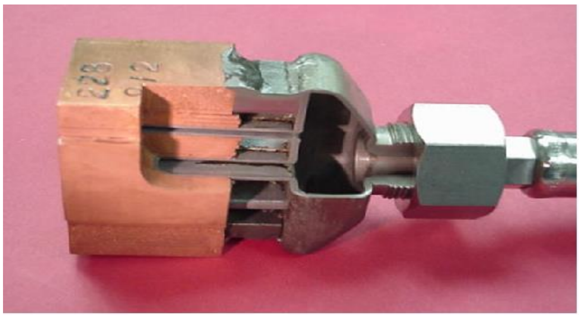

Fig. 2. Cross-section of connection between stator bar and water chamber

Turbogenerators of this type are widely known all over the world. They are designed and continuously improved to meet the market requirements for proven reliability, highest efficiency and low lifecycle cost. Let us dwell on some design aspects that have made great contribution to ensuring the compliance with the design requirements of the Turkish grid operator and codes and standards in the field of nuclear energy and construction of seismic-resistant nuclear power plants.

The GIGATOP 4-pole frame (see Fig.1) is designed in compliance with ATEX / EC directives and GOST and IEC requirements. An important aspect in the design of the frame is its mechanical integrity. The frame shall withstand static loads (gravity forces), hydrogen explosion inside the machine, loads from generator operation and short circuits (alternating loads), seismic loads, loads from handling and transportation (shocks, swinging). All these aspects were incorporated in the design of the Akkuyu NPP generator frame.

To ensure the hydrogen safety requirements are met, the stator frame, after welding and machining, was subjected to hydrostatic tests at 10 bar.

The technology of stainless steel hollow conductors (tubes) (see Fig. 2) used in the GIGATOP turbogenerators for direct water cooling of the stator bars, helps avoid their clogging as a result of oxidation, which is often the case with hollow copper conductors, reduce additional losses in stator slots and eliminate the risk of leaks and moistening of stator's interphase areas [2].

The stainless-steel tubes are welded to the water boxes, which are located at the extremities of the bar, at a certain distance from the brazed copper lugs providing electrical connection. The water tightness of the cooling water circuit is tested against strict criteria during the manufacture and erection of the machine. Over the past 40 years, the stainless-steel hollow conductor technology has demonstrated excellent reliability in operation.

Fig.3. Stator bars insulation manufacturing process

For large GIGATOP 4-pole turbogenerators, stator bars have four stacks of strands with a special cross-transposition. Not only does it allow to minimize losses due to circulating currents, but also makes the bar solid all over the length of the stator active part [3].

As concerns the main insulation of the Akkuyu generator stator winding, it is based on the Micadur® system utilizing a synthetic compound introduced back in the late 1950s. Since that time, the Micadur® system has been continuously evolving and today it reliably meets the highest process requirements. The Micadur® insulation is based on the VPI (Vacuum Pressure Impregnation) insulation technology. The complete insulation system meets the requirements of thermal class 155 (F), and the generator is designed to operate within the limits of class 130 (B). The experience of using the Micadur® insulation system in the GIGATOP 4-pole generator demonstrates perfect mechanical and electrical characteristics and guarantees high reliability of the machine. During stator bar manufacturing and at various stages of stator winding assembly, the stator winding insulation is tested, including high-voltage tests and tangent delta test. The test voltage for manufactured bars is 4 times the rated value. As the insertion of the bars in the slots progresses, the test voltage is reduced in steps according to the established schedule. When fully assembled in the generator on the test bench, the stator winding is subjected to the standard IEC test voltage of two times the rated voltage + 1 kV.

Alternating currents are induced on the rotor surface of the synchronous generator in unbalanced conditions. It is therefore necessary to provide a path for these induced currents to avoid damage due to overheating. For that purpose, a separate, so-called “damper” winding is installed on the turbogenerator rotors.

To meet the requirements of the NPP designer for turbogenerator operation in unbalanced conditions (I_2=0.08·In; I_2^2·t=6 s), which are more stringent than IEC ((I_2=0.05·In; I_2^2·t=5 s). Consequently, a more powerful damper system shall be used on the turbogenerator rotor. The damper system used in this turbogenerator includes solid high-conductivity wedges over the entire length of the active part of the rotor, which are electrically connected to the damper conductors and segments located under the retaining rings. The damper assemblies form a closed loop and electrical circuit with low resistance for the current induced in the active part of the rotor (especially for eddy currents with a base frequency of 100 Hz). To further improve some of the electrical contacts in the damper circuit,

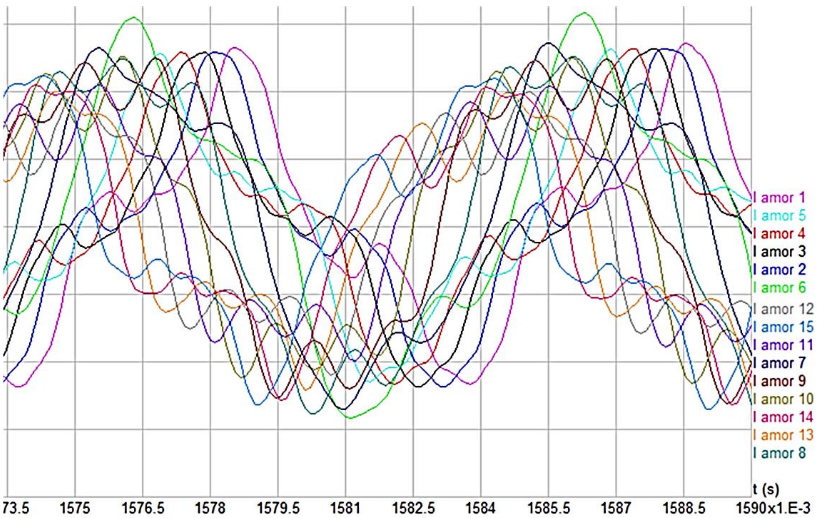

Fig. 4. Example of Akkuyu turbogenerator damper system calculation (Courtesy of GE)

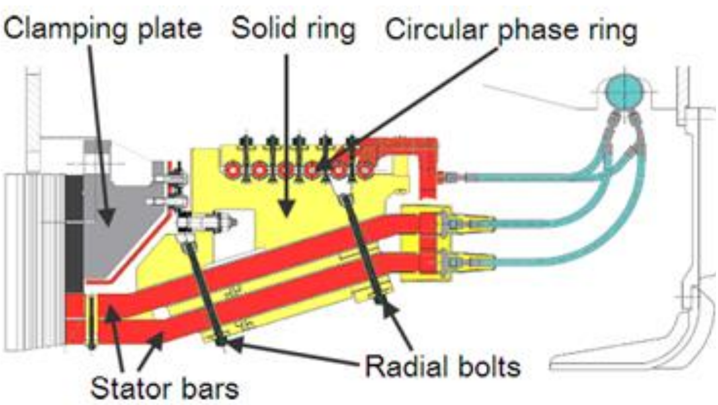

Fig.5. GIGATOP 4-pole turbogenerator end winding zone showing stator end winding support structure

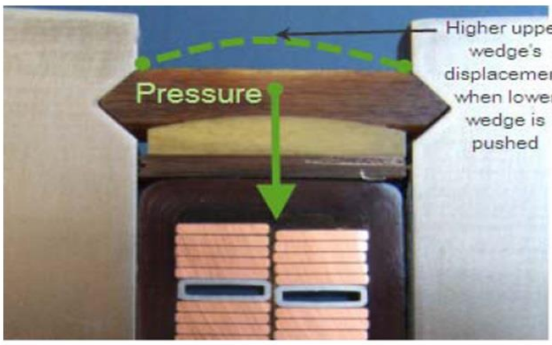

Fig.6 Concave-convex wedging system

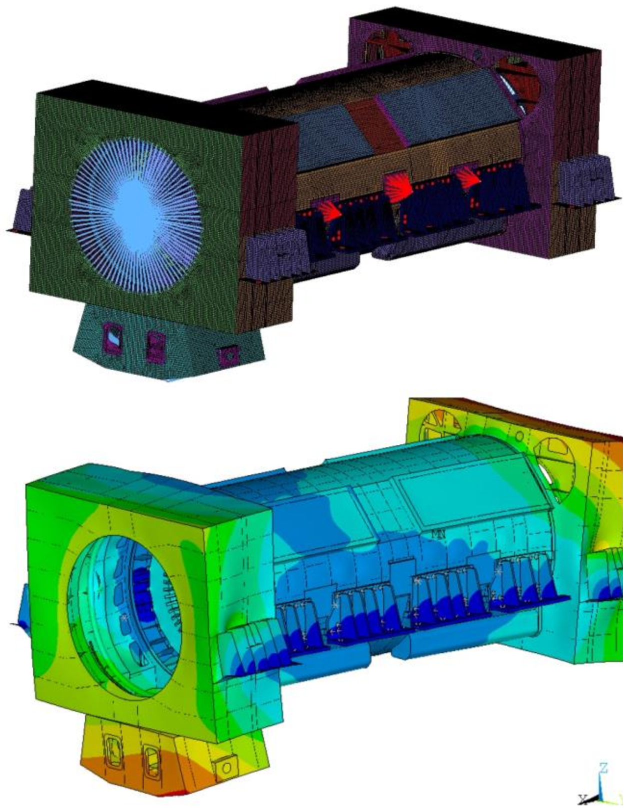
Fig.7 Finite element simulation of seismic condition

silvering is used in some locations. The R&D design studies (see Fig.4) confirmed reliable operation of the machine and full compliance with the contractual requirements.

During operation (and, in particular, in transient conditions) of powerful turbine generators, the stator end windings are exposed to significant electromagnetic forces and thermal expansion of the generator stator bars simultaneously. Thermal expansion and applied forces can vary depending on the operating conditions; therefore, it is necessary to ensure reliable integrity of the stator end windings. The end winding support system in combination with the end windings shall have a reliable offset between natural frequencies and exciting frequencies.

The GIGATOP 4-pole end winding support structure design (Fig. 5) is unique. This attachment is diametrically and tangentially stiff to ensure a low level of vibration of the end windings and phase rings, but flexible axially to allow free thermal expansion of end windings. The radial studs allow the operator to easily re-tighten the stator end windings during maintenance.

In large turbogenerators, high current in stator slots requires reliable and stable wedging of the winding so that it can withstand without damage an alternating load in normal and abnormal operating conditions and overload conditions with a prolonged decrease in voltage at machine terminals (for example, to -10 %). The slot wedging system used in the Akkuyu turbogenerator is a patented convex-concave system (see Fig. 6). It provides constant pressure on the stator bars and can compensate for initial shrinkage and thermal expansion of the bars during the machine operation, allows permanent attachment of the bars in the stator core and ensures high machine reliability. During scheduled shutdowns, the stator slot wedging condition can be checked using a robot. The wedges can be re-tightened, if necessary.

A study of the seismic spectra affecting the machine components was performed to assess seismic resistance of the turbogenerator following a design basis earthquake. The study was based on a three-dimensional model (see Fig.7) and considered the response spectra at the equipment elevation and foundation vibrodamping requirements. The seismic resistance study was performed in accordance with the seismic-resistant NPP design standards. From the point of view of static and dynamic strength of the components, parts and entire structure of the turbogenerator, the most important criteria are the capability to withstand various constant and alternating loads during short circuits, out-of-phase synchronization, nominal operation, transportation and handling.

The calculation of:

- The stresses in the main static parts of the generator
- The deflections between the rotor and the static parts

show that the design criteria (stresses under the Yield Strength of the material, no interference between the rotor and the static parts) are fulfilled.

This calculation demonstrates that Akkuyu NPP generator is safely designed to withstand the given seismic accelerations regarding material strength aspects, displacement on the turbo-generator table, and interferences between static and rotating parts.

4. ACCEPTANCE AND TESTS

4.1 Conformity assessment and equipment acceptance

The following was performed as part of equipment conformity assessment: review of design documentation and terms of reference, conformity assessment against quality plan inspection points, obtaining permission to start manufacturing from the Turkish authority (NDK), detailed review of end-of-manufacturing reports provided by both the manufacturers of parts, components and raw materials and turbogenerator manufacturer GE, witnessing of equipment tests at various stages of manufacturing.

4.2 Tests in stator winding assembly area

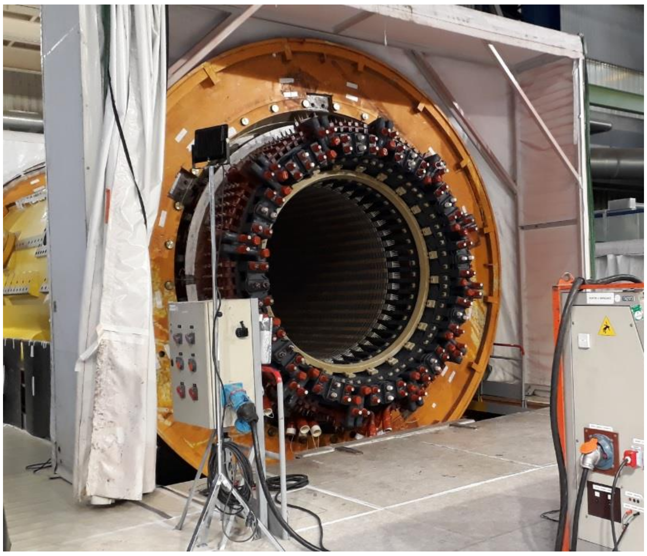

Fig.8 Test of wound stator at winding assembly pit

The stator winding assembly (image courtesy of GE) was followed by measuring the stator winding insulation with direct current in cold state. In addition, a number of important tests have been performed, which are beyond the test program but determine the reliability of the equipment, correct assembly of the stator winding and some values that would be problematic to measure on the assembled machine. For example, high-voltage tests, checking of the level of partial discharges, tangent delta test, stator winding capacitance and impedance measurement (with the rotor removed). An important test was the bump test of the stator core, end winding and phase rings support structure. From the reliability standpoint, it is important to check whether the natural frequency of these parts is sufficiently off-set from all the exciting current frequencies likely to occur during the operation of the power system, to which the generator is connected. This frequency spectrum is determined by the requirements of the grid operator. The tests demonstrated reliable off-set of the natural frequencies and confirmed compliance of the turbogenerator with the requirements of the Turkish grid operator against these indicators.

4.3 Balancing pit tests

Fig.9 Test of rotor at balancing pit

The rotor winding assembly was followed by rotor tests at the balancing pit (image courtesy of GE). In particular, according to the test program, the rotor winding resistance at direct current in cold state was measured and the rotor was tested at an increased speed of 1.2 times the rated one for 2 minutes (in accordance with IEC 60034-3). Additionally, the rotor balancing tests in cold and hot states were performed, rotor winding flux monitoring and tests were performed. The rotor flux monitoring was performed with a measuring coil during the rotor tests in a heated state with direct current fed to the rotor, by measuring the rotor winding impedance with alternating current and at various speeds, by pulse method on rotor at standstill. High-voltage tests and rotor winding capacity measurement were performed on rotor at standstill.

4.4 Tests during generator assembly on the test bench

During the turbogenerator assembly on the test bench, running tests within the scope of the test program were performed, including the frame gas tightness tests, winding tightness and flow tests. These tests are performed only for stator components when the rotor is withdrawn but take a long time to complete.

Fig.10. Test of stator during assembly on the test bench for running test

4.5 Acceptance tests of complete generator on the test bench

The main objective of testing the turbogenerator on the test bench is to obtain test characteristics of the equipment confirming the design parameters of the equipment, electromagnetic, energy, thermal, vibration and noise characteristics, and help obtain the parameters describing the mathematical model of the turbogenerator under normal and abnormal operating conditions, and check readiness of instrumentation sensors, electromagnetic compatibility and

assess possible hydrogen leakage areas.
The factory test bench configuration imitates the in-situ conditions. The turbogenerator is installed on a fairly strong foundation and connected to all the auxiliary systems necessary to cool it, lubricate the bearings and ensure shaft sealing. During the tests, all of the test bench equipment including all necessary electrical and process relay protections must be in operation.
The turbogenerator is driven by a motor having a capacity enough to cover the losses in the turbogenerator under the test conditions. It is common practice to use the Ward Leonard group comprising several electrical machines mechanically coupled in series to form a common driving shaft line. However, the Ward Leonard arrangement is bulky and less performing compared to the modern AC drive – a GE asynchronous motor with frequency converter. The latter was used to test the Akkuyu turbogenerator.

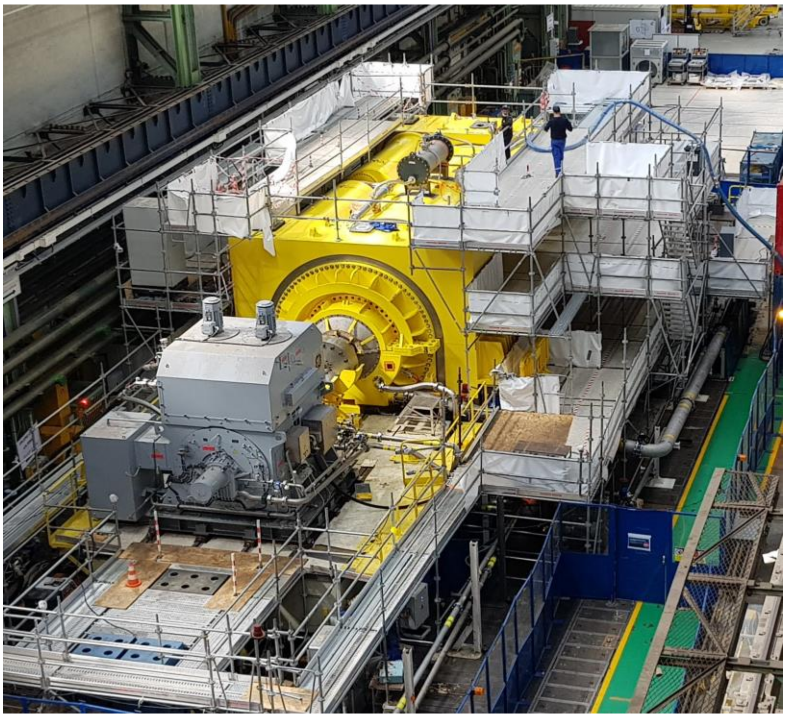
Fig.11. Akkuyu NPP turbogenerator during running test

In general, the scope of tests on the Akkuyu turbogenerator on the factory test bench meets the IEC standards.
A distinctive feature of large turbogenerators is the large size of their magnetic core, which requires more time for thermal stabilization of the machine in each of the tests, and therefore more time to complete the tests.
To meet the Akkuyu NPP requirements, it was important to perform the short-circuit test with temperature stabilization at up to 110% of rated stator current, which is compliant with the plant General Design requirement that the rated output of the machine shall be maintained in case of a long-term voltage drop at turbogenerator terminals down to 90% of the rated value. Stator winding temperatures in this condition remained within the normal operating range.

Parameter description	**Discrepancies between measure and calculation values, %**	**IEC tolerance, %**
Efficiency, %	+0.7%Total Losses	+10%Total Losses
SCR	0%	±15%
Xd, p.u.	+0.5%	±15%
X’d, p.u.	-2%	±15%
X’’d, p.u.	-0.35%	±15%
X_2, p.u.	-0.7%	± 30%
X_0, p.u.	-16.7%	± 30%
J, kg·m^2	+1.5%	10%

The parameters given in the table above represent a comparative analysis of the design data obtained and the measured data from the actual tests of the Akkuyu turbogenerator.
Tested THD value (0,42%) is in line with grid requirement and IEC standard (≤ 5%).

That the difference between the design and test data is only minor attests to the high quality of the tests and accuracy of the calculations.
The efficiency obtained from the calibrated machine test is very close to the design value and meets the plant General Design requirements (not less than 98.9%).
Rotor shaft inertia calculated from retardation test is in line with IEC criteria as per tolerance.
During such tests as no-load without excitation, no-load at rated voltage and sustained short circuit at rated current the noise level investigation has been performed around the generator. The measurement result is below 90 dB(A) and, as specific acoustic walls will be installed on site, will fully satisfy the General designer criteria 85 dB(A).
According to test program it was necessary to define some specific characteristics coming from Russian practice of Nuclear power plants. For example, regulation characteristic – is dependence on rotor current versus stator current at rated voltage, rated power factor and speed of rotation. The characteristic is determined by Potier diagram calculation built on base of saturation tests and Potier reactance.

5. CONCLUSIONS

Design features of the TA 1200-78 generator allow to fulfil Turkish grid requirement, specific conditions of Power Plant General Designer, as well as mechanical requirement linked to seismic spectra of Akkuyu site. Electrical characteristics and efficiency have been confirmed through an extensive running test campaign which demonstrated accuracy of calculation tools used to validate the generator design.

This generator is answering the need of covering market requirements from different nuclear reactor types (e.g., VVER-1200 and VVER TOI projects), market regions and grid codes as Turkish grid and also opens future perspectives for the design of 60 Hz 1200 MWe generators. In addition, TA 1200-78 has high reactive power capabilities which answer a growing demand of the market due to the integration of intermittent energy sources.

BIBLIOGRAPHY

[1] R. Joho, Y. Sabater, H. Ferretto, D. Abraham, W. Ferens “Hydrogen/water-cooled turbogenerators: A mature technology on the move”, CIGRE Session 42 – 2008, Paper A1-107.
[2] J. Oliver, J. Michalec, B. Zimmerli, R. Joho, N. Krick, A, Huber “Generator Winding Design – Amos 3 with 25 years of experience”, IEEE, Vol. 16, NO. 1, March 2001.
[3] J. Haldemann, “Transposition in Stator Bars of Large Turbogenerators”, IEEE Transactions on Energy Conversion, vol. 19, nr3, sept, 2004, pp. 555-560.
[4] P. Chay, M. Buquet, B. Wahdame, V. Fernagut, S. Magois “Impact of grid code evolution on the design of the generators for nuclear plants (Half speed, power above 800 MVA)” CIGRE Session 2018, Paper A1-104.