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Nonlinear Trend Analysis of Mill Fan System Vibrations for Predictive Maintenance and Diagnostics

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Abstract—**Present paper considers nonlinear trend analysis for diagnostics and predictive maintenance. The subject is a device from Maritsa East 2 thermal power plant a mill fan. The choice of the given power plant is not occasional. This is the largest thermal power plant on the Balkan Peninsula. Mill fans are main part of the fuel preparation in the coal fired power plants. The possibility to predict eventual damages or wear out without switching off the device is significant for providing faultless and reliable work avoiding the losses caused by planned maintenance. This paper addresses the needs of the Maritsa East 2 Complex aiming to improve the ecological parameters of the electro energy production process.**

Keywords—**Technical diagnosis, fault diagnosis, predictive maintenance, manufacturing execution system (MES), enterprise resource planning (ERP).**

I. INTRODUCTION

THE predictive maintenance includes four stages: predictive diagnosis, estimation of potential looses, decision making for device maintenance and maintenance schedule arrangement. Technological diagnosis as the basis for predictive maintenance is established field of scientific and applied investigations. Top-managers of leading factories in the chemical, petrochemical, silicate industry, energy, metallurgy, mining industry in Europe and around the world have adopted in their current practice that economic success and competitiveness depend heavily on the security of technological facilities and low cost of maintenance them. Predictive maintenance based on diagnosis, prolongs the life of machines and aggregates, reducing downtime, maintain optimal level of production, ensure compliance with the precise timing of delivery of production (raw materials, energy), allows for effective management of maintenance of facilities, using the least staff and costs, planning and repairs according to actual conditions of machines and in the most appropriate time in accordance with the tasks of the subsystems of Enterprise Resource Planning (ERP). The results of the system to predictive maintenance are critical for a number of user groups from industry and engineering – specialist maintenance and repair, operators and dispatchers, designers of industrial systems with great complexity, so as to ensure high reliability, fault tolerance and availability. One of the study tasks is evaluating the probability of failure of element, machine or center as a time function. This is important from engineering point of view in order to adjust the machine inspection policy.

According to the International Standardization Organization (ISO) ”Prognostics is time for estimation of damage and risk for one or several future damages”, [1]. Thus technological diagnosis can be understood as a process of estimation of Remaining Useful Life (RUL) before damage occurs, which is estimated based on the current status of the facility and last operating mode [2].

The current state can be considered as the degree of implementation of the specified functionality. The diagnostics is not classified in only two or three classes, but is conceived as a continuous process of degradation. Quantitative evaluation of the degree of degradation is the result of applying the diagnostic methods on the current measurement data from sensors and Supervisory Control And Data Acquisition (SCADA) or Decentralized Control System (DCS) measurements with special diagnostic equipment. Thus predictive maintenance should be seen as a process of prediction and evaluation of future behavior [3], [4]. Critical stage is forecasting the development of degradation of the facility. Highly debatable issue is the assessment of the accuracy of the forecast. Two approaches are outlined for formulation of the metrics for evaluation [3], [5]. One of them is connected to risk assessment of a forecast. The other is defined based on the quality of the action taken for preventive or corrective maintenance.

The second approach is based on measurements and data – driven. There are numerous other approaches, but all can refer to two types of techniques – artificial intelligence (AI) and the theory of probability and mathematical statistics. Between the artificial intelligence techniques have become particularly popular the methods of artificial neural networks and neuro-fuzzy networks. These are flexible and general approaches for predictive maintenance [6]. It is shown that their effective will be improved if is using different techniques such as:

- radial-based recurrent neural networks [7],
- wavelet neural networks [8],
- and robust neural networks [9].

The results are illustrated by different examples using machines with rotating parts [10].

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In last few years is increasing interest in the diagnosis based on the method of precedents (Case-Based Reasoning – CBR) [11]. This method is effective in the absence of sufficient measurements and especially for analysis and retrieval of precedents with their attributes and relationships. The adaptation procedure is implemented in the base of rules derived from experts. The results in paper [12] show that it is appropriate to combine the diagnostic method based on the precedents with neural network or fuzzy logic, which will mitigate the disadvantages of the method. Similar results are contained in [13].

The predictive maintenance, as a complex interdisciplinary field of science, technology and economy is far from completion. Its application in the industry faces a number of complexities. They are related to problems of technological diagnostics (limited opportunities for application of active diagnosis, lack of repeatability in testing objects, extremely large complex of facilities, equipment variability in their life cycle, inevitably a high degree of uncertainty), procedures for decision making for proactive or corrective actions to maintain, the methods for the scheduling of the action, integration into Manufacturing Execution System (MES) and Enterprise Resource Planning (ERP) systems.

From industrial application viewpoint, the maximal number of fault diagnostic applications in process industries are based on process historian based approaches. This is due to the fact that process history-based approaches are implementing modeling an a priori knowledge. Further, even for processes for which models are available, the models are usually steady – state models. It would require considerable effort to develop dynamic models specialized towards fault diagnosis applications. The scope of the process history based systems as applied in the industry is mainly restricted to sensor failures. There are very few industrial applications in published literature that deal with parametric failures. Among the process history based approaches, statistical approaches seem to have been well studied and applied. The reason for this might be that with the current state-of-the-art in applications, detection seems to be a bigger concern than detailed diagnosis. Hence, statistical approaches that are easy to build and which do very well on fast detection of abnormal situations have been successful in industrial applications. Chemical processes are inherently nonlinear in nature. While the theory of linear quantitative model-based approaches is quite mature, the design and implementation for nonlinear models is still an open issue.

Fault diagnosis shares with other process operations the realization that with powerful knowledge representation schemes, one can capture the expertise of operators and control engineers that was gained over years of experience with process plants. Process specific knowledge can be used to improve general purpose methodologies. There is a close coupling between diagnosis and process operations design of chemical plants. The proper design of a chemical plant can reduce the burden on the task of diagnosis. Also, the information from diagnosis can be used to continuously improve the performance of process operations. The information from fault diagnosis can be incorporated into the traditional solution paradigms of other process operations. The aim of this paper is to provide a brief overview of various methods and operations modules that would particularly share information with the fault diagnosis module and also outline the nature of interaction that one can expect.

II. PROBLEM FORMULATION

In the presented paper we have chosen to analyze a device from Maritsa East 2 power plant – a mill fan. Maritsa East 2 thermal power plant (TPP) has built up eight blocks – 4 × 175 MW and 4 × 210 MW. In historic plan in 1962 a decision has been taken for building up Maritsa East 2 TPP, and since 1970 the electro energy of least price cost for the country is produced in Maritsa East 2 TPP. At the end of 1995 8th energy block has been connected in parallel to the energy system of the country by which the second stage of Maritsa East 2 TPP enlargement was completed. Achieved installed capacity is 1450 MW. This turns Maritsa East 2 TPP into the biggest thermal power plant in the Balkans. After following reconstructions and modernizations installed capacity at the moment reaches 1556 MW as in the end of 2009 block 6 was cut off for the purpose of modernization and increasing its capacity to 230 MW. The Maritsa East 2 TPP being the largest thermal power plant on the Balkan Peninsula and the choice of the given power plant is not occasional.

The mill fans are used to mill, dry and feed the coal to the burners of the furnace chamber. They are together milling and transporting devices. Mill fans are most often used for power plants burning brown and lignite coal. In general these are large centrifugal fans which suck flue gases with temperature around 800-1000 °Cfrom the top of the furnace chamber. In the same pipe the coal is fed, thus diminishing the drying agent temperature and drying the coal prior entering the fan. The coal is being milled by the fast rotating rotor of the fan and turn into coal dust. This dust is transferred to separator which returns the bigger particles to the fan.

The separator can be tuned for a desired dust granulometric size. One of the most important parameters to control is the discharge temperature of the dust-air mixture. For the considered mill fan it should be between 145-195 °C. Lower than 145 °Cmay cause clogging of the mill and higher than 195 °Cmay cause the dust to be fired in the ducts prior the burners. This temperature is also a measurement for the load of the mill. The lower the temperature the higher the load is more coal is fed to the mill. The part which suffers the most and should be taken care of is the rotor of the mill fan. Because of the abrasive effect of the coal it wears out and should be repaired by welding to add more metal to the worn out blades.

The mill fans (MF) are centrifugal fans of the simplest type with flat radial blades adapted for simultaneous operation both like fans and also like mills. The basic components of a mill fan are (Fig. 1): steel body , covered by bar shield plates *2* thick 7080 mm, and a rotor, consisting of a mill wheel *3* with twelve blades *6*. The rotor is fixed by a console to a shaft *4*, located upon two roll bearings [14].

The mill wheel blades *1* (Fig. 2) bear shield beats *2* thick 30-40 mm, directly beating the coal particles. The fuel entering the mill is sucked to the beating elements of the mill-fan

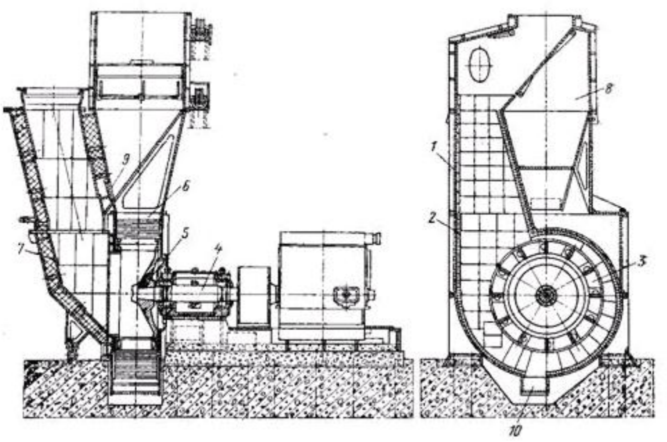

Fig. 1. Mill fan.

rotor together with the drying agent (usually hot gases with a temperature of 950-1100^{o}C). The located before the mill fan descending mine is the place for intensive drying of the fuel where a good deal of the external moisture is reduced; in the milling zone, i.e. between the shield bars -blades an additional drying takes place and also an effective milling of the dried fuel.

The ground product with the cooled drying agent is forced by the dozing rotor of the aggregate into a centrifugal or inertial separator *3* from where the big particles return to the mill and the small ones are carried out by the gas stream through the dust pipes to the burners. At the output end of the pipe for returning big particles from the separator a cone valve is set to regulate the amount of recycling gas from the separator downwards to the bottom of the fuel-delivering drying mine to induce into the mill fan.

Whenever it is necessary to reduce the intensiveness of drying, the recirculation of the cooled drying agent is intensified (increased). Metallic parts and the trioxide are caught in a specific box *10* in the down section of the corpse. The higher the productiveness of the mill fan, the greater its diameter; this is accompanied by a deterioration of the even fuel distribution along the blades, by an intensified local wearing-out of the blades, also of the trioxide disc and a decrease of the milling effectiveness. The drying-agent temperature after the drying mine, i.e. before the very mill fan, must not exceed 450-500^{o}. The percentage of 0_2 in the damp mixture before the mill can reach 2,5 % and the part of 0_2 together with the moist evaporation in the drying mine is reduced to less than 15-16 %; this ensures the installation against explosions this makes the installation explosion-proof.

The total pressure developed by the mill fan equals to 1-2 kPa (100-200 mm water column) and it is directed to overcoming the resistance of the drying path which is under pressure and also of the resistance of the separator, the dust piping and the burners.

Coal milling systems with mill fans are widely used in the fossil fired power plants, due their possibility to simultaneously dry, mill and transport the coal to boilers furnace chamber.

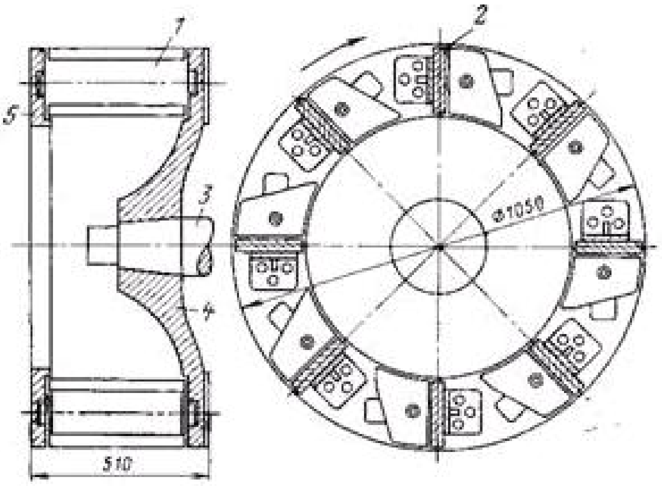

Fig. 2. Mill fan rotor.

As drying agent are used hot flue gases from the furnace chamber with low oxygen content which makes the process explosion proof for very high temperatures. This process also diminishes the nitrogen oxides emissions. These features make the mill fan system suitable for boilers firing low caloricity lignite.

For 210 MW power units the milling rotor has diameter $D = 3.4m$, width $b = 0.9m$ and rotation speed $n = 490rpm$. There is also a system for drying agent temperature control. Such mill fan is shown in Fig. 1.

Drying agent flow depends on the amount of coal to be milled. Thus if the mill gets loaded the discharge temperature decreases and vice versa.

Coal and flue gases enter the mill through a special duct taking gases from the top of the furnace chamber. The rotor works as fan and a mill. After milling the coal dust gets into a separator, where the milled fractions are directed to the burners or back for additional milling depending on their size.

The boiler which milling system is studied is a Benson type once-though sub-critical boiler. There are four mills per boiler. Each mill fan system has four radial bearings two in the mill and two in the motor. All the data used in the present research are obtained from the historian system of the Distributed Control System (DCS).

III. PROCESS CONTROL SYSTEM

Experion® Process Knowledge System (PKS) is a cost-effective open control and safety system that expands the role of distributed control. It addresses critical manufacturing objectives to facilitate sharing knowledge and managing workflow. Experion provides a safe, robust, scalable, plant-wide system with unprecedented connectivity through all levels of the plant as illustrated in the following high-level view of the architecture. The Experion unified architecture combines DCS functionality and a plant-wide infrastructure that unifies business, process, and asset management to: Facilitate knowledge capture; Promote knowledge sharing; Optimize work processes; Accelerate improvement and innovation.

The Experion platform is well suited for both small and large systems. It provides the power and flexibility required to handle the full spectrum of process control and safety applications. Experion offers state-of-the-art Decentralized Control System (DCS) capabilities that include Abnormal Situation Management (ASM), Safety Management, and Information Management technologies. Experion interfaces with Foundation Fieldbus, Profibus, DeviceNet, HART, LON, ControlNet and Interbus. Robustness, security, compliance, control, safety, and reliability are plant-wide. Its distributed control features include a complete continuous, logic, sequential, and drive object-oriented control environment hosted on fully redundant controllers. Experion Process Knowledge System features include:

- Sophisticated human-machine interface.
- Tightly integrated databases, engineering tools, and control and safety applications.
- Operational integration of control and safety applications.
- Open, deterministic, high-speed control network communications system for predictable and repeatable control linking servers, controllers, and remote I/O.
- A configurable Control Execution Environment (CEE) provides deterministic, consistent, and reliable control application execution.
- A single builder tool, Configuration Studio, allows integrated application configuration.
- Three CEE-based controllers: The C200 Process Controller is a compact and cost-effective solution located close to the process with direct IO connections. It is ideal for integrated regulatory, fast logic, sequential, and batch control applications. The C300 Process Controller is the next generation controller that builds on the reliability and robustness of the C200 controller to provide even more versatile control integration through innovative mounting and connecting techniques. The Application Control Environment (ACE) is ideally suited for supervisory control solutions and integration with third party control systems. It is hosted on a server grade computer platform.
- Safety Instrumented Systems (SIS).
- The Simulation Control Environment (SCE) supports system simulation on computers without requiring dedicated controller hardware or process connections.
- Redundancy support for servers, networks, and controllers.
- Distributed System Architecture (DSA) that integrates multiple servers into a single operational system.
- Support for internationalization/localization.
- Interfaces for wide variety of third-party controllers and protocols.
- A cost-effective architecture that – makes extensive use of open technologies and commonality of hardware, and is scaleable from just a few points, to thousands of points.

The measurements of the necessary mode quantities for mill fan in the DCS or SCADA system are rather inaccurate due to the significant changeability of the conditions for measurements (wear, slagging, sensor pollution) and also due to the great amount of external disturbances (dust and humidity of fuel, imprecise dosing of coal, stohasticity of temperature of the intake oven gases due to non-stationarity of the flame position) [15]–[19]. The symptoms in a diagnostic problem are always indirect and they are of stochastic nature (changes of temperature of the dust-air mixture (DAM) at the separator output related to the average one for the DPS, the flame position (horizontal, vertical), the relative power consummation for grinding, corrected rotating frequency for the raw fuel feeders (RFF)) [16]–[20].

IV. EXPERIMENTAL RESULTS

Mill fans are a part of the equipment of power units that are most often repaired due to intensive erosion of the operative wheel blades in the process of grinding of low-calorific lignite coal from the Trayanovo 1 and Trayanovo 2 mines with high percentage of dust (28%-45% of the dry mass).

In spite of the constructive measures to use steels with high resistance index in critical parts of the mill fan, their interval between two successive repairs equals to 2-2.5 months. The mill fans are of critical importance for the automation of the power-unit (PU) supply, so their technical state is an object of strict monitoring, repair and on-line duty according to the operative dispatcher time-table. The control range of mill fan is small, therefore the primary power control and especially the secondary power control is realized by stopping and starting some of the mill fan.

The experimental research is done in the Bulgarian national Maritsa East 2 thermal power plant. The plant has four double blocks with direct-current boilers 175 MW each and four monoblocks with drum boilers 210 MW each. The fuel for both types of blocks is one and the same: low-quality Bulgarian lignite coal from the Trayanovo 1 and Trayanovo 2 mines with caloricity of 1200 – 1600 kkal/kg (5000 – 6700 kkal/kg). The basic data are obtained from steam-generator 6 of block 3. The steam generator has four mill fans. There is a decentralized control system (DCS) mounted over the steam generator. All used data are recorded in the Historian system of DCS. The duration of the observations is 8 months in 2010. Two types of data are used for the research – vibrosignals from mill fan and data about the basic mode parameters related to mill fan.

The mill fan vibration state may become a rather useful component of their diagnostics to determine their affiliation to some zone of efficiency – *S1* – the normal one; *S2* – partial damages; still possible exploitation with lowered mode parameters (e.g. loading) and measures for current maintenance (lubrication, jamming bolt joints of mill fan to the bearers, technological adjustments (angles of rotation of valves, jalousie); *S3* – zone of serious damages, requiring immediate stopping at the first opportunity (stop the unit). The mill fan vibration state may become a rather useful component of their diagnostics to determine their affiliation to some zone of efficiency (see Tab. 1). Where:

- S1 – the normal one;
- S2 – partial damages; still possible exploitation with lowered mode parameters (e.g. loading) and measures for current maintenance (lubrication, jamming bolt joints of

mill fan to the ground), technological tunings (angles of rotation of valves, jalousie);
- S3 – zone of serious damages, requiring immediate stopping at the first chance (stop the unit).

The mill fan state is multidimensional. The basic components are grinding productiveness *B* [t/h], fan productiveness *W* [m^3/h] and vibration state S^V_{MB} (amplitude of vibrations *A* (or velocity/acceleration of vibrations)).

Exemplary limits for the workability of the Maritsa East 2 power plant monoblocks of 8 MW each are shown in Tab. 1.

TABLE I

Component	*B*	*W*	*A*
S, dimention	t/h	m^3/h	mm
S_1	55	200 000	6
S_2	48	180 000	7
S_3	<40	<140 000	>8

Analogical are the limits of workability and also of the mill fans for the double-blocks of Maritsa East 2 power plant they are installations with 4 mill fans each.

The basic problem for diagnostics of the mill fan technical state is the impossibility for direct measurement neither of the components *B*, *W*, *A*. Difficulties with the assessment of the mill fan vibrostate is the object of interest below.

It is a major problem that the increased values for vibrations may not refer to the technical state of the mill fan. They may be due to:

- Hydrodynamic instability in the sectors between the blades of the operative wheel;
- Uneven filling of the operative wheel with coal dust;
- Personnel faults;
- Worsened quality of fuel and especially the contents of dust of dry mass A^d.

The process of changing the mechanical properties which are likely to induce increasing vibrations is basically due to uneven worn-out blades of the operative wheel, but also due to traditional sources of vibrations in mechanical systems [21]

- Damaged bearings;
- Unbalanceness;
- Uncoaxiness;
- Insufficiently robust joint of the mill fan with the bearers;
- Lubrication problems.

The results from the few references for research of the nature of vibrations in the mill fan [22], [23], and also of similar systems [24], [25], our observations included, and show that there are enough reasons to treat these vibrations as nonlinear.

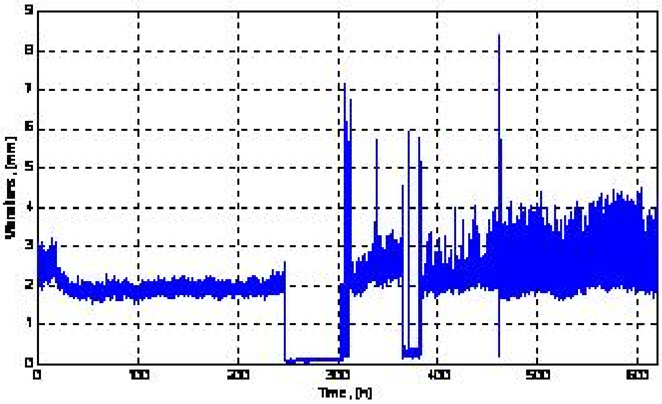

Fig. 3. Distribution of reflecting objects for the computer simulation.

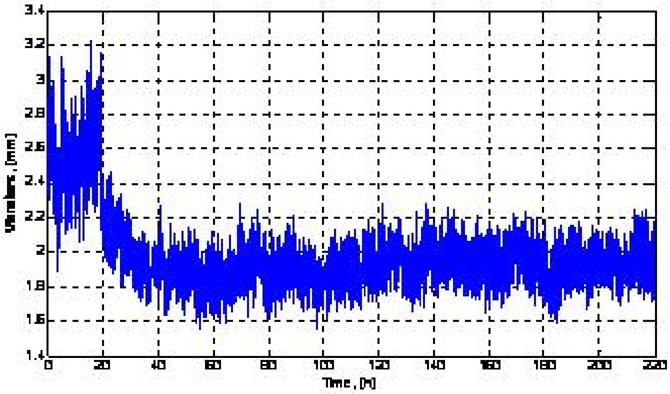

Fig. 4. Passive SAR raw signal.

Prognostic maintenance of a mill fan is considered in the presented paper. It is based on the vibration of the nearest to the mill rotor bearing block. In the present paper the analysis is done using data archived by the installed on the site DCS Honeywell Experion PKS R301. The observation period is 16.12.2010 – 16.01.2011. On 31.12.2010 the rotor of the mill fan is changed. After the replacement it has been working for 378 hours. The period chosen allows for vibrations analyzes before and after the replacement. In Fig. 3 are shown the vibration values in millimeters as a function of the mills rotor working hours.

Presented data shows working and idle states of the device before and after replacing the rotor. Next figure shows vibration rates before rotor replacement.

Due to higher nonlinearity of the device a nonlinear trend analysis for diagnostics and predictive maintenance is done. Regression analysis is done in Matlab environment. It was found that a polynomial of degree 7 fits the data best. Results are presented in the next figure. From industrial application viewpoint, the maximal number of fault diagnostic applications in process industries are based on process historian based approaches. This is due to the fact that process history-based approaches are implementing modeling an a priori knowledge.

It is observed that after the replacement the vibrations with new rotor have higher amplitudes than with the worn out one. This is because of the abrasive wear out of the rotor – the blades become thinner and the rotor becomes lighter. The new rotor is heavier so the vibrations are more intensive even though the rotor has been carefully balanced.

After preliminary data processing including idle periods removal in Fig. 6 are shown the vibration rates after rotor replacement. It is plain to see the vibration rate is higher. Taking into account the observed trend before rotor replacement it is possible to prognosticate the next planned device maintenance

- b

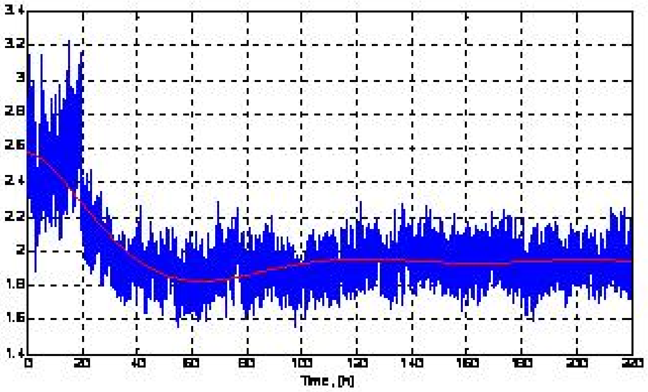

Fig. 5. Computer simulation results for a) TDC and b) RDA imaging algorithms.

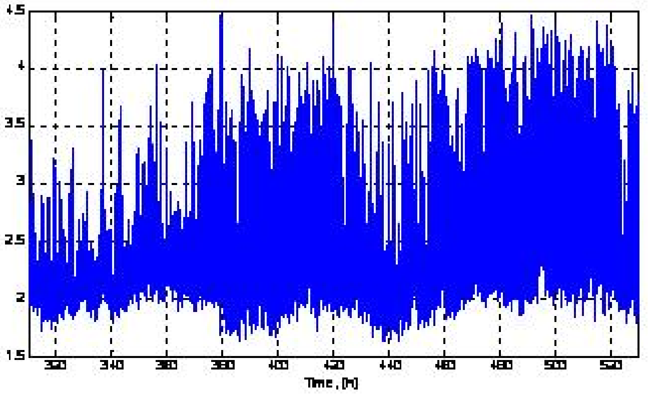

Fig. 6. Experiment organizational scheme.

shutdown.

V. CONCLUSIONS

This paper proposes a nonlinear trend analysis for diagnostics and predictive maintenance. Vibration rates of a mill fan system for Maritza East 2 power plant have been analyzed. The obtained results show that nonlinear trend analysis may be successfully applied to estimate and predict changes of the mill rotor state. Because of the chosen device features it is important to mention the necessity of additional information regarding the exploitation rates. In the considered example this is expressed in knowledge about the planned maintenance and rotor replacement shutdowns. To increase the usability of the proposed diagnostic procedures it is also necessary to take into account the efficiency rates of the process, which would allow for a better picture about the necessity of effective and in time prognostic maintenance of the thermal power plant devices.

Vibrosignals may be successfully used as a substantial additional symptom for isolation and diagnostics of mill fan system which is not done at present. The assessment of the mill fan vibration state is a complex problem due to the exceptionally big uncertainty in the measurements which follows from the temporally re-covered changes of multimode factors. The mill fan vibration state S_{MB}^{V} is a valuable integral indicator for its efficiency.

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