Diagnostics as a source of knowledge and strategy for coal-fired power units operated in a flexible mode

Jerzy Trzeszczyński and Ewa Trzeszczyńska

Kurzfassung

Ergebnisse aus der Diagnostik als Grundlage für Know-how und Strategien zum flexiblen Betrieb von Kohlekraftwerken

Unter den rechtlichen, wirtschaftlichen und technischen Anforderungen an Kraftwerksblöcke sind letztere aktuell sehr entscheidend. Der technische Zustand von Kraftwerken und ihren Einrichtungen bestimmt deren Sicherheit und Verfügbarkeit. Für konventionelle Kraftwerksblöcke, insbesondere für solche, die in Zukunft im Versorgungssystem noch weitreichender als bisher Netzstabilität gewährleisten werden, sind erhöhte Flexibilität und hohe Verfügbarkeit die wünschenswerten Merkmale. Solche können mit durch qualitativ hochwertiges, ständig aktualisiertes Know-how aus dem Betrieb gewährleistet werden. Eine systematische Diagnose und eine darauf aufbauende Instandhaltung mit angemessenem Umfang führen zudem zu akzeptablen Kosten. Dazu wurde ein Diagnosesystem entwickelt, das Lebenserwartung und Ausfallvorhersage integriert, wobei insbesondere die Betriebsbedingungen von Kraftwerksblöcken einer Leistungsklasse berücksichtigt werden.

Eine umfassende Diagnose ermöglicht es, die Systemkomponenten und deren Betriebsbedingungen eingehend zu erfassen, auch dann, wenn Hersteller-Know-how nicht – mehr – verfügbar ist. Solches Know-how ermöglicht nicht nur die Optimierung von Instandhaltung sondern auch die Modernisierung von Systemkomponenten unter Berücksichtigung des zukünftigen Betriebsregims des Kraftwerks sowie der Anforderungen des Betreibers und der sich dynamisch ändernden Situation auf dem Energiemarkt.

Authors

Dr. Eng. Jerzy Trzeszczyński
CEO

Ewa Trzeszczyńska
Deputy Director
PrzedsiębiorstwoUsług Naukowo-Technicznych „Pro Novum" Sp. z o.o.
Katowice, Poland

Introduction

Among the requirements for power units which are legal, economic and technical, the latter is the most important. The technical condition of power equipment determines their safety and availability. For conventional power units, especially those, which in the future will stabilize power system even more than before, rationally increased flexibility and high availability will be their most desirable features. Such expectations can be ensured by high quality constantly updated knowledge, which comes from properly organized and performed diagnostics, as well as maintenance based on it, having the appropriate scope and level at acceptable costs. To achieve this, a complete diagnostic system, which integrates lifetime expectancy and failure prediction, taking into account in particular the operating conditions of units of the same class, has been developed.

Comprehensive diagnostics allow to learn the design and technology of device components and their operating conditions to a degree similar to the knowledge of the supplier, which is particularly important when the devices are operated longer than the supplier is on the market. Such knowledge allows not only to optimize the scope and costs of technical maintenance, but also to modernize the equipment, taking into account the strategy of the power plant as well as the operator's requirements and the dynamically changing situation on the energy market.

Coal-fired units in Polish power system

The European Union's policy of climate neutrality assumes complete decarbonization of the power sector in the next 30 years, which means, among others, resignation from the construction of new coal-fired units and gradual decommissioning of existing generating units, followed by their operation in unusual and increasingly difficult conditions. For the Polish electricity system it is an extremely big challenge. This is due to the current fuel structure, which is shown in Figure 1. With a relatively small share of RES, however, with a significant predominance of energy from onshore wind farms and with the priority of its reception by the power system, conventional power units, especially those

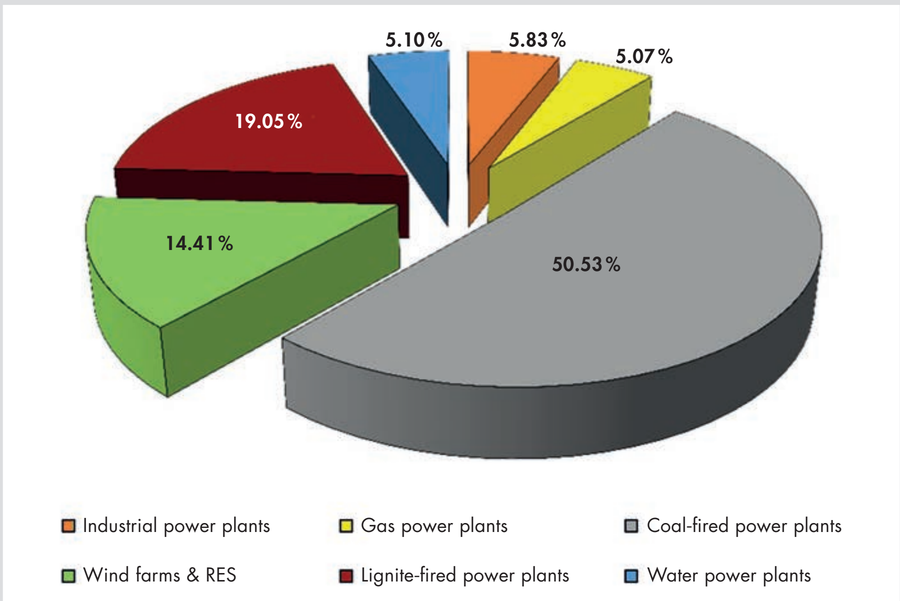


Fig. 1. Fuel structure of the Polish power system, as of December 31, 2018.

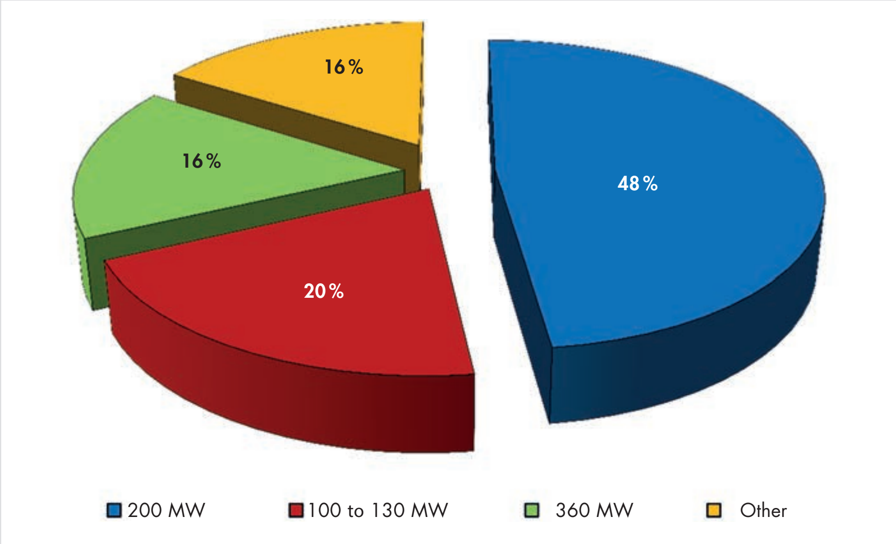


Fig. 2. The structure of Polish power system due to the power of generating units.

Tab. 1. General characteristics of 200 MW power units and the probable scenario of their further operation.

Characteristics of 200 MW power units	
Time of operation	220,000 – about 300,000 hrs
Total numer of starts	1100 - 1600
Maximum power	about 240 MW (designed 220 MW)
Technical minimum	110 - 160 MW (designed 130 MW)

Tab. 2. The probable scenario of further operation of 200 MW power units.

Expected period & conditions of further operation	
Time of operation	about 350,000 hrs (until about 2035)
Total numer of starts	about 3000
Scenario of further operation: – Basic (P) – Regulating-reserve (RR) – Stand-by (RZ)	 4,500 hrs/year – 4500 MW 1,500 hrs/year – 2500 MW 300 hrs/year – 3000 MW

burning coal, operate in an increasingly flexible mode. This situation will deepen (Table 1), also because of over 800 MW of recently built high-capacity coal- and lignite-fired units, which should be treated as an additional potential source of system instability in the event of their failure. The power system is also stabilized by growing energy imports, but the assumed increase in wind and photovoltaic generation will continue to pose growing challenges for the stabilization of the power system. One of the remedies for this situation may be an appropriate strategy for the operation of 360 MW and 200 MW units, which, due to their number (respectively 15 and about 40 units) as well as design features and good technical condition, can play a significant role in the perspective of up to 2030 (Figure 2 and Table 2).

The described diagnostic system, which is a source of knowledge that can be used to ensure not only the safety of long-operated power units, but also their operating strategy, on the example of 200 MW class units, may show better their features and advantages.

Basic construction data and operating parameters

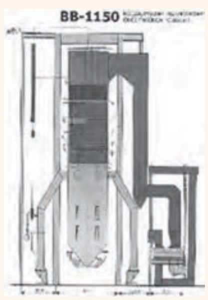
Power units class 200 MW and 360 MW have been the basis of the system since they were put into service. They can be replaced only in the long run after having planned a rational alternative for them. Boilers of 200 MW power units of type OP-650, OB-650, EP-650 are the devices with a dust furnace and natural refrigerant circulation; they are fired with coal (OP, EP) or lignite (OB), have irradiated screen combustion chambers. Boilers of 360 MW power units of type BP-1150 and BB-1150 are the dust and flow boilers fired with coal or lignite respectively.

Basic construction data and operating parameters are shown in Table 3 and Table 4.

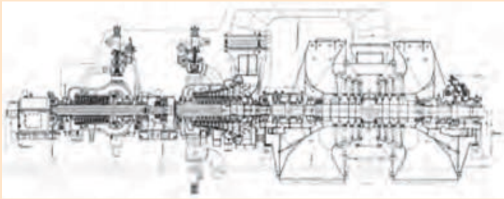
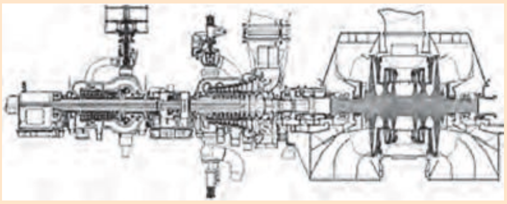
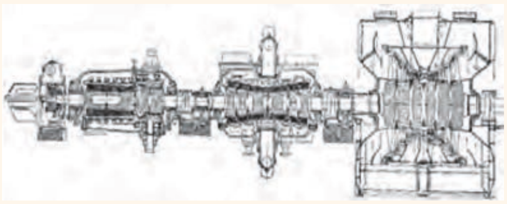
The service lifetime of power units is usually not related to the working time of their main and auxiliary devices as well as important construction nodes and components (Table 3 and Table 4) as they have been modernized many times. Their current technical condition means that they meet the requirements of the IED Directive 2010/75/EU, the Operator and the Office of Technical Inspection and most of them will meet the BAT Conclusions requirements, which will become effective from July 2021. Their availability and maintenance costs are at an acceptable level.

Numerous modernizations mean that in the last period of operation there should be expected damages more typical for the first period of operation, i.e. design errors, manufacturing and assembly errors of their modernized parts, than those connected with the remaining lifetime of critical (thick-walled) elements. These units, including the 200 MW class, have undergone a modernization cycle related to improving their efficiency. Those of them, which have undergone this process, have their efficiency fully increased to approx. 38 %. Such efficiency is roughly demonstrated by modern supercritical coal-fired units that operate in a flexible mode.

Tab. 3. Boilers of 200 MW and 360 MW power units; Source: Folder of Rafako SA (own study).

Power of unit	Type of boiler	Scheme of boiler	Basic operation parameters	
			Pressure of live steam	Temperature of live steam
215 MW, after modernization to 242 MW	OP-650		13.5 MPa	540 °C
	EP-650		13.8 MPa	540 °C
	OB-650		13.8 MPa	540 °C
360 MW	BB-1150		18.3 MPa	540 °C
	BP-1150		19.0 MPa	570 °C
After modernization to 394 MW	BB-1150 (after modernization)		18.3 MPa	540 °C

Tab. 4. Turbine sets of 200 MW and 360 MW power units; Source: Folder of Rafako SA (own study).

Power of unit	Type of turbine set	Scheme of boiler	Basic operation parameters	
			Temperature and pressure of intake steam to HP part	Temperature and pressure of intake steam to MP part
	13K215			
215 MW, After modernization to 242 MW	13K225 after modernization according to Alstom		535 °C 12.75 MPa	535 °C 2.31 MPa
	13K225 after modernization according to Westinghouse			
360 MW	18K360 before modernization		535 °C 17.6 MPa	535 °C 4.0 MPa
After modernization to do 394 MW	18K360 after modernization		547 567 °C 17 to 18.37 MPa	568 °C 4.19 to 4.22 MPa

An important advantage, especially of 200 MW units, is their construction, enabling the extension of the durability of the main thick-walled (critical) elements far beyond the design time when using regeneration and revitalization, the costs of which do not exceed 30 % of the value of the new element.

Diagnostics as a source of lifetime extension strategies

Periodic tests and assessments of critical elements, especially of units of 200 MW class, indicated that almost all damages of critical/thick-walled elements are of thermal and fatigue character. Creep degradation was and still is rare and their source is additional stress caused by construction, assembly, repair and maintenance errors. This was fully confirmed by destructive testing of the elements (HP and MP rotors, HP and MP casings and valve chambers as well as bends of live steam and superheated steam pipelines) from the decommissioned power units after exceeding 250,000 hours of operation and the results of ongoing destructive testing of these elements as well as drums and steam superheater chambers performed on trepanning samples.

For cast-steel element technology of revitalization was developed, which consists in repairing by welding defects after removing damaged in the form of operational cracks combined with heat treatment, structure, regeneration and removal of unacceptable deformations (HP and MP casings) by thermal and mechanical treatment. The earliest revitalized cast-steel elements of turbines are operated without failures around 150,000 hours from completing this process. The regeneration of the structure has improved the plasticity of the material, making them more resistant to cyclic thermal fatigue damage both at the stage of crack initiation and their propagation.

Properly performed diagnostics made it possible to identify non-optimal solutions for fastenings of steam and water pipelines and some design errors of drums and rotors (e.g. shape of holes and heat grooves). Modernizations carried out on this basis have permanently eliminated damages of piping installations. The operating time of the pipelines modernized in this way the earliest exceeded 300,000 hours.

An important source of lifetime extension is failure analysis performed in a way that allows determining not only the cause of a direct failure or damage but also an indirect cause. In particular, determining the indirect cause has the advantage of eliminating or significantly reducing the risk of subsequent failures. To monitor the risk of failure in online mode, systems for remote monitoring of the technical condition of the main thermo-mechanical components of power units have been developed in the form of the IT Platform LM System PRO+® were equipped with a risk analysis module, which classically understood the risk of failure as a product of its probability and consequence, updates on-line depending on the current value of risk, including the operating conditions and the quality of technical maintenance, and the consequences of a failure depend on the cost of removing its effects and the value of loss of production. In this way the risk of failure of heating surfaces of boilers OP-650 and BP-1150 (Table 2) is being monitored on-line. The service is performed in a SaaS (Software as a Service) mode, which means that it does not require the purchase of a software or license.

Diagnostics as a source of knowledge for flexibility improvement

Conventional power units are entering the last phase of operation. Depending on the current technical condition and the degree of meeting the current and foreseeable legal requirements, especially regarding the emission level, the horizon of their further operation may be from several to a dozen or more years.

One of the significant limitations may be meeting the operator's flexibility requirements (Figure 3). Its radical improvement may prove impossible due to some design features of coal-fired power units designed 30 to 40 years ago. The costs of some extensive modernization may also prove unacceptable.

Also in this case, the knowledge of the previously performed diagnostics and the accompanying operation of the unit with improved flexibility may prove useful. Good knowledge about the current technical condition of the unit and the possibility of its selective improvement, as well as identification of the remaining lifetime of critical/thick-walled elements and the possibility of its full, safe use create the basis for developing a low-cost improvement in flexibility, the concept of which is presented in Figure 4.

The improvement of flexibility is understood primarily as acceleration of start-ups from individual thermal states and reduction of the technical minimum. Technical audits of the units and tests show that the critical / thick-walled elements of boilers and turbo sets have considerable reserves of lifetime, which can be safely used even by significantly accelerating their heating. In general, greater problems are caused by operational limitations: relative elongation in the turbine flow systems and – when operating with a lower technical minimum - combustion stability when operating with basic fuel, maintaining safe circulation of the medium in the boiler furnace chamber and steam parameters at the outlet of the boiler and at the last stages of the LP part of turbine. Diagnostics in these cases should enable correct and quick assessment of the effects of more intense work of structural elements / nodes exposed to conditions conducive to damage.

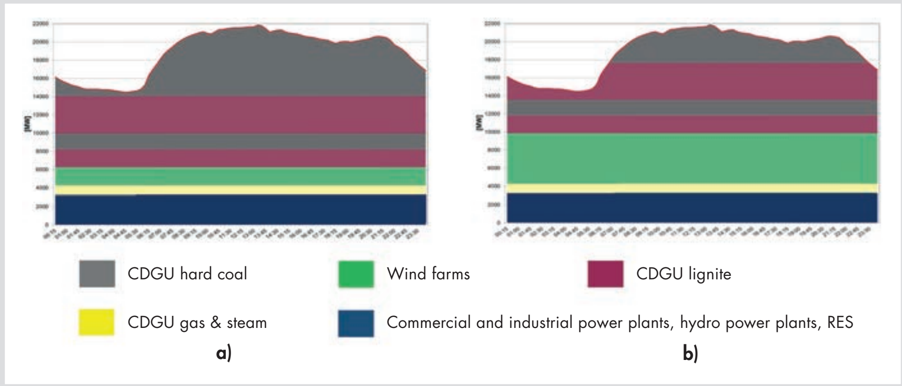


Fig. 3. Strategies of the power system Operator in the scope of satisfying the temporary needs for electricity: a) 2016, b) forecast for 2020 (with periods of increased power generation by wind farms). Source: PSE (own study).

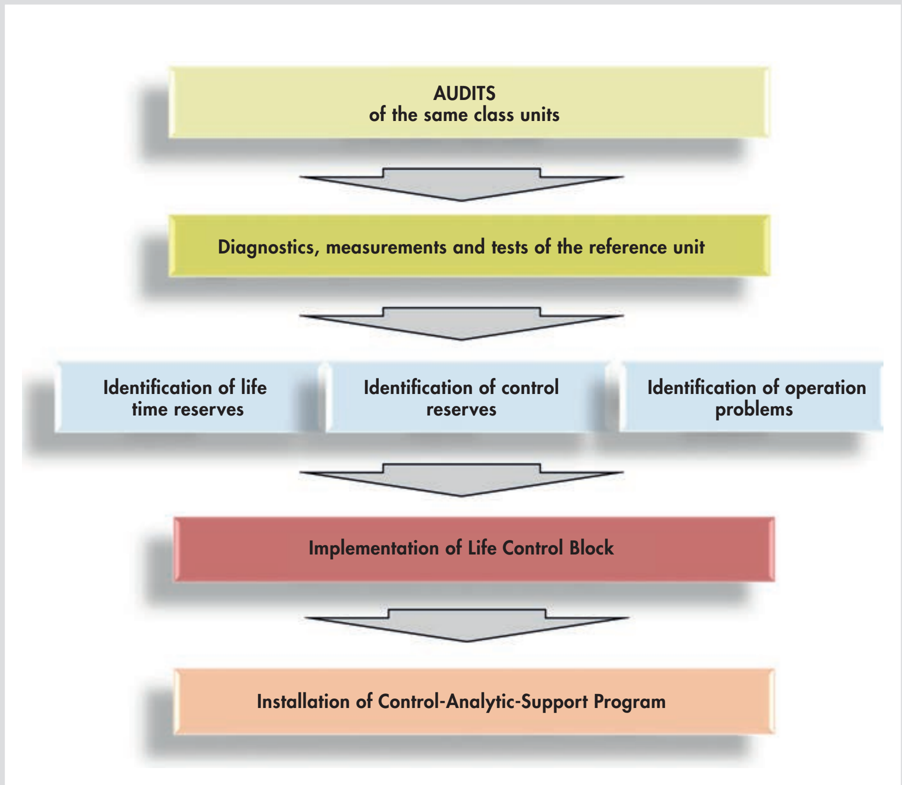


Fig. 4. Diagram of the flexibility improvement procedure of 200 MW class power units based on the knowledge from diagnostics at the stage of method implementation and supervision of more flexible operation.

Diagnostics for elements and pieces of equipment in the last phase of operation

The cycle load operation of a significant part of the power units causes fatigue to a greater extent than creep leads to damage to many of their components. The cracks should be as accurately located and dimensioned as possible (length, depth), which can usually be ensured by integrating the results of endoscopic and ultrasonic examinations. Repair of cracks located on the internal surfaces of the elements is generally technically impossible and organizationally (long time of prefabrication of new elements) and economically (especially in the last phase of the elements and / or devices' service) unjustified. For cases where the cracks have fatigue character, a methodology of conditional exploitation of damaged elements was developed. Their technical condition is assessed on the basis of BS 7910 – 2013 + A1: 2015 [7]. If the element can be approved for further operation, the depth of cracks is monitored online using computing tools, and when necessary, crack sizes are periodically checked by selecting NDT methods appropriate for the specific case.

In order to implement the described methodology the existing sensor system must be verified in the area of temperature and steam pressure as well as metal temperatures for suitability for calculations of the required quality. If the measuring system does not meet the requirements, additional sensors should be installed optimizing their location due to the accuracy of current analysis of their effort.

The assessment of the technical condition of damaged elements should be accompanied by simulation of various working conditions using the finite element method (FEM). The critical criterion should be the critical crack sizes and the acceptable limit load reserve. Material properties are best taken on the basis of end-of-life tests [6].

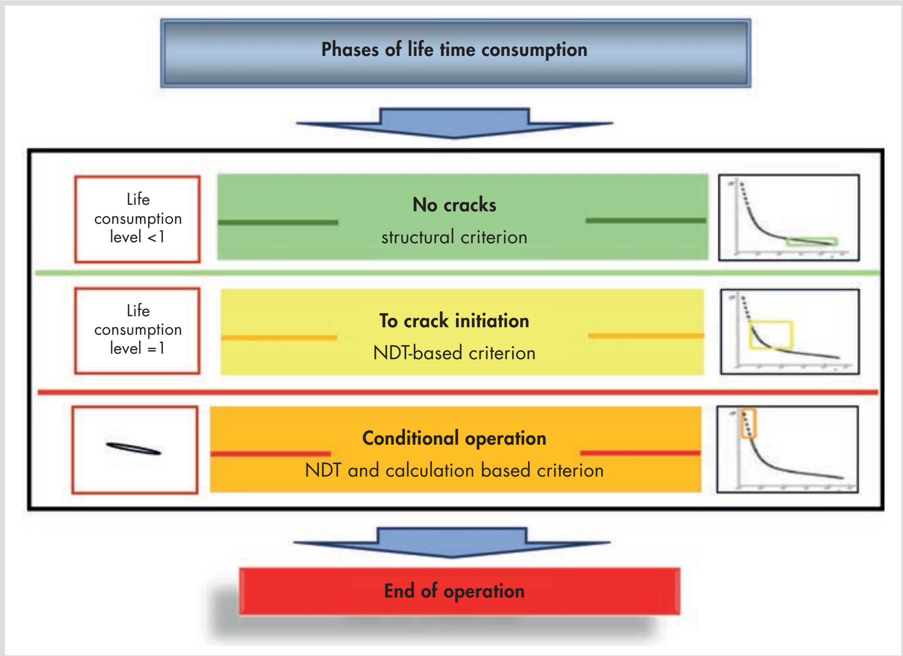


Fig. 5. Use of Life Consumption of the critical components depending on the mode, conditions and strategy of operation.

The prefabrication of new elements exposed to thermo-mechanical fatigue should include the performance of additional measurements ensuring the possibility of conducting calculations of exhaustion of durability from fatigue in the most accurate way possible.

The monitoring and conditional operation of the components uses the measuring and analytical module of the IT Platform LM System PRO + ® [3]. Depending on the results of ongoing analysis of the technical condition of the elements, decisions are made regarding the possibility of their further safe operation, including the performance of NDT control tests to the appropriate extent.

After completing the diagnostic supervision, ending with the replacement of elements or the end of their service lifetime, it is recommended to perform destructive tests to the extent that allows determining the nature of the damage and the actual size of the cracks in various phases of conditional operation.

Figure 5 presents a diagram of the diagnostic supervision process for an element exposed to thermo-fatigue damage.

Diagnostics supported by exchange of knowledge and experience

The operating experience of users of the one-type or very similar to each other equipment, have the highest status, because they allow both the identification of the most important problems and provide proven methods of solving them.

The combination of the results of tests performed during planned and emergency overhauls and the results of the analysis of operating conditions and availability allows for obtaining advanced knowledge for planning the scope of diagnostics, overhauls and expenditure on maintenance of technical condition [4, 5].

For this purpose testing standards, a remote diagnostic system and a web portal integrating information, knowledge and experiences of many users of the same class of power equipment have been developed.

The internet portal is a place where common knowledge is created on the scale of users of one class of power equipment (Figure 5). 200 MW units will remain an important part of the power system in the foreseeable future. The portal integrates standstill and operational/remote diagnostics in a way that allows current updating of the technical condition assessment of

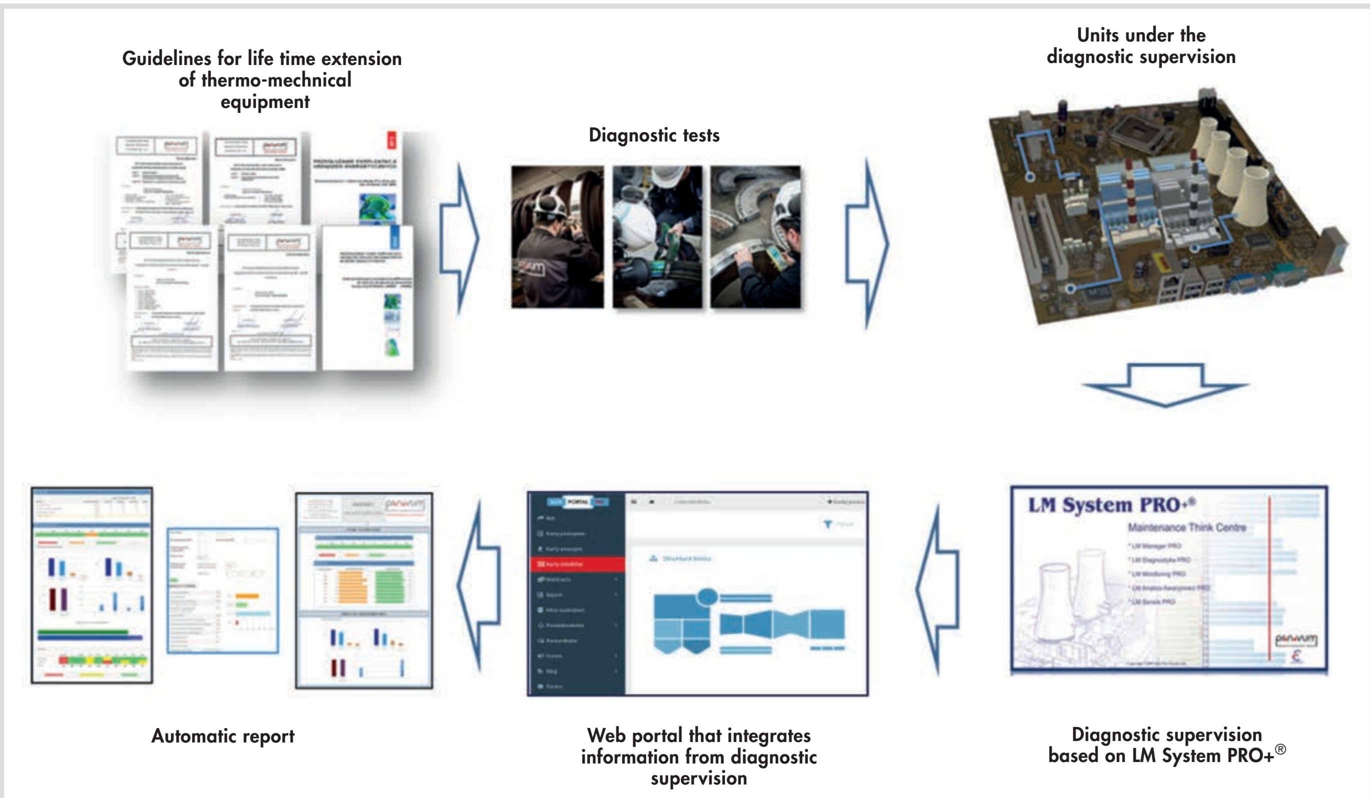


Fig. 6. Diagnostic system for power units 200 MW class using an IT portal.

thermo-mechanical equipment and verification of their durability forecast. It can act as a strong tool supporting the work of engineers dealing with maintenance issues in the conditions of continuous transformation of the power sector, which means the operation of conventional units in conditions less and less typical for them.

The portal communicates with the users in the website mode while maintaining all the necessary security requirements. This applies both to reports addressed to individual users as well as joint reports.

Summary and conclusions

Properly modernized units of 200 MW and 360 MW class may prove to be safe in operation and available in the next time horizon supporting the gradual transformation of the Polish power system in accordance with the European green deal scenario.

Diagnostics, treated as a source of advanced technical knowledge, has created a significant share in the possibility of implementing such a strategy, especially in the case of 200 MW power units, which created conditions for low-cost extension of operation through:

- lifetime extension of critical or thick-walled components of main thermo-mechanical power equipment, well above design durability,
- improving their flexibility.

In the last phase of operation of conventional power units diagnostics should be a source of advanced knowledge to a greater extent than before. Limited possibilities of using the previous experience and the loss of technical expertise of the personnel may turn out to be a greater threat than the loss of durability of power unit components.

In order to significantly reduce such a threat, diagnostics should be organized and performed in the described below manner:

- organized as a process appropriately integrated with operation, where standstill of the unit is also treated as important part of the operation,
- performed in a remote mode, which creates conditions for increasing quality, reducing costs and using advanced analytical methods,
- supported by failure analysis, associated with the analysis of working conditions and maintenance costs,
- test results of decommissioned components should be assured of high status,
- enabling the transfer of information, knowledge and experience from many objects of the same class using the AI methods,
- use the methodology and criteria of fracture mechanics to a greater extent than before, which enable the use of the lifetime reserve of elements with material discontinuities of the nature of thermo-mechanical cracks, when repair/replacement is unacceptable for economic reasons.

Diagnostics equipped with more functions than before does not have to be more time-consuming and more expensive than previously used. Properly organized and implemented, it can be maintenance-free, especially in the area of reporting current knowledge and guidelines for the operation strategy.

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Mr Gregor Scharpey | phone: +49 201 8128-200 | E-mail: mark@vgb.org