

Radosław CECHOWICZ
Paweł STĄCZEK

COMPUTER SUPERVISION OF THE GROUP OF COMPRESSORS CONNECTED IN PARALLEL

KOMPUTEROWY SYSTEM NADZOROWANIA ZESPOŁU SPRĘŻAREK PRACUJĄCYCH W UKŁADZIE RÓWNOLEGŁYM*

The paper presents the original solution of the control and monitoring system of the compressed air production plant. The plant was supplying the mid-size production system. The developed solution is consistent with the Condition-Based Maintenance approach. Its aim was to integrate the functions of direct control and monitoring of the process to ensure the best possible working conditions of machines (compressors) and to extend the period of their operation. The implementation of the described solution allowed: to eliminate the need for human presence in an environment with very high levels of noise, to improve the quality of the process by stabilising the course of its basic characteristics (variables), to automate the handling of alarm conditions, to increase machines' reliability through their rational use and ensuring proper working conditions, and to document the process. Freeing the operator from the common, repetitive control tasks and equipping him with diagnostic tools enabled him to detect threats (potential failures) sooner and to undertake appropriate corrective actions.

Keywords: monitoring, diagnosis, operation of compressors, Statistical Process Control, Condition Based Maintenance.

W pracy przedstawiono własne, wdrożone rozwiązanie problemu automatyzacji sterowania i nadzorowania procesu wytwarzania sprężonego powietrza na potrzeby średniej wielkości systemu produkcyjnego. Opracowane rozwiązanie jest zgodne z podejściem Condition-Based Maintenance. Jego istotą było zintegrowanie funkcji sterowania bezpośredniego oraz nadzorowania przebiegu procesu w celu zapewnienia możliwie najlepszych warunków pracy maszyn i wydłużenia przez to okresu ich eksploatacji. Wdrożenie opisanego rozwiązania pozwoliło na: wyeliminowanie konieczności przebywania ludzi w środowisku o bardzo dużym poziomie hałasu, poprawę jakości procesu poprzez ustabilizowanie przebiegu jego podstawowych charakterystyk (zmiennych), zautomatyzowanie procedur obsługi sytuacji awaryjnych, zwiększenie niezawodności maszyn poprzez ich racjonalne wykorzystanie i zapewnienie prawidłowych warunków pracy, oraz dokumentowanie przebiegu procesu. Uwolnienie operatora od zadań sterowania i wyposażenie go w narzędzia wspomagające diagnostykę procesu spowodowały, że był on w stanie wcześniej wykryć zagrożenia dla przebiegu procesu (potencjalne awarie) i podjąć stosowne działania zaradcze.

Słowa kluczowe: nadzorowanie, diagnostyka, eksploatacja sprężarek, statystyczne sterowanie procesem.

1. Introduction

The paper describes the compressed air plant control and monitoring system that is based on the idea of Condition-Based Maintenance (CBM), i.e. performing maintenance and repair only when the need for such actions results directly from machine observation, and not when it is imposed by the maintenance schedule. The idea of CBM is growing in popularity as evidenced in works [6] and [8] where the most common solutions and diagnostic methods were summarised.

Three main components should be taken into consideration to successfully implement the CBM strategy: acquisition of data containing information about the status of the monitored devices, processing of the obtained information (data), and decision-making mechanism. The precise diagnosis is essential in CBM systems as it is used as a basis for decisions on maintenance and repair actions [11].

Potential benefits of CBM approach are twofold: firstly, service operations are performed when there is a real need for them (good parts are not replaced just because their planned operation time has expired), secondly, the danger of machine failure due to premature part wear is eliminated. The properly implemented CBM system makes possible to reduce the maintenance costs of the machines and

increase the overall performance of a manufacturing system by eliminating the downtime associated with equipment failures.

One of the methods to monitor the state of the process that can be used in CBM is using control charts, which are well known part of a broader strategy of statistical process control (SPC). The main purpose of the control charts is to detect and signal deviations from the natural variability of the process (of selected quality characteristics). This approach has been used, for example, in [5]. Control charts, proposed by Shewhart [10], were used for the first time in the automotive industry to evaluate the quality of the production batch.

The compressed air plant, for which the described method was developed, was composed of four reciprocating compressors working in parallel, and supplying the factory distribution network. There were various devices and machines (receivers) connected to the compressed air distribution network in the factory. They had different air consumption characteristics (cargo handling systems, transport devices, auxiliary devices, and hand tools). The demand for air during the manufacturing system operation was characterised by high dynamics. For this reason, the development of a static plan of compressor operations was a difficult task. The production of compressed air had to be controlled and monitored continuously by the operator who, having

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie www.ein.org.pl

access only to the current readings of measurement devices, had to make decisions about switching on or off the compressors and had to carry out maintenance work according to the maintenance plan. Due to the time-consuming nature of these operations and the considerable number of measurement points, the evaluation of technical condition of the compressors was made occasionally, a few times a day. Therefore, it could happen that the machines worked temporarily under adverse conditions (e.g. overload), which was one of the causes of their failures and downtime. This, in turn, led to problems with the receivers connected to the air distribution network.

To improve this situation, it was decided to automate the control and diagnosing of the process of production of compressed air. Additional prerequisites to automate the process were: the need to improve the working conditions of the operator, the need to stabilise the pressure in the compressed air distribution network, the requirement for an automatic documenting of the manufacturing processes [9].

2. Control of the compressed air plant

A system for automated control and monitoring of the compressed air plant was developed and implemented. In this system, the values of the basic variables of the process were monitored continuously and control algorithms guaranteed correct operation conditions for each of the machines, as well as uniform loading of all compressors. A detailed description of the control algorithms for individual machines and the entire plant was given in the works [2] and [3].

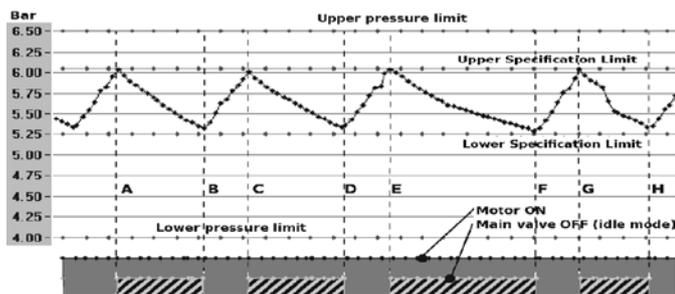


Fig. 1. Time chart for pressure in the network and the status of the compressor with low compressed air demand

In Fig. 1 the recorded pressure waveform in the air distribution network is shown. The recording was done during the time of low air consumption (low load of the compressed air plant). At that time, it was enough to use just one compressor to satisfy the demand. The motor driving the reciprocating compressor was working all the time, and the air was pumped only during the periods of B–C, D–E and F–G. In the remaining time (intervals A–B, C–D, E–F and G–H) the compressor inlet valves were deliberately opened (idle mode).

The duration of each interval of quasi-periodic waveform resulted from the rate of pressure rise or fall, that is from the air flow rate to the receivers. The main objective of the automatic control system was to maintain the pressure in the air distribution network within the tolerance limits 5.25..6.05bar (LSL..USL). In Fig. 1, the alarm limits are also marked. There is a sudden drop in the air pressure, shown in Fig. 1, in the period G–H. This drop was caused by a temporary increase in air demand. The system responded to it with the shortening of the idle time of the compressor.

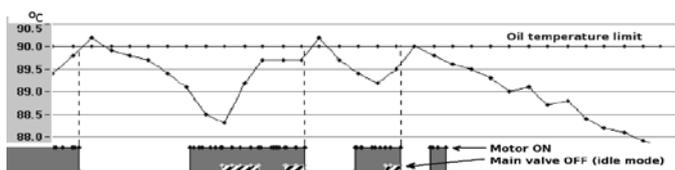


Fig. 2. Temporal switching off the compressor motor caused by exceeding the maximum temperature of the oil

The process data record shown in Fig. 2 documents the oil temperature alarm event and switching off the compressor motor that followed. Such situations did occur when the compressor was working for long time during the summer heat. The compressor (precisely, the motor) was turned off each time when the predicted oil temperature value went beyond the set limit of 90°C (three events are marked in the graph). After the temperature went below the limit, the compressor was switched on again (automatically, by the control system).

The pressure drop shown in Fig. 3 is the result of thermal overload of one of the compressors. In the segment A–B the machine was working correctly. In the time B–C there was an increased demand for compressed air, which resulted in an increase in the switching frequency of the compressor. At the end of this time (in the moment C) the oil temperature went beyond the limit. The compressor was automatically switched off and then, after the oil temperature went below the limit, switched on again. Since the increased demand for compressed air continued throughout the time C–D, the following emergency shut-downs resulted in the gradual decrease of air pressure in the network. Eventually, the pressure went down to a very low level and reached the lower limit, activating an alarm and alerting the technical staff about the situation. When the alarm was signalled, some of the pneumatic devices were switched off by the users, which reduced the demand (at the end of the time C–D). From that moment on, the air pressure remained within tolerance limits. During the time shown in Fig. 3 only one compressor was working (other machines were switched off permanently by the factory personnel).

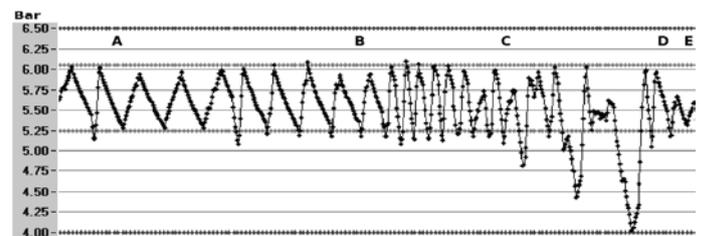


Fig. 3. Compressed air pressure fluctuations caused by the thermal overload of one of the compressors

3. Monitoring and diagnostics

The values of the main variables of the compressed air manufacturing process were recorded and presented on the operator screen in the form of readings (numeric values) and time graphs (similar to these shown in Fig. 1..3). The following analogue variables were monitored for the diagnostic purposes:

- air temperature at the outlet of each compressor,
- oil temperature in the sump,
- oil pressure in the compressor lubrication system,
- air pressure in the distribution network.

Additionally, signals from the oil temperature and oil pressure limit switches were recorded.

The work [2] describes the method used for the quality evaluation of the process of the production of compressed air and the obtained results. The process capability index [7], calculated for air pressure p in the distribution network, was $c_{pk}=0.578$ during typical work conditions (typical demand for compressed air). The relatively low value of the capability index means, that statistically during approximately 7% of the working time the pressure p was outside the tolerance limits. It results from the properties of the control algorithm used, and the properties of the actuators – the compressors. The momentary output of the compressor resembled a discrete signal (each of the four machines could be in one of the three states: active, idle, or standby). Furthermore, there were technological limits imposed on the control system such as maximum number of motor starting events per hour and maximum continuous operating time. These conditions meant that the na-

ture of the changes in the air pressure at the output (in the distribution network) was quasi-periodic and the extreme values of the pressure p in one cycle often went outside tolerance limits – Fig. 4.

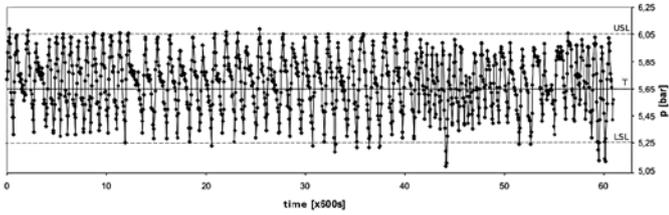


Fig. 4. The air pressure in the distribution network during the normal work of the compressed air plant (typical demand for air)

If the process correctness were evaluated only on the basis of the actual value of the pressure p in the network, it would result in frequent generation of unjustified alarms caused by typical fluctuations of the process variable. It was therefore decided to monitor the average value of the pressure p calculated over a suitably selected range (window) of time.

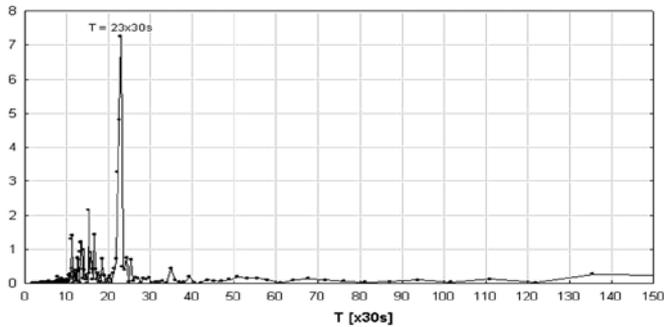


Fig. 5. The frequency spectrum of the signal of the air pressure in the distribution network

The frequency analysis of the monitored quality characteristics p (Fig. 5.) under typical production conditions (Fig. 4.) indicated the existence of a dominant oscillation frequency equal to:

$$f_1 = \frac{1}{23 \cdot 30s} = 0.0014Hz \quad (1)$$

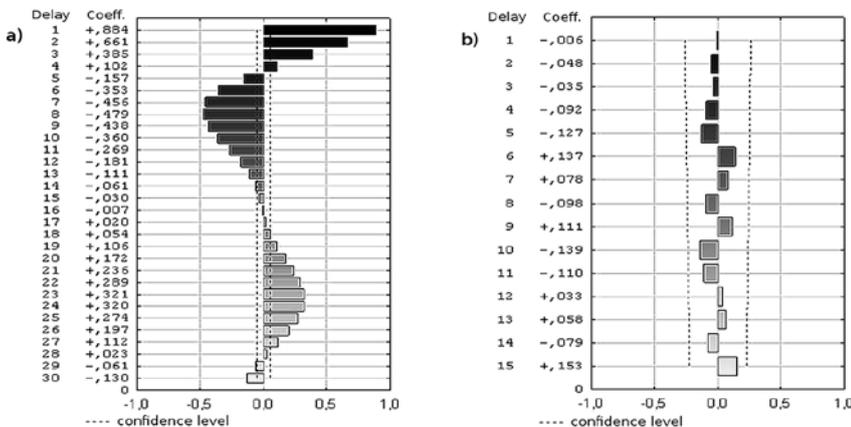


Fig. 6. Autocorrelation coefficients of the air pressure time-series: a) for raw data (variable p , the interval between successive measurements 30s), b) for the average of the subsequent 23 measurements (variable p_{23})

where the period of 30s is a constant interval between successive measurements of the value of variable p . Quasi-periodic nature of the pressure fluctuations p is also confirmed by the results of autocorrelation analysis (Fig. 6), where the ratio of the autocorrelation function for the shift of $N_1=23$ observations reaches the local extreme.

For the purpose of detecting irregularities in the course of the compressed air production, a new variable p_{23} was created. Variable p_{23} was the arithmetic mean value of 23 consecutive measurements of the p . Variable p_{23} calculated for the normal work conditions (the source data taken from Fig. 4) shows no deviations from the normal distribution (Fig. 7). Also, the time-series of the newly created variable does not show the existence of autocorrelation, which was verified by performing the appropriate statistical test [1] (Fig. 6b). It was therefore justified to use standard control charts X/R [7] to monitor the course of the compressed air manufacturing process with the quality characteristics p_{23} .

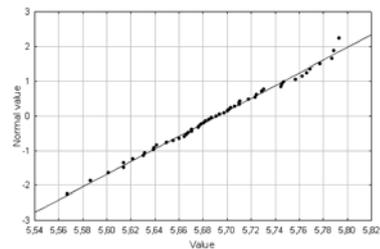


Fig. 7. Normality test for the p_{23} variable being the arithmetic average of 23 consecutive observations of the variable p

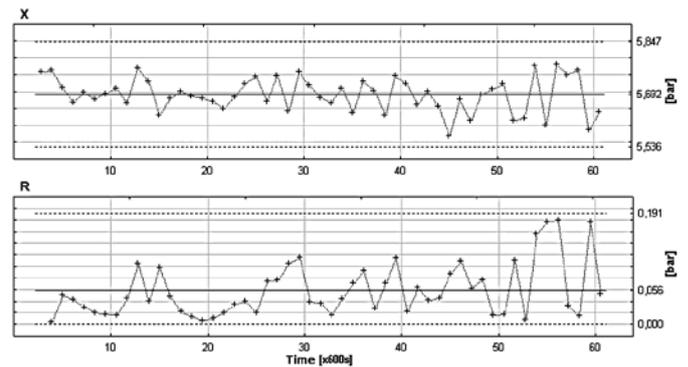


Fig. 8. Control charts X/R for the variable p_{23} during the normal process run (source data from Fig. 4), the sample size $n=1$

X/R charts for the variable p_{23} made for the normal work of the compressed air plant (from measurements shown in Fig. 4) are shown in Fig. 8. Sample size for the card was set to $n=1$ to reduce the time delay to detect and signal the disturbance of the process, which may be as long as: $N_1 \cdot n \cdot 30s = 11.5$ minutes. The central line of the X control chart for pressure variable p_{23} is equal to the average of the process assumed to be under control (Fig. 4). The small eccentricity of the process:

$$\hat{p}_{23} - T = 5.692 - 5.650 = 0.042 = 0.05(USL - LSL) \quad (2)$$

results from the properties of the compressor control algorithm and was accepted in terms of technological requirements. The control limits LCL , UCL were calculated from the standard deviation of

the variable p_{23} (for the same period) which equalled $\sigma_{23}=0.052\text{bar}$. The statistics of X/R that are shown in Fig. 8 confirm the absence of significant deviations from the typical variability in the quality characteristics p_{23} .

The course of air pressure p changes in the distribution network during high air demand fluctuations in amplitude and in frequency was shown in Fig. 9. At the beginning of this period, during a small load of the system (for about 30 minutes), only one compressor was working. At the end of this period (about 30th minute), the air demand

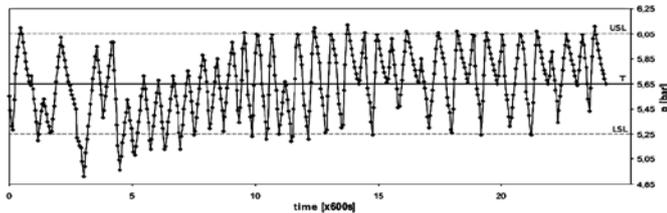


Fig. 9. The air pressure in the distribution network during the time of high demand fluctuations (disturbances)

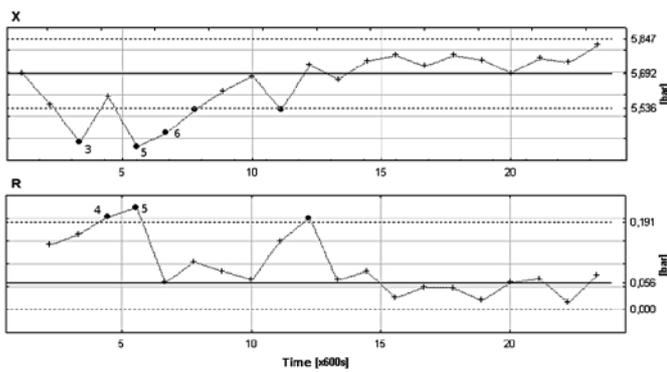


Fig. 10. Control charts X/R for the variable p_{23} at the time of process disturbances (source data from Fig. 10), sample size $n=1$

increased rapidly, which can be seen in the chart as a steep drop in the network pressure curve. The load in network was, at that moment, so large that one compressor could not supply enough air, so the control system automatically turned on the second machine. From the 35th minute on, the average pressure in the network was increasing. There was, however, a significant, highly dynamical and random “noise” (typical air consumption pattern for the devices performing handling and material displacement operations). It was not until the 80th minute when the network pressure p was within tolerance limits.

Control charts X/R ($n=1$) for the variable p_{23} made from the data shown in Fig. 9 are presented in Fig. 10. The points on the X chart (samples No. 3, 5, and 6) and on the R chart (samples No. 4, and 5), clearly indicate the disturbances in the process (insufficient air pro-

duction). In this situation, the computer control system generates an alarm to notify the operator that the system cannot meet the demand with just two working compressors (the two remaining compressors were switched off permanently). If these conditions lasted for a longer time, a thermal overload might occur (as the one shown in Fig. 3), which would then result in the shutdown of the compressors and a total halt in the compressed air production. Thanks to the alarm generated by the X/R charts, the operator could manage the situation before critical alarm occurred and react appropriately by allowing another compressor to work or by reducing the load in the network.

4. Summary

Based on experience of the operators and analysis of the data from nearly two years of operation of compressors with a modernised control and supervision system, three most common causes of compressor downtime were identified:

- high oil temperature and compressor output air temperature,
- high air humidity,
- breakdown (disconnection) of the measurement device or limit switch.

The number of machine malfunctions caused by factors a) and b), was significantly reduced through the use of control charts, whose task was to detect deviations from the natural variability of the process as early as possible. Thanks to the quick diagnosis and applied countermeasures, the compressors were not overloaded and, as a result, were not shut down.

Interference caused by factors from group c) was random and occurred sporadically. As there was no possibility to diagnose the state of the measurement and limit switch circuits, the control and monitoring system did not signal the possibility of failure caused by the events from this group. A similar approach to the assessment of a single compressor was presented in the work [4].

The tangible result of the implementation of the computer control and monitoring system was a significant reduction in the numbers of failures in the compressed air plant. The operator of the system, equipped with diagnostic tools (control charts), could accurately predict the possibility of failure in the majority of cases before they emerged.

Another significant outcome from the implementation of the system was the possibility to control the compressed air network load (compressed air consumption) by the production management personnel. Thanks to the information from the monitoring system, it was possible to plan production operations so as not to cause high and long-term load of compressors, which was the most common cause of emergency production stops.

References

- Box GEP, Jenkins GM. Analiza szeregów czasowych. PWN, Warszawa, 1971.
- Cechowicz R, Stączek P. Autonomous Control of Compressed Air Plant. Advances in Manufacturing Science and Technology 2010, 2(34), 71-81, Rzeszów.
- Cechowicz R, Stączek P. Automatykacja Procesu Produkcji Sprężonego Powietrza. IM Inżynieria Maszyn R. 11, z. 1 (2006), 112-119.
- Chen R, Yao W. Experimental Investigation on Reciprocating Air Compressor Performance. Advanced Materials Research 2012; 230-232: 1269-1273.
- Gupta S, Maiti J, Kumar R, Kumar U. A control chart guided maintenance policy selection, International Journal of Mining, Reclamation and Environment 2009; 23(3): 216-226.
- Jardine A, Lin D, Banjevic D. A review on machinery diagnostics and prognostics implementing condition-based maintenance, Mechanical Systems and Signal Processing 2006; 20(7): 1483-1510.
- Montgomery DC. Introduction to Statistical Quality Control. Wiley, 1997.

8. Prajapati A, Bechtel J, Ganesan S. Condition based maintenance: a survey. *Journal of Quality in Maintenance Engineering* 2012; 18(4): 384-400.
9. Rembold U, Nnaji BO, Storr A. *Computer Integrated Manufacturing and Engineering*, Addison–Weseley, 1993.
10. Shewhart WA. *Economic Control of Quality of Manufactured Product*. Macmillan And Co. Ltd, London, 1931.
11. Zhang Z, Zhou Y, Sun Y, Ma L. Condition–based maintenance optimisation without a predetermined strategy structure for a two–component series system. *Eksploatacja i Niezawodność – Maintenance and Reliability* 2012; 14(2): 120-129.

Radosław CECHOWICZ

Paweł STĄCZEK

Faculty of Mechanical Engineering

Lublin University of Technology

Nadbystrzycka 36, 20–816 Lublin, Poland

E–mail: wm.ka@pollub.pl
