Advanced System for VVER Steam Generator Inspection

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Abstract

From the safety point of view, steam generator (SG) is a very important component of a nuclear power plant. Only a thin tube wall prevents leakage of radioactive material from the primary side into the environment. Therefore, it is very important to provide inspections for early damage development detection and apply appropriate corrective actions during outage. Application of the nondestructive examination (NDE) technique, that can locate degradation and measure its size and orientation, is an integral part of nuclear power plant maintenance.
The inspection system of steam generator is consists of remotely control manipulator, testing instrument and software for data acquisition and analysis. In the recent years the inspection systems are evaluating to a much higher level of automation, efficiency and reliability resulting in a lower cost and a shorten outage time. Electronic components have become smaller and deal with more complex algorithms that leads to integrated control system into manipulator's structure. These kind systems are very fast, precise, reliable and easy to handle.
The whole inspection, from the planning, examination, data analysis and final report, is now a highly automated process, which makes inspection much easier and more reliable.
This paper presents the new generation of INETEC's VVER SG inspection system as completely solution for steam generator inspection and repair.

Key words: VVER, steam generator, NDE, UT, ET

1. Introduction

Steam generators are heat exchangers that use the heat from the reactor core on the primary side to produce the steam on the secondary side for driving turbines for electrical power production. Design of steam generators includes a tube bundle with a large number of the tubes that ends at the tube sheet on the collector wall. VVER type of steam generator has two cylindrical collectors with the manway at the top used for equipment installation. Standard inspection scope covers EC testing inside the tubes, ultrasonic testing (UT) of the collector welds and tube plugging.

The tubes are susceptible to several degradation mechanisms like outside stress-corrosion cracking (ODSCC), either circumferential or axial or intergranular attack (IGA) which can result with cracking. Crack defects can also be initiated from primary side in form of primary water stress corrosion cracking (PWSCC). Other common degradation form is volumetric loss of tube material due to wear, wastage, pitting corrosion and impingement. Inspection aim is to detect any new flaw but also monitor existing damage development by comparing historical data.

Recently, Inetec has developed a new generation of the VVER steam generator inspection system, using modern technologies and great experience from the previous inspections. Now, electronic components are distributed over the manipulator, very close to the drivers increasing the speed of the whole machine, improving cable management and reducing noise of the measuring signal. With advanced algorithms built into low-level software manipulator has become more precise, reliable and easier to operate. It includes three modules: ET module for tube inspection, UT module for

collector welds and a plugging module. Each module can be easily mounted on the main elevation carriage.

Manipulator is controlled by PC software, which is synchronized with Inetec EddyOne software package. New features, such as real-time 3D visualization, inspection simulation, generation of log file and machine video, are integrated into the software. The whole inspection, from the planning, examination, data analysis and final report, is now a highly automated process, which makes inspection much easier and more reliable. All the features of the new system will be described in the paper.

2. Inspection System

Today modern technology enables development of the complex and highly automated robotic systems which are very precise, reliable and easy to handle. CASTOR is a new generation of INETEC's VVER steam generators inspection system that meets cutting-edge technology solutions, company know-how and experience from previous inspections. Effort made in development resulted in "all-in-one solution" that provides Eddy Current and ultrasonic testing. Also, there is plugging module that is used to perform corrective operations in case of defect or leakage detection. Manipulator is remotely controlled by manipulator control software, which is part of Inetec EddyOne software package. New features, such as real-time 3D visualization, inspection simulation, generation of log file and machine vision, are integrated into the software. The whole inspection, from the planning, examination, data analysis and final report, is now a highly automated process, which makes inspection much easier and more reliable.
Figure 1 shows the manipulator, which is used to deliver the probe in front of each tube that has to be inspected according the inspection plan.

Manipulator is in the shape of elevator with two vertical guides and carriage with exchangeable modules for inspection. It possesses two movement axes, one vertical linear along the guides and one rotation. Area that can be reached with rotational axis is 400 degrees, so there are no exclusion zones. Translational axis, which is used for elevation of the main carriage, covers all range of inspection from the bottom weld to the top of collector. In that way, all tubes and welds can be inspected. Also, it is possible to move the manipulator in safe docking position on the top of the guide rails in order to change the probe spools or use another testing module.
As shown in Figure 1, cable management is improved and all cables that have to be connected to manipulator are power, communication and air supply cable. Air supply is necessary to extend and retract centering mechanism and operate the guide tubes, rotation probe unit, UT and plugging module. Also, it is used to open and close the pusher wheels and control the wheels pressure which will be described later.

In figure 2, block scheme of the manipulator with installed EC module is given. It shows the main parts of the control system:

- PSU – Power Supply Unit with communication system
- CU – Controller Unit with Emergency stop button
- EDU – Elevation Drive Unit
- RDU – Rotation Drive Unit

Figure 1 CASTOR – new generation of INETEC's VVER SG inspection system

Power supply unit provides 3kW@48 VDC supply. With low-voltage level operator's safety is increased, especially if wet conditions are present. In case of any emergency, there is emergency button on the controller unit and remote emergency button that can be in operator's room. Communication system with Ethernet switch for control system components and two-channel audio system is integrated in power supply unit. There is also Ethernet to optical converter, so user can choose whether to use Ethernet or optical communication between manipulator and operator's workstation.

CU – Controller Unit is main part of IMEC2 control system where all communication, power and emergency cables are connected. CU sections are: junction Printed Circuit Board (PCB) with electrical terminals, main controller, external I/O unit, servo drive for rotation motor, pneumatic system for pressure regulation and control of centering mechanism operation. All control components are connected via EtherCAT communication protocol and can be addressed from main controller. So, all inputs and outputs like air pressures, valves states, motor speeds, limit switches etc. are set from the central controller and user can watch them on the screen. It is important for safety reasons that centering mechanism operation and guide tube pressure supply can work without electrical power. It is achieved by manual actuators on the front door of the CU. Also, there are indicators of installed air pressure and 48V & 24Vpower supply.

EDU – Elevation Drive Unit is central part of IMEC2 manipulator where all other modules are connected. EDU is consisted of electronic and pneumatic components. Among all electronic components, main electronic parts in EDU are servo drive for elevation motor and EtherCAT communication junction module. Pneumatic components include pressure sensor and pneumatic valves for guide tube operation and other manipulator features.
RDU – Rotation Drive Unit is a separate box where rotation motor is mounted. It is connected to CU – Controller Unit with two cables, the 4-wire cable for motor connection and the 12-wire cable for hall sensor, encoder and temperature switch signals.

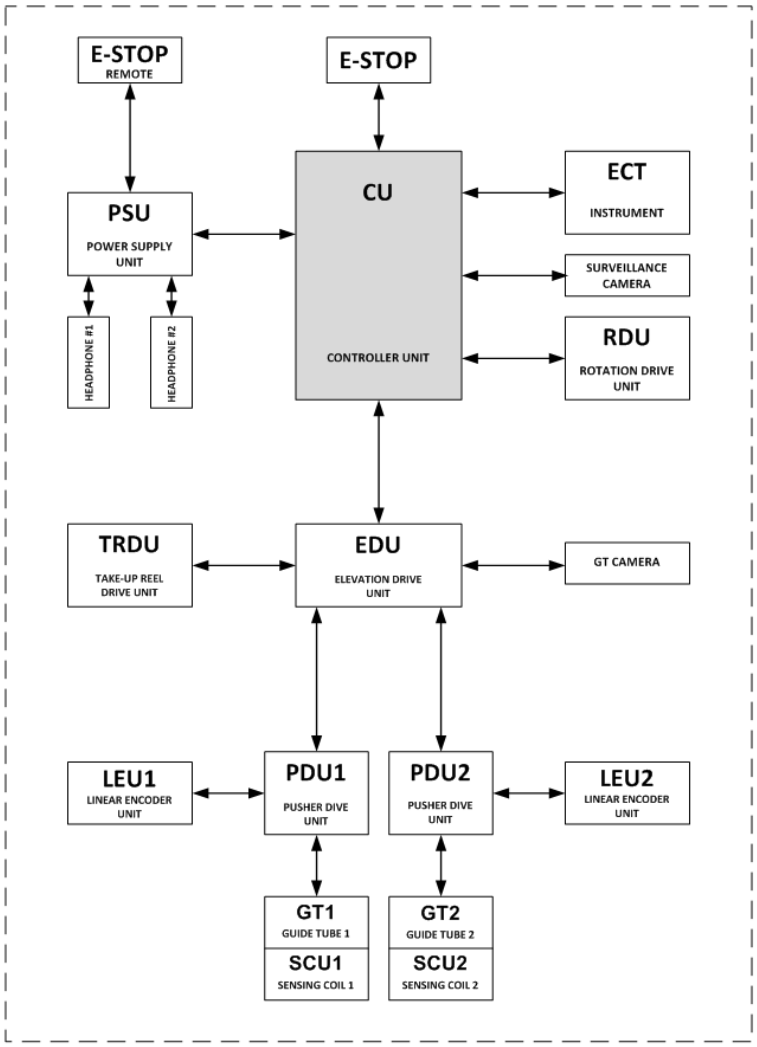


Figure 2. – Control System Block Scheme (with EC module installed)

Eddy current module (figure 3) operates as dual pusher system where PDU units push the probes in the pipes of steam generator and TRDU unit is dual two take-up reels winding system with brushless motors. Both pushers are connected with linear encoder and sensing coil units which are used to detect exact probe position. Sensing coil unit is usually used to stop the probe when it is pulled out of the tube. In case that probe is not active or damaged, there is additional mechanical switch which is used as hard stop switch.

Figure 3. Eddy current module

Pusher drive units can perform the inspection with pulling speed from 0.5 mm/s to 2600 mm/s so different probes can be used, such as bobbin, rotating and array probes. Two probes could be used at the same time in order to reduce inspection time. Additional new feature gives a possibility of different guide tube orientation, vertical or horizontal, depending on inspection plan.
Drive wheels of the pusher are now positioned at the back of the module, which provides easy replacement of the probes and makes the probe path simple and smooth with big radius that increases the lifetime of the probe. New control system gives an opportunity to control pushing/pulling force in range up to 1000 N, so probe can reach third bend of the tubes in the steam generator. This is possible to do by controlling the wheels motor torque and pneumatic pressure on wheels opening and closing system. If linear encoder as additional accessory is used, then system can detect and deal with the slipping effect between the probe and drive wheels. Anti-slipping control (ACS) algorithm is created in order to handle that situation. Algorithm increases the wheel pressure according to difference between wheels encoder and linear encoder speed so slipping effect is reduced and probe lifetime is increased.
The reels are driven by torque motor and controlled by intelligent algorithms, keeping the probe cable always in a tension mode and allowing positioning the reels directly on carriage or even on top of the manipulator.

During inspection, machine vision is used as a secondary system for position verification. In case of any mismatch between machine vision system and position sensors based position, inspection is halted and user receives warning message.
CASTOR inspection system supports all common Eddy Current instruments, e.g. Zetec TC7700, MIZ-85. It can perform inspection with variety of probes with different diameters, including bobbin, array and rotating probes. Additional RPU – Rotational Probe Unit can be installed in place of guide tubes in order to perform inspection of collector wall.

In order to perform UT testing, PDU units are replaced with UT unit (figure 4). It is placed at the bottom of the main carriage so it can reach the lowest weld in the collector. Mounting process is

significantly simplified with four screws and two quick release connectors. Electronic box on main carriage is over-pressurized for underwater inspection, in other case water supply is used. Two end effectors with probe sets work simultaneously at opposite side of collector in order to balance the load and to reduce inspection time. Each set carries four UT or ET probes.

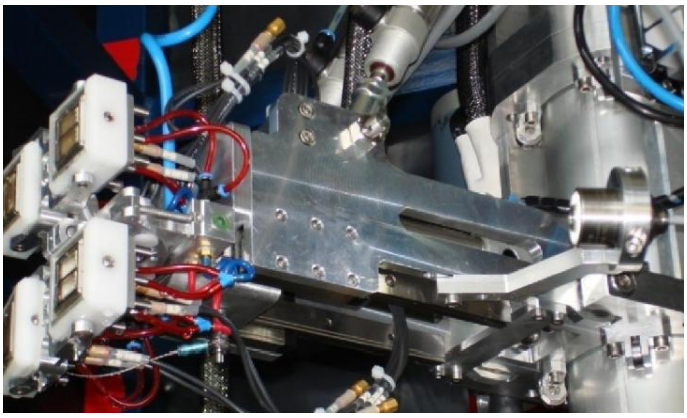


Figure 4. UT module

If unacceptable damage is detected on the tube it should be excluded from the usage. In such case, Inetec's solution is mechanical tube plugging (figure 5). A process containing several steps: tube end rolling, tube rolling and mechanical plug installation. This approach leads to the fast plugging, possibility to remove the plug and very good records in service life.

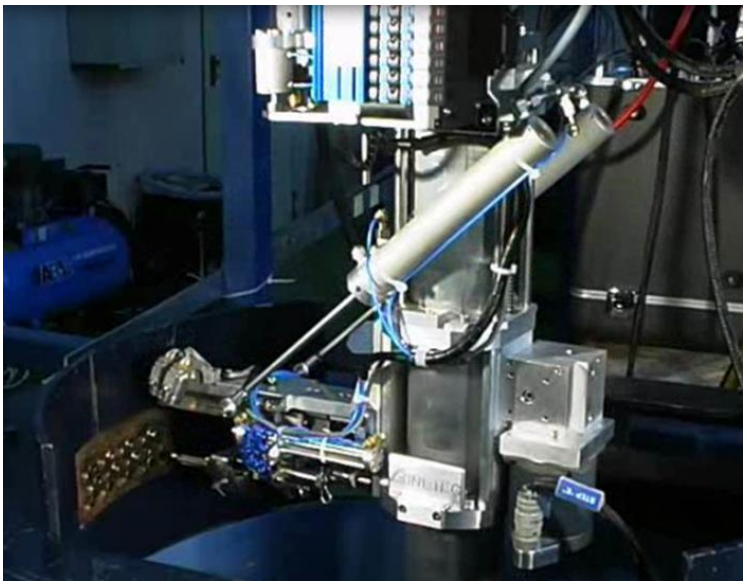


Figure 5. Plugging module

3. Software package

Standard software package for SG inspection includes four essential components: inspection management, manipulator control, data acquisition and data analysis (figure 6). Inspection management (figure 7a) is used for planning inspection, managing inspection data and generating final report.

It transfers a list of the tubes that should be inspected to the manipulator control software. In the automatic inspection mode manipulator control sort the list of the tubes optimizing inspection time. Inspection management deals with enormous amount of data that a stored on the large capacity storage device. Data include recorded signals from thousands of tubes per each SG with one or

various probe. Also, historical data is used from previous inspections due to comparison purposes. Usually data are centralized and analysts can use them from different locations via Ethernet connections. EddyOne inspection management is designed as web application which is new features in such a kind of software, enabling easy access to the software from any locations and handling users permissions.

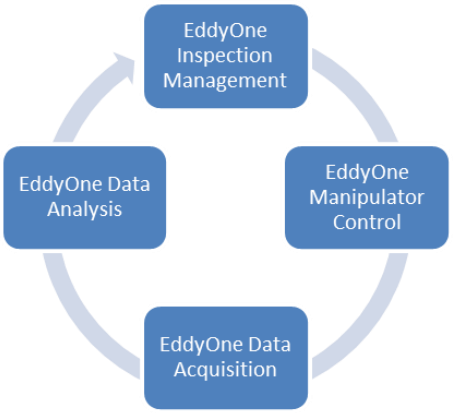
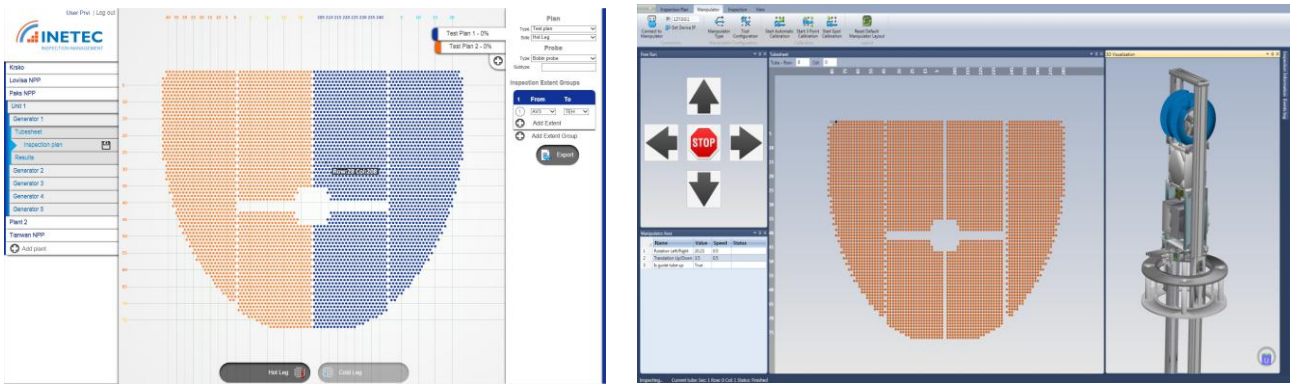


Figure 6. EddyOne software package

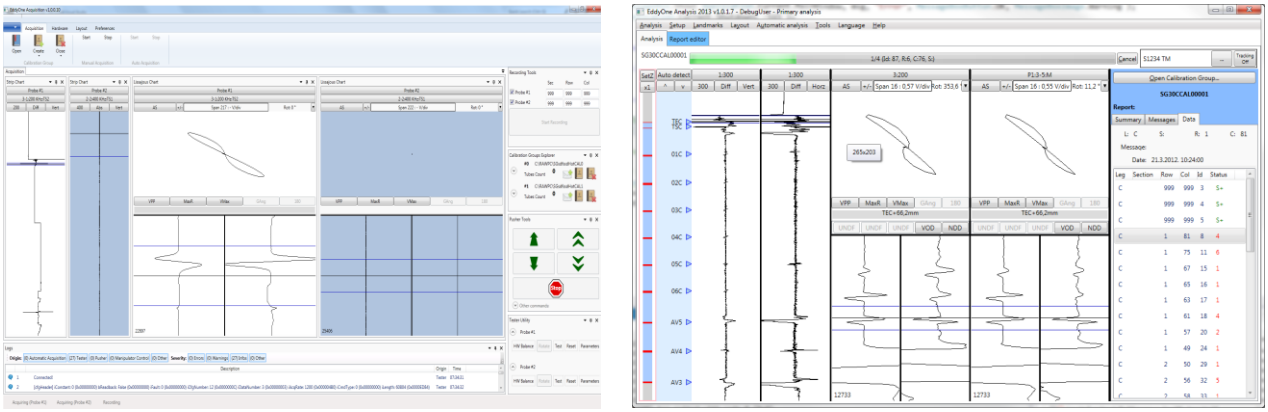
EddyOne manipulator control (figure 7b) is software with very intuitive interface and operator need minimum of time to get start using it. It is synchronized with inspection management shearing data and information of inspection progress. Reconfigurable windows maximizing comfort enabling operator to choose a setup to watch. New features such as real time visualization, inspection simulation or generation log file are added in the software. Machine vision is integrated part as a secondary position verification tool that runs in the background comparing manipulator position obtained from the encoders and from the vision system. In the case of the mismatch of results operator is alerted.



a) **b)**

Figure 7. EddyOne inspection management software (a) and EddyOne manipulator control software (b)

Data acquisition application is used for purpose of acquiring eddy current data during inspection process. It is connected directly to the EC instrument and manipulator control software. Because of practical reason probe pusher controls are part of the data acquisition interface that means that operator during inspection most of time works with this application. In the case of automatic acquisition mode operator only control the inspection process while the manipulator control and data acquisition software runs all activity of the inspection system regarding the inspection plan. EddyOne acquisition software can works with different kind of probes and it is also open for different type of EC instruments.



a) b)

Figure 8. EddyOne acquisition (a) and EddyOne analysis software

Data analysis application is used during inspection process for purpose of acquired data evaluation. Its task is to display the signal recorded on tubes in the mode suitable for the analysts. The applications produced by different companies have standard interface with which is accustomed to analysts. In the first time of inspections only one analyst was analyzing the acquired data, today a team of at least five members works on different level of analysis process.

First, two independent analysts, called primary and secondary, evaluate the data in parallel and give preliminary results. After that more experience analyst, called resolution, compares the results from primary and secondary, resolves any discrepancies and confirms reported indications. Second resolution reviews the results again, perform the detail analysis and disposition indications that would require further diagnostics. Finally, an independent analyst who is reporting directly to the utility verifies that the resolution analysts are consistently resolving calls and providing feedback. Analysis crew is usually located at remote sites or at centralized analysis centers. Most countries required analysis personnel to be certified under the Qualified Data Analyst (QDA) testing program.

In order to reduce analysis time and inspection costs, automatic analysis is implemented into analysis software. It can replace primary or secondary analyst or even both if different detection algorithms are used. Key element of the automatic analysis is good set up and it should be performed by well trained and experience analyst. In that case preliminary results could be obtained almost in a real time with small number of false calls and none of missing flaws. Automatic analysis shows good performance when applied in SG with well-known degradation modes but it has limitations to identify new degradation modes it cannot completely replace humans. Automatic analysis of the data recorded from the VVER SG is integrated part of the EddyOne software package.

4. Conclusion

In order to increase nuclear power plant productivity big effort has been made to reduce the number of outages and outage time which defines requirements for development of the new inspection systems. They have to provide faster inspection, be compact for easier installation and bring much more information about SG condition which is input for structural integrity assessment, fit for service and operational assessments.

New degradation mechanisms that might be emerged due to life extension of NPP as well as tighter regulatory requirements of flaw detection are additional challenge for inspection systems. Beside that the level of radiation exposure for the personnel involved in the SG inspection should be reduced according to ALARA.

New generation of INETEC's VVER steam generators described in this paper is designed to satisfy all regulatory requirements and recommendations. The whole inspection, from the planning, examination, data analysis and final report, is now a highly automated process, which makes inspection much easier and more reliable.

11. References

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